WOODHEAD PUBLISHING IN TEXTILES



Clothing appearance and fit: Science and technology

J. Fan, W. Yu and L. Hunter

CRC

The Textile Institute

WP

Clothing appearance and fit:
Science and technology

Clothing appearance and fit: Science and technology

J. Fan, W. Yu and L. Hunter



The Textile Institute

CRC

CRC Press
Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Cambridge England

Published by Woodhead Publishing Limited in association with The Textile Institute
Woodhead Publishing Limited
Abington Hall, Abington
Cambridge CB1 6AH
England
www.woodhead-publishing.com

Published in North America by CRC Press LLC
2000 Corporate Blvd, NW
Boca Raton FL 33431
USA

First published 2004, Woodhead Publishing Limited and CRC Press LLC
© 2004, Woodhead Publishing Limited
The authors have asserted their moral rights.

Every effort has been made to trace and acknowledge ownership of copyright. The publishers will be glad to hear from the copyright holders whom it has not been possible to contact concerning: Figures 1.2, 3.4, 6.1, 6.3, 6.5, 6.6, 7.3, 7.9, 8.26, 8.27, 10.4 and 10.7; Tables 6.3, 6.4, 6.5, 6.7, 6.12, 6.13 and 6.14.

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. Reasonable efforts have been made to publish reliable data and information, but the authors and the publishers cannot assume responsibility for the validity of all materials. Neither the authors nor the publishers, nor anyone else associated with this publication, shall be liable for any loss, damage or liability directly or indirectly caused or alleged to be caused by this book.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming and recording, or by any information storage or retrieval system, without permission in writing from the publishers.

The consent of Woodhead Publishing Limited and CRC Press LLC does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from Woodhead Publishing Limited or CRC Press LLC for such copying.

Trademark notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation, without intent to infringe.

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

Woodhead Publishing Limited ISBN 1 85573 745 0
CRC Press ISBN 0-8493-2594-3
CRC Press order number: WP2594

The publisher's policy is to use permanent paper from mills that operate a sustainable forestry policy, and which have been manufactured from pulp which is processed using acid-free and elementary chlorine-free practices. Furthermore, the publisher ensures that the text paper and cover board used have met acceptable environmental accreditation standards.

Project managed by Macfarlane Production Services, Markyate, Hertfordshire (macfarl@aol.com)
Typeset by MHL Typesetting Limited, Coventry, Warwickshire
Printed by TJ International Limited, Padstow, Cornwall, England

Contents

List of figures ix
List of tables xv
Preface xvii
Acknowledgements xix

1 Perception of body appearance and its relation to clothing 1
J FAN

1.1 Introduction 1
1.2 Beauty 1
1.3 Facial attractiveness 3
1.4 Body physical attractiveness 4
1.5 Body image 8
1.6 Modification of body appearance by dressing 9
1.7 References 13

2 Subjective assessment of clothing appearance 15
J FAN

2.1 Introduction 15
2.2 Assessment of fabric surface smoothness 15
2.3 Assessment of seam appearance 20
2.4 Assessment of crease retention 24
2.5 Assessment of appearance retention of finished garments 25
2.6 Reliability of subjective assessment 27
2.7 References 29

3 Subjective assessment of clothing fit 31
W YU

3.1 Definition of fit 31
3.2 Influences on clothing fit 32

3.3 Testing methods for dimensional fit 33
3.4 Subject rating scales 37
3.5 Subjective fitting guide 38
3.6 Conclusions 41
3.7 References 41

4 Objective evaluation of clothing appearance 43
J FAN, L HUNTER AND F LIU

4.1 Introduction 43
4.2 Objective evaluation of fabric wrinkling 43
4.3 Objective evaluation of fabric pilling 54
4.4 Objective evaluation of seam pucker 60
4.5 Objective evaluation of overall garment appearance 66
4.6 References 68

5 Objective evaluation of clothing fit 72
W YU

5.1 Introduction 72
5.2 Moiré optics 72
5.3 Algebraic evaluation of clothing fit 78
5.4 Clothing waveform 80
5.5 Pressure evaluation of clothing fit 84
5.6 3D modelling of pressure fit 86
5.7 Conclusions 86
5.8 References 87

6 Fabric properties related to clothing appearance and fit 89
L HUNTER AND J FAN

6.1 Introduction 89
6.2 Reviews 92
6.3 Fabric objective measurement (FOM) 92
6.4 References 111

7 Garment drape 114
L HUNTER AND J FAN

7.1 Introduction 114
7.2 Reviews on drape 114
7.3 The measurement of fabric drape 115
7.4 Empirical prediction of static drape 117
7.5 Dynamic fabric drape 122
7.6 Seamed fabric drape 122

7.7	Modelling fabric and garment drape	123
7.8	Drape models in commercial CAD and Internet systems	125
7.9	Concluding remarks	130
7.10	References	131
8	3-D body scanning W YU	135
8.1	Introduction	135
8.2	Global development of body scanners	136
8.3	Principles and operations of body scanning technologies	145
8.4	Benchmarking	161
8.5	Challenges of 3D body scanning	164
8.6	Concluding remarks	166
8.7	References	167
9	Human anthropometrics and sizing systems W YU	169
9.1	Terms and definitions	169
9.2	Traditional anthropometry	171
9.3	Historical development of sizing system	174
9.4	Latest national size survey using 3-D body scanner	177
9.5	International sizing	182
9.6	Principles of sizing systems	184
9.7	Conclusion	190
9.8	References	193
10	Garment design for individual fit M Y KWONG	196
10.1	Introduction	196
10.2	Pattern alteration for fit	196
10.3	Prediction of garment patterns from body measurements	203
10.4	Three-dimensional (3-D) apparel design systems for pattern generation and garment fit	207
10.5	Virtual fitting on the Internet	226
10.6	References	229
Index		234

Figures

1.1	Golden ration in nature, design and architecture.	2
1.2	Beautiful faces fitted with beauty masks.	4
1.3	Ideal Greek proportions of female figure.	5
1.4	Ideal Greek proportions of male figure.	6
1.5	Female body figures having varying WHR.	7
1.6	(a) Plot of log(VHI) versus log(AR) by male viewers; (b) plot of log(VHI) versus log(AR) by female viewers.	8
1.7	Nine-figural scale of Thompson and Gray, 1995.	10
1.8	Interaction between viewer, clothing, body and environment.	10
1.9	Effect of design on the perception of body proportion.	12
1.10	The perceived body size grades of the thin model, medium model and obese model.	12
2.1	Lighting equipment for viewing test specimens.	16
2.2	View device for pilling assessment.	17
2.3	ICI Pilling Box Tester.	18
2.4	Martindale Tester.	18
2.5	Random Tumble Pilling Tester.	19
2.6	Photographic Comparative Ratings for Single and Double Needle Seams.	21
2.7	Viewing Apparatus for Garments.	23
2.8	Grade scale of yoke position.	24
2.9	Grade scale of armhole position.	24
2.10	Grade scale of buttonhole placket position.	24
2.11	Grade scale of button placket position.	25
2.12	Grade scale of pocket position.	25
2.13	Rating Scale for the Appearance of Wool Suits.	26
3.1	Criteria for qualitative evaluation of clothing fit.	32
3.2	Difference between the (a) new and (b) conventional dress form.	36

3.3	Digital human body model based on anatomical landmarks.	36
3.4	Taninaka's Dress stand.	37
3.5	Wearer acceptability scale.	38
3.6	Fit evaluation scale.	39
4.1	SAWTRI Wrinklemeter.	44
4.2	(a) The measuring system using laser triangulation; (b) The laser scanner from CyberScan.	56
4.3	Schematic set-up of the image-analysis system.	59
4.4	The 3-D Model Maker laser scanner.	64
4.5	(a) Subjective Grade vs Log(σ^2) for Yoke seam; (b) Subjective Grade vs Log(σ^2) for Pocket seam; (c) Subjective Grade vs Log(σ^2) for Placket seam; (d) Subjective Grade vs Log(σ^2) for Armhole seam.	66
4.6	Objective evaluation of overall garment appearance.	68
5.1	Moiré measurements of the human body.	73
5.2	Schematic setup of the moiré system.	74
5.3	Moiré image of bra cup.	75
5.4	Moiré system for jacket measurement.	75
5.5	Moiré image of jacket.	76
5.6	Sectional analysis of clothing fit.	76
5.7	Polynomial curves of centre back profile.	77
5.8	Maternity support.	78
5.9	Outer suit.	78
5.10	Example of a Signature Curve on the bodice.	80
5.11	Cross-sectional profile of body and clothing at the waist line; body shape, clothing shape, calculated clothing shape.	81
5.12	Cross-sectional shape of clothing at the waistline and its derived waveform.	82
5.13	Clothing waveform of different sizes: 9, 11 and 13.	82
5.14	Cross-sectional waveforms of various clothing materials at (a) the hip level, (b) the waist level and (c) the bust levels for a body size no. 9.	83
5.15	Magnitude of the wavelet transform at the bust line waveform of a body size no.9: (a) cross-sectional clothing shape, (b) amplitude of waveform, (c) magnitude of the wavelet transform.	83
5.16	Manufacture of soft mannequin.	84
6.1	Process used by experts in the subjective evaluation of fabric handle.	90
6.2	A history of the textile technology of the twentieth century.	92

6.3	System for the objective evaluation of fabric handle.	95
6.4	The KES-F system for measuring fabric mechanical properties.	98
6.5	Principles used in the KES-F instruments for the objective measurement of fabric mechanical and surface properties.	99
6.6	Typical deformation-recovery curves for (a) fabric extension or lateral compression, and (b) fabric bending or shear, showing the energy loss during a complete cycle as the shaded area.	100
6.7	Relation between the three primary hands and the mechanical properties.	101
6.8	Basis of objective evaluation of KES-FB system.	102
6.9	High TAV zone for suit expressed by the three components.	104
6.10	'Tailoring Control Chart' and high quality zone from wear comfort.	104
6.11	The FAST control chart for light-weight suiting fabrics.	110
7.1	Cusick's Drapemeter.	116
7.2	Drape image.	116
7.3	Some factors contributing to fabric drape behaviour.	117
7.4	An image analysis system for measuring static and dynamic drape behaviour of fabrics.	118
7.5	Particle-based model.	125
7.6	Visualisation of garment in 3D.	127
7.7	Computer screen of Maya Cloth™.	128
7.8	Cloth simulation in Syflex.	129
7.9	Virtual draping of clothing in My Virtual Model™.	130
8.1	Horizontal sliding gauge and vertical sliding gauge.	136
8.2	(a) Algin Method and (b) Gypsum Method.	137
8.3	Silhouette analyser.	138
8.4	Fujinon Moiré Camera in 1980s.	139
8.5	Output of Conusette's scan.	139
8.6	Digital output from Voxelan laser scanner.	140
8.7	Cubic's hardware structure.	140
8.8	Close look at CubiCam.	141
8.9	CubiCam's optical design.	142
8.10	SYMCAD OptiFit.	145
8.11	Schemetic set up of 2D photographic methods.	146
8.12	Schemetic set up of LASS system.	147
8.13	Figure of moiré image of human body.	149
8.14	RSI DigiScan 2000.	151
8.15	Figure of TC^2 PMP theory.	152
8.16	TriForm 3D Body Scanner.	153

8.17	3D Scanner's ModelMaker.	154
8.18	Cyberware WB4 Scanner.	155
8.19	Vitus body scanner.	156
8.20	Voxelan's HEV-1800HSW scanner.	157
8.21	FastScan scanner.	158
8.22	IR Sensor.	158
8.23	LED with PSD system.	159
8.24	Stereo picture.	160
8.25	Schematic diagram of stereoscopy.	160
8.26	Cubic Compact Model and Entire Body Model.	162
9.1	Critical anatomical points.	170
9.2	Key body landmarks.	171
9.3	Definition of vertical body measurements.	172
9.4	The year of birth versus the average stature of Japanese people aged 20.	179
9.5	Three measuring postures.	179
9.6	Distribution of figure types in ISO (1991).	187
10.1	Cross sectional view of the geometric model for the experimental pattern.	204
10.2	Computer pattern draft of experimental pattern.	204
10.3	Locations of photographic measurements.	205
10.4	Design of blouse superimposed onto photographs of the human body.	208
10.5	Location of the crucial shaping points.	209
10.6	Division of the body into triangular sections.	210
10.7	The mapping of the garment at the bust level.	211
10.8	Diagram of two vertical cross sections of the body and a 'last' for a basic skirt.	212
10.9	Diagram of a 'last' for a basic skirt.	213
10.10	The selection of base sections and an example of a different growth ratio for the bust section.	214
10.11	The generic feature model of a mannequin with detailed features listed.	216
10.12	The generation of the bodice dummy; (a) a pair of images captured by two cameras; (b) reconstructed mesh structure and shaded surface for right front panel; (c) assembled bodice model with four panels.	217
10.13	The overview of the 3D garment design system operations.	220
10.14	Garment piece with a superimposed equimesh grid.	222
10.15	Multistrand garment-piece pattern.	223
10.16	The Overlaps eliminated by the spreading out of strands.	223

10.17 The integration of the design interface, the pattern flattening and the fabric drape engine, a) stylished 3D garment panel design with dart, b) garment panel triangulation with dart, c) 2D flattening of panel with dart, d) 3D drape of panel with texture rendering. 224

Tables

2.1	Rating standard based on standard three-dimensional replicas	23
2.2	Rating standard based on photographic standards	23
3.1	Advantages and disadvantages of fitting standards	34
3.2	Exercise protocol	34
6.1	Assessment of fabric performance in apparel	89
6.2	Fabric properties that are related to tailoring performance, appearance in wear, and handle	91
6.3	Basic fabric mechanical properties and related quality and performance attributes of fabrics and garments	94
6.4	Application of fabric objective measurement technology	94
6.5	The sixteen parameters describing fabric mechanical and surface properties	100
6.6	Primary hands	101
6.7	Influence of measured parameters on PHV	102
6.8	The desirable range of mechanical properties for high-quality suit production	103
6.9	The range of mechanical properties for fabric to be rejected	103
6.10	Interrelation between difficulties in sewing process and ranges of mechanical parameters	103
6.11	The criteria for ideal fabric	105
6.12	Summary of CSIRO's FAST system	108
6.13	Fabric properties associated with problems in garment making	109
6.14	Fabric properties associated with potential poor garment appearance in wear	109
7.1	Drape coefficients (%)	119
8.1	Major 3D scanner manufacturers	162
8.2	Comparison between different body scanners	163

9.1	Examples of latest size designations in various countries	182
9.2	German men's figure type categorisation	187
9.3	American sizing system	188
9.4	Classification of the French tables according to types	188
9.5	Japanese garment types and key dimensions	189
9.6	Size labelling and body measurements in various countries	190
9.7	Comparison of size interval and drop value of men in different countries	191

Preface

Decoration, modesty and protection are the three most fundamental reasons for people to wear clothing. Two of these, decoration and modesty, are directly influenced by the appearance and fit of the clothing. The question which arises is how clothing should be designed, manufactured and dressed so as to provide not only good individual fit, but also body image enhancement. The subject is interdisciplinary, involving science of beauty, social psychology, human anthropometrics, fashion and textile design and technology. Most books related to the subject cover aspects, such as sociology (e.g. dressing for the right occasion) and dress-making, and there is a lack of a comprehensive treatment of the subject, particularly from the scientific and technological perspective.

This monograph is the first book aimed at providing a critical appreciation of technological developments and scientific understanding in areas related to clothing appearance and fit, bridging the science of beauty, fashion design, fabric and garment evaluation technology, garment drape, as well as human anthropometrics and sizing.

The book is divided into ten chapters, each dealing with a specific topic. Chapter 1 considers body attractiveness or image and how it relates to clothing material and design parameters. Both classical theories of beauty and recent findings on the interrelationship between body image, body measurements and clothing are discussed. Chapters 2 and 3 present and discuss the techniques, methods and standards used by the industry and researchers for assessing clothing appearance and fit. Chapters 4 and 5 review research and development on objective measurement technologies for the evaluation of clothing appearance and fit. Chapters 6 and 7 deal with fabric objective measurement, relevant fabric properties and garment drape. R&D and related aspects on body measurement, anthropometrics and sizing systems are covered in Chapters 8 and 9. The last chapter reviews published work on garment design and pattern alteration for achieving good clothing appearance and fit.

The book is intended for a wide spectrum of readers, including students, researchers and academics, as well as professionals in the clothing and textile industries. For easy comprehension, the text is supplemented by illustrations and

photographs wherever possible. Although it is essentially a research monograph, it includes considerable industrial standards, techniques and practices. It is therefore not only useful for the academia, but also provides a handy reference for professionals in the industry.

Jintu Fan, Winnie Yu and Lawrance Hunter
Hong Kong

Acknowledgements

We would like to express our sincere gratitude to all individuals and organisations who have directly or indirectly contributed towards the publication of this book. In particular, we would like to acknowledge:

- Mei-ying Kwong, Lecturer at the Institute of Textiles and Clothing, The Hong Kong Polytechnic University, for her contribution of Chapter 10.
- Lilian Lau Lai-yan, Research Assistant at the Institute of Textiles and Clothing, The Hong Kong Polytechnic University, for her excellent assistance in formatting the manuscript, preparation of index and coordination among the authors.
- Al-Pun Chan, PhD student, for collecting literature about draping models applied in commercial CAD systems and Internet websites.
- Dr Fu Liu, Postdoctoral Research Fellow, for drafting parts of Chapter 4.
- Marcus Tung, Research Assistant at the Institute of Textiles and Clothing, The Hong Kong Polytechnic University, for his assistance in the literature search and database management of Chapters 3, 5, 8 and 9.
- Dr Kenneth Wang, for proof-reading of Chapters 3, 5, 8 and 9.
- Institute of Textiles and Clothing, The Hong Kong Polytechnic University, for funding the work through its Area of Strategic Development Programme.

Jintu Fan
Winnie Yu
Lawrance Hunter

1

Perception of body appearance and its relation to clothing

J FAN

1.1 Introduction

Our appearance is our most apparent individual characteristic. Although we are taught that we should not judge others by their appearance alone, relying on appearance to guide personal decisions and social interactions is not only natural, but inescapable.[1] The body and the way it is clothed and presented is a primary medium of expression, for it makes statements on the condition of society itself.[2]

Few people have a perfect body. Most people would like to improve their appearance with appropriate clothing, by camouflaging their less desirable attributes and highlighting the more attractive aspects of their bodies.[3] In order to design garments to present the best image of the wearer, it is necessary to understand the perceptions of beauty, body attractiveness and body image as well as how the perception of body appearance can be modified through clothing.

1.2 Beauty

What is beauty? Are there properties processed by an object which count towards beauty in all cases and which are sufficient or necessary for an object to be judged beautiful? One school of thought is that 'beauty is in the eye of the beholder', that individual attraction is a result of personal experience, cultural background and specific circumstances. Naomi Wolf, in her book, *The Beauty Myth*, argues that there is no such thing as a quality called beauty which exists 'objectively and universally'.[4,5] Some modern philosophers also believe that there are no principles of beauty, although there is a rational basis for genuine judgement of beauty.[6] They argue that it is always possible to find an object which can be judged to exhibit principles identified as those of beauty but which does not evoke a pleasurable response, and conversely there may be objects which are experienced as beautiful but which do not exhibit the identified principles. Nevertheless, the assumption that beauty is just an arbitrary personal

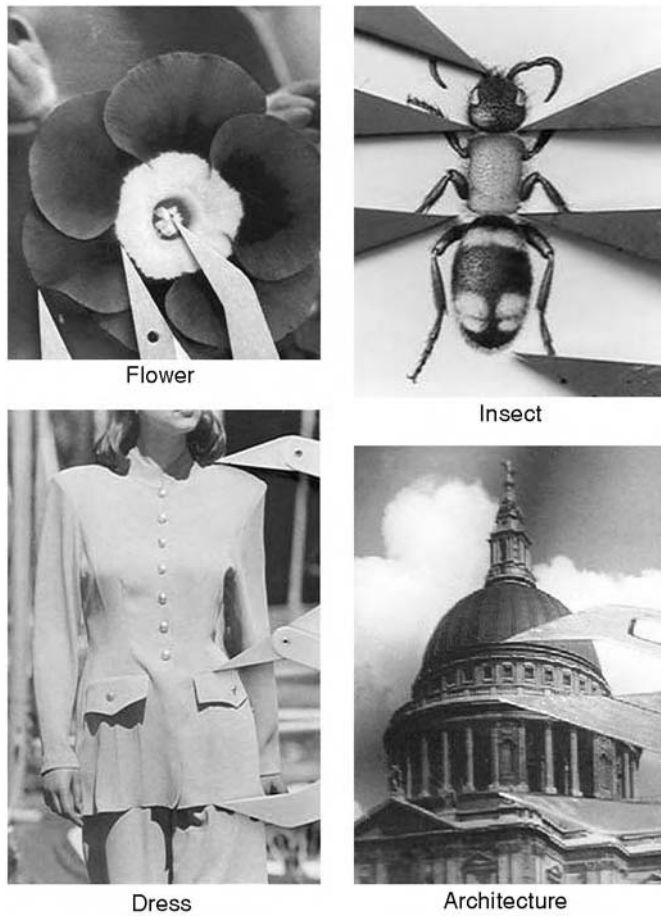


Figure 1.1 Golden ratio in nature, design and architecture. Source: Photographs by courtesy of Dr. Eddy Levin, London. http://www.goldenmeangauge.co.uk/golden.htm

preference may simply not be true. It cannot explain the fact that even two-month-old infants prefer to gaze at faces that adults find attractive.[7]

If there are universal principles of beauty, what are they? Ancient Greeks believed that the world is beautiful because there is a certain measure, proportion, order and harmony between its elements.[6] For centuries, the Golden Ratio or Golden Proportion, a ratio of 1:1.618 has been considered as the perfect ratio for beauty (see Fig. 1.1). It can be seen in nature and is used for art and architectural design. Linguists discovered that, although the same sound may mean entirely different things in different languages, there is a universal grammar underlying the combination of the sounds.[8] Similarly, it has been

suggested by many philosophers that beauty stems from the relationship between the elements comprising the whole.[9] Evidenced from the rhyme of music and poetry, philosophers in the twentieth century realised that such beauty is likeness tempered with difference or the fusion of sameness and novelty. Modern psychologists[10] and biologists[9] have echoed such a claim. They found that men and animals, exposed for some time to a particular sensory stimulus, prefer new stimuli which are slightly different from the one with which they are familiar. 'The likeness tempered with difference' is pleasing to the classification process, which is important for biological survival.[9]

1.3 Facial attractiveness

What would a universally beautiful face look like? Galton in his pioneering paper of 1878 reported an important discovery that a composite face produced by superimposing different photographs of faces is more attractive than any of the individual photos, suggesting that facial beauty relates to averageness. This hypothesis was tested and confirmed by Langlois and Roggman in 1990, who used a computerised version of the technique developed by Galton.[7] The principle of 'averageness being attractive' has a biological foundation. It was proposed by biologists that, during most periods, evolutionary pressures operate against the extremes of the population.[11] People with average physical properties have the best chance of survival, and therefore people tend to be attracted to, and mate with, partners having average features.

However, averageness is not the only criterion for beauty. Rhodes *et al.*[12] found that facial symmetry is also important. Attractiveness increased with an increasing level of symmetry. The preference for symmetry also has a biological reason. Apart from averageness and symmetry, some extreme traits, such as the peacock's tail, can be a sign of quality and health in a mate and therefore favoured in the selection process. Using composites of both Caucasian and Japanese faces, Perrett *et al.*[13] showed that the mean shape of a set of attractive faces is preferred to the mean shape of all the faces in a sample. Attractive composite faces can be made more attractive by exaggerating the shape difference from the sample mean. Therefore, an average face shape is attractive, but not optimally attractive. Human preferences could exert a directional selection pressure on the evolution of the shape of a human face.

Perrett *et al.*[14] further showed that more feminine female faces are preferred to average faces. A more feminine male face is also preferred above the average and masculine faces. Enhanced masculine facial characteristics increased both perceived dominance and negative attributes (for example, coldness or dishonesty) relevant to relationships and paternal investment. This preference applied across UK and Japanese populations but was stronger for within-population judgements. They believed that humans have a selection pressure that limits sexual dimorphism and encourages neoteny.



Figure 1.2 Beautiful faces fitted with beauty masks. Source: http://www.bbc.co.uk/science/humanbody/humanface/beauty.golden.mean.shtml

The beauty of a face has also been measured by Marquardt,[15] who claimed that beautiful faces of all races (including babies) fit his 'Universal Beauty Mask', which is mathematically created from the Golden Ratio (see Fig. 1.2). The degree of conformance of one's face to the 'Universal Beauty Mask' is a measure of beauty.

1.4 Body physical attractiveness

The classical average Greek body proportions have been widely considered as ideal for centuries.[3] The Greek ideal male and female figures are shown in Figs 1.3 and 1.4, respectively. The various body dimensions are measured in the unit of head length. For both the male and female, the height is approximately seven and half head lengths, with the fullest part at the hipline and wrist level dividing the total length exactly in half. The neck is about one-third the length of the head, and the shoulder line slopes a distance of a half head length from the level of the chin. The fullest part of the bust or chest is located two head lengths from the crown. The waistline, which coincides with the bend of the elbow, is two and two-thirds of a head length from the crown. The knees are five and half head lengths from the crown and the ankles are seven head lengths from the crown. Male and female proportions differ only in circumference ratios. For the ideal female, the width of the hip frontal view is almost the same as the shoulder width. The shoulder width of the ideal male is greater than the width of his hips. There is also a greater difference in the depth ratios from front to back in the female figure than there is in the male with respect to bust/waist and waist/hip relationships.

Despite the wide appeal of the average Greek body proportions, the concept or perception of beauty ideals has never been static. It varies from time to time and from culture to culture. From the fifteenth to the seventeenth centuries in western cultures, a fat body shape was considered sexually appealing and fashionable. The ideal woman was portrayed as plump, big-breasted and maternal. By the nineteenth century, this had shifted to a more voluptuous,

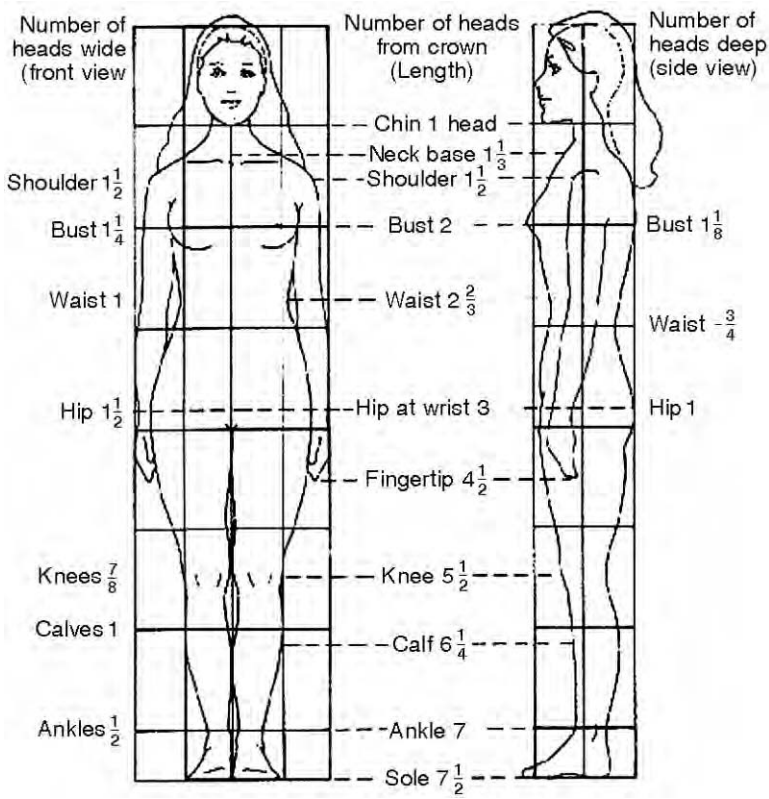


Figure 1.3 Ideal Greek proportions of female figure. Source: Horn M. J. and Gurel L. M. (1981). *The Second Skin,* Third Edition. Copyright (© 2003 by Fairchild Publications, Inc. Reprinted by permission of Fairchild Books, a division of Fairchild Publications, Inc.).[3]

corseted figure, idealising a more hourglass shape. In modern western culture, thinness coupled with somewhat inconsistent large breasts and a more toned, muscular physique has become the ideal of feminine beauty.[16]

In addition to historical factors, cultural differences play a significant role in the concept of beauty. For example, traditional Chinese culture associates plumpness with affluence and longevity, and Arab cultures associate greater body weight with female fertility.[17] Yu and Shepard[18] investigated the female body preferences of the culturally isolated Yomybato village in southeast Peru and discovered that the female body preferences of the Yomybato males are strikingly different from those prevalent in the modern western culture. Yomybato males ranked the 'over-weight' female figure as most attractive, healthy and preferable for marriage (see Fig. 1.5).

Evolutionary psychology suggests that female physical attractiveness is based on cues of health and reproductive potential. Two putative cues to female

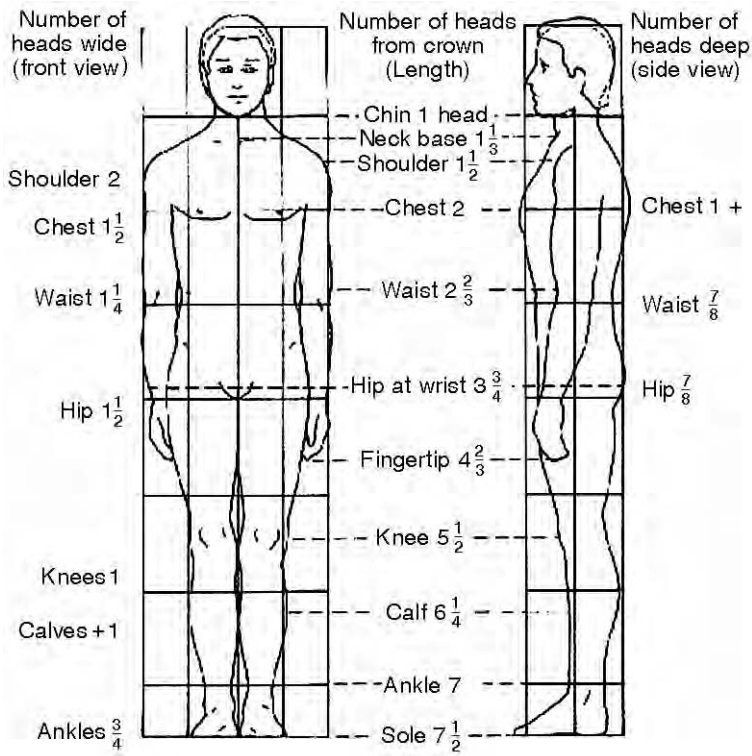


Figure 1.4 Ideal Greek proportions of male figure. Source: Horn M. J. and Gurel L. M. (1981). *The Second Skin*, Third Edition. Copyright (© 2003 by Fairchild Publications, Inc. Reprinted by permission of Fairchild Books, a division of Fairchild Publications, Inc.).[3]

physical attractiveness are shape (particularly the waist-hip ratio or WHR) and body mass index (BMI). Earlier researchers believed that a low WHR (i.e. a curvaceous body) corresponded to the optimal fat distribution for high fertility and hence female attractiveness.[19,20,21] However, recent studies by Tovee and co-workers[22, 23] have shown that the body mass index (BMI), rather than WHR, is the primary determinant of female attractiveness. Tovee *et al.*[23] confirmed their findings by deliberately using a set of body images which has an inverse correlation between BMI and WHR. Nevertheless, Tovee *et al.*[23] and other earlier researchers have not tested their findings on 3-D female images. In a recent study by Fan *et al.*,[24] 3-D images of 31 Caucasian females, having varying body weights (BMI ranged from 16 to 35), were shown to 29 male and 25 female viewers, who were asked to rate their physical attractiveness. The results showed that the body volume divided by the square of the height, defined as volume height index (VHI), is the most important and direct visual determinant of female physical attractiveness. Figures 1.6(a) and 1.6(b) plot the

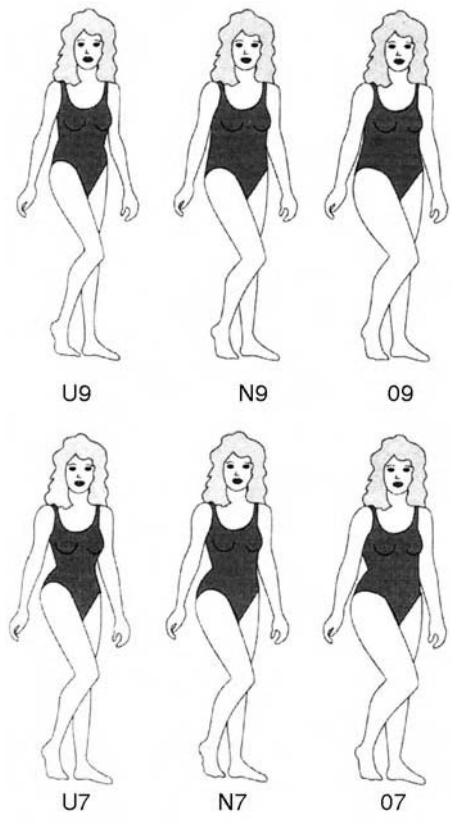


Figure 1.5 Female body figures having varying WHR. Source: Singh 1993.[20]

relationship between log(VHI) and log(AR) (i.e. the logarithm of attractiveness rating) for male and female viewers, respectively. VHI accounted for about 90 per cent of the variance of attractiveness ratings. Other parameters which affect body attractiveness include WHC (the ratio of waist height over the chin height) and AWHR (the deviation of the ratio of waist over hip from the ideal ratio). This suggested that human observers may first use VHI as a visual cue, which is also a key indicator of health and fertility due to its strong linear relation to BMI. To fine tune the judgement, observers may then use body proportions. Fan *et al*. further showed that there could be perceptual reasons for humans to use VHI or the associated BMI to determine body attractiveness and fit. They also showed that the effect of the body physical parameters on the perception of female physical attractiveness appears to conform to Stevens' power law of psychophysics.[24]

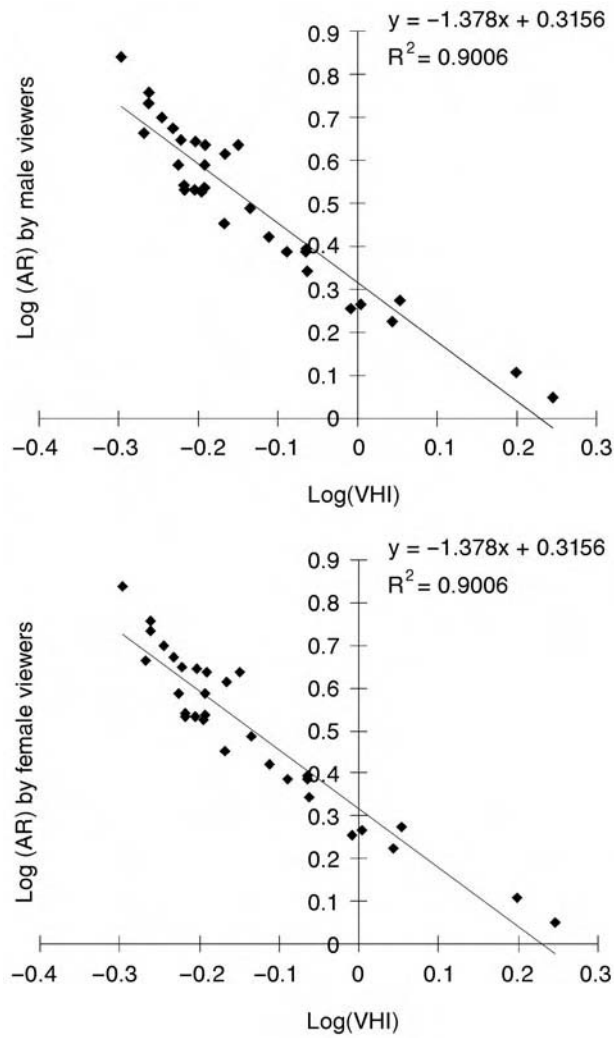


Figure 1.6(a) Plot of log(VHI) versus log(AR) by male viewers; (b) plot of log(VHI) versus log(AR) by female viewers. Source: Fan *et al.* 2004.[24]

1.5 Body image

The internal representation of one's own outer appearance, i.e. perception of one's own body, is termed body image.[16] Body image is important as it is strongly related to self-esteem and the development of personality attributes.[25,26] A positive view of one's own looks may heighten one's self-esteem and leads to bold, successful interpersonal or business ventures, whereas a poor view of the physical self may weaken one's confidence.

Research on body image can be traced back to the beginning of the twentieth century, when the association between body image and brain damage was identified by neurologists and neuropsychologists. Subsequently, researchers realised the multidimensional nature of body image, namely that body image is attributed to both conscious and unconscious factors, such as emotions, attitudes, wishes and social relationships. Studies on the self-perception of body appearance began in the 1940s. Between the 1940s and the 1950s, numerical scales were designed to self-rate the perception of body attractiveness and appearance. It was found that a high percentage of women were dissatisfied with their body. From the 1960s, increasing evidence has been found that body image affects eating disorders and mental distress. The neurological basis and clinical aspects of body image are beyond the scope of this book, but the reader is referred to the literature review in this area by Thompson *et al*.[16]

Schematic figures or silhouettes of varying sizes, from thin (underweight) to heavy (overweight) are widely used for assessing body image. The subjects are asked to pick out the ideal figure and their conception of the figure that most closely matches their own. The difference is a measure of the satisfaction with one's own body (i.e. body image). The frequently used figural scale is the nine-figural scale developed by Stunkard *et al*.[27] The lack of consistent gradations of the figures of such figural scales were pointed out as a potential source of error.[28] Thompson and Gray[29] advocated their own nine-figural scale (see Fig. 1.7), which has similar differences in adjacent figures. Gardner *et al*.[30] later described the careful development of two scales, a two-figural scale and a thirteen-figural scale. However, Stunkard[31] argued that the two new scales have no greater validity than the previous scales as demonstrated by the correlation between scale values and measured values of body mass index and weight. Another potential problem with a standardised figure rating is that the subject may find that none of the sizes and dimensions reflected by the figures match their own. Subsequently, computer programs have been developed to allow subjects to change the figure freely until it matches their own body.[32]

1.6 Modification of body appearance by dressing

1.6.1 Interaction between viewer, environment, body and clothing

The appearance of the clothed body is a perception of the viewer (whether of the wearers themselves or others) in a social and climatic context. It involves interaction between body, clothing, the viewer and environment (see Fig. 1.8). In mathematical terms, the appearance is a complex function of body, clothing and environment (including social, cultural and other norms). Such a visual unit has been appreciated by DeLong,[33] who defined the interactive unit as Apparel-Body-Construct. Viewing an Apparel-Body-Construct is not just to scan and

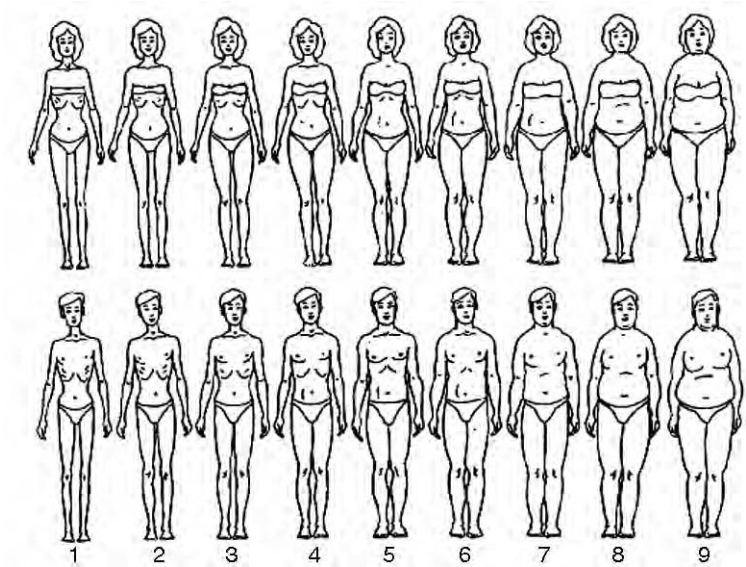


Figure 1.7 Nine-figural scale of Thompson and Gray, 1995.[29]

understand the visual components, such as line, shape, colour, texture, body shape, etc., which has its own meaning and expressive characteristics, but to perceive the contextual relationship between the components. DeLong[33] pointed out that the perception of clothing appearance is influenced by the Gestalt effect, that is the whole is more than the sum of its parts. For example, the same jacket may appear different depending on what garments are combined with it.

1.6.2 Changes in body cathexis

Satisfaction with body appearance and its separate parts is termed as 'body cathexis'. Body cathexis is an evaluation of body image and self concept. A low

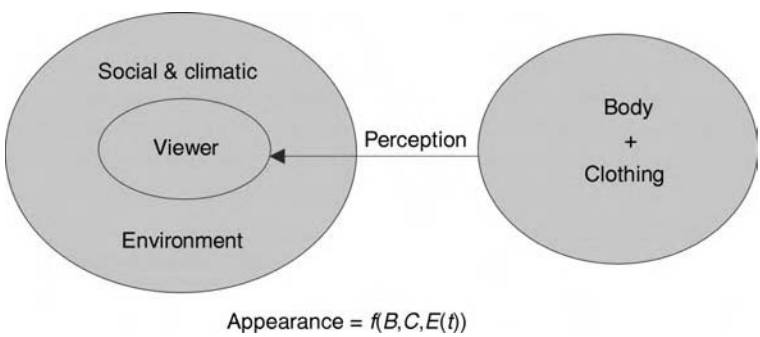


Figure 1.8 Interaction between viewer, clothing, body and environment.

value of body cathexis indicates dissatisfaction with one's own body appearance.

Body cathexis is highly related to the satisfaction of the fit of the clothing. It was reported that normal weight groups were most satisfied with their body and clothing fit.[34] The overweight group showed much less satisfaction with their body and clothing fit. McVey[35] found that ill-fitting branded garments which are expensive and fashionable give a message to the consumer that something is wrong with their body. However, less fashionable and less expensive private label merchandise does not carry the prestige to affect the consumer's opinion of their own body. LaBat and DeLong studied the body cathexis and the perception of clothing fit of 107 female consumers.[34] They found a strong correlation between body cathexis and satisfaction with clothing fit. Markee *et al*.[36] investigated the body cathexis of the nude body and the clothed body of 29 working women. They found that these working women were significantly more satisfied with their clothed bodies than with their nude bodies, showing the importance of dress in enhancing the perception of body appearance.

1.6.3 Illusion created by dress

The principles of illusion can be applied to the design of dress so as to camouflage the undesirable body attributes and to make the person's appearance closer to the ideal. Horn and Gurel[3] have shown that, for a shorter figure with a sloping shoulder, the Muller-Lyer principle can be applied to create an appearance of increased shoulder width and body height (see Fig. 1.9). Design A in Fig. 1.9 can make the wearer look closer to the ideal proportion. A slender figure can be made fuller by adding fullness at the bustline and hipline and reducing the visual width of the waistline. A short figure can look taller by minimising horizontal lines in the design. In general, parts of the body which are judged to be too large can be subdivided into smaller areas or counterbalanced by increasing the visual size of the surrounding elements. Body proportions which are considered too small may be masked or increased in size through the use of perspective and gradient techniques, or by minimising the size of adjacent elements.

Fan *et al*.[37] conducted an experimental investigation into the effect of garment size on the perceived body size. The perceived body sizes of three Chinese males (thin, medium and obese build) wearing different sized white T-shirts were assessed. Within the limits of commercially available T-shirt sizes, it was found that, for thin and medium build persons, the perceived body size is bigger when wearing T-shirts in a larger size. However, for an obese person, wearing a large size T-shirt tends to make him look thinner (see Fig. 1.10).

The perception of human faces may also be changed by hair styles and collars. For example, a round face may look better in a straight pointed collar and a square face may look better in a large collar to achieve the illusion of an oval face, which is the ideal in western culture.[38]

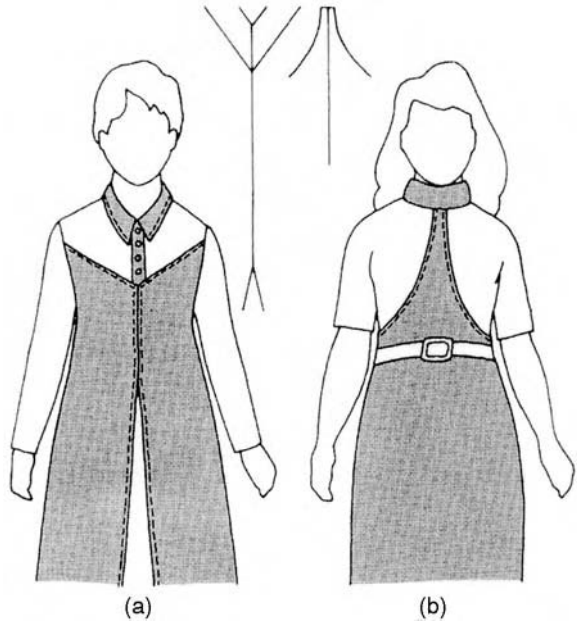


Figure 1.9 Effect of design on the perception of body proportion. Source: Horn M. J. and Gurel L. M. (1981). *The Second Skin*, Third Edition. Copyright (© 2003 by Fairchild Publications, Inc. Reprinted by permission of Fairchild Books, a division of Fairchild Publications, Inc.).[3]

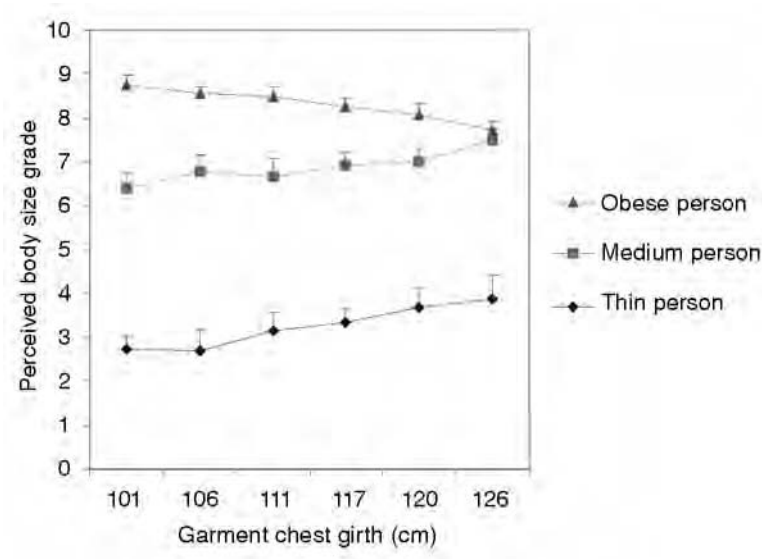


Figure 1.10 The perceived body size grades of the thin model, medium model and obese model.

Davis[39] summarised the visual design principles, such as repetition, parallelism, radiation, gradation, etc., and provided 'recipe-style' guidelines for manipulating fabric texture, style, lines, decorative details, shape, form, colour, pattern, etc., to achieve the desirable visual appearance.

1.7 References

1. Johnson K K P and Lennon S J (eds), *Appearance and power*, Oxford, Berg Publishers, 1999.
2. Young M, 'Dressed to commune, dressed to kill: changing police imagery in England and Wales', in Johnson K K P and Lennon S J (eds), *Appearance and power*, Oxford, Berg Publishers, 1999.
3. Horn M J and Gurel L M, *The second skin*, 3rd edn, Boston, Houghton Mifflin Company, 1981.
4. Etcoff N L, 'Beauty and the beholder', *Nature*, 1994 **368**(6468) 186–187.
5. Wolf N, *The beauty myth*, New York, Morrow, 1990.
6. Gaut B and Lopes D M, Chapter 20 in *The Routledge companion to aesthetics*, London, Routledge, 2001.
7. Langlois J H and Roggman L A, 'Attractive faces are only average', *Psychol Sci*, 1990 **1**(2) 115–121.
8. Pinker S, *The language instinct*, New York, W. Morrow and Co., 1994.
9. Humphrey N K, 'The illusion of beauty', *Perception*, 1973 **2**(4) 429–439.
10. McClelland D C, Atkinson J W, Clark R A and Lowell E L, *The achievement motive*, New York, Appleton-Century, 1953.
11. Symons D, *The evolution of human sexuality*, Oxford, Oxford University Press, 1979
12. Rhodes G, Proffitt F, Grady J M and Sumich, A, 'Facial symmetry and the perception of beauty', *Psychon B Rev*, 1998 **5**(4) 659–669.
13. Perrett D I, May K A and Yoshikawa S, 'Facial shape and judgements of female attractiveness', *Nature*, 1994 **368**(6468) 239–242.
14. Perrett D I, Lee K J, Penton-Voak I, Rowland D, Yoshikawa S, Burt D M, Henzi S P, Castles D L and Akamatsu S, 'Effects of sexual dimorphism on facial attractiveness', *Nature*, 1998 **394**(6696) 884–887.
15. Marquardt S, 'Can beauty be measured?', *URL:* http://www.beautyanalysis.com/index2_mba.htm 2002.
16. Thompson J K, Heinberg L J, Altabe M and Tantleff-Dunn S, *Exacting beauty: Theory, assessment, and treatment of body image disturbance*, Washington, DC, American Psychological Association, 1999.
17. Nassar M, 'Culture and weight consciousness', *J Psychosom Res*, 1988 **32** 573–577.
18. Yu D W and Shepard G H, 'Is beauty in the eye of the beholder?', *Nature*, 1998 **396**(6709f) 321–322.
19. Zaadstra B M, Seidell J C, Van Noord P A H, Velde E R, Habbema J D F, Vrieswijk B and Karbaat J, 'Fat and fecundity: Prospective study of effect of body fat distribution on conception rates', *Brit Med J*, 1993 **306**(6876) 484–487.
20. Singh D, 'Adaptive significance of female physical attractiveness: Role of waist-to-hip ratio', *J Pers Soc Psycho*, 1993 **65**(2) 293–307.
21. Singh D, 'Body shape and women's attractiveness: The critical role of waist-to-hip ratio', *Hum Nature-Int Bios*, 1993 **4**(3) 297–321.

22. Tovee M J, Maisey D S, Emery J L and Cornelissen P L, 'Visual cues to female physical attractiveness', *Proc Roy Soc Lond: Bio Sci*, 1999 **266**(1415) 211–218.
23. Tovee M J, Hancock P J B, Mahmoodi S, Singleton B R R and Cornelissen P L, 'Human female attractiveness: Waveform analysis of body shape', *Proc Roy Soc Lond: Bio Sci*, 2002 **269**(1506) 2205–2213.
24. Fan J, Liu F, Wu J and Dai W, 'Visual perception of female physical attractiveness', *Proc Roy Soc Lond: Bio Sci*, 2004 **271** 347–352.
25. Rudd N A and Lennon S J, 'Body image: Linking aesthetics and social psychology of appearance', *Cloth Text Res J*, 2001 **19**(3) 120–133.
26. Ushida S, Yamauchi M and Masuda Y, 'The influence of individual difference variables upon the estimation of body image-self-esteem and need for uniqueness', *J Japan Res Asso for Text End-Uses*, 2000 **41**(11) 910–920.
27. Stunkard A J, Sorensen T, and Schulsinger F, 'Use of the Danish adoption register for the study of obesity and thinness', in Kety S S, Rowlond L P, Sidman, R L, and Matthysse S W (eds.), *The genetics of neurological and psychiatric disorders*, New York, Raven, 1983 pp. 115–120.
28. Gardner R M, Friedman B N and Jackson N A, 'Methodological concerns when using silhouettes to measure body image', *Percept Motor Skill*, 1998 **86**(2) 387–395.
29. Thompson M A and Gray J J, 'Development and validation of a new body-image assessment tool', *J Pers Ass*, 1995 **64**(2) 258–269.
30. Gardner R M, Stark K, Jackson N A and Friedman B N, 'Development and validation of two new scales for assessment of body image', *Percept Motor Skill*, 1999 **89**(3) 981–993.
31. Stunkard A, 'Old and new scales for the assessment of body image', *Percept Motor Skill*, 2000 **90**(3) 930.
32. Schlundt D G, and Bell C, 'Body image testing system: A microcomputer program for assessing body image', *J Psychopathol Behav Assessment*, 1993 **15**(3) 267–285.
33. DeLong M R, *The way we look: Dress and aesthetics*, 2nd edn, New York, Fairchild Publications, 1998.
34. LaBat K L and DeLong M R, 'Body cathexis and satisfaction with fit of apparel', *Cloth Text Res J*, 1990 **8**(2) 43–48.
35. McVey D, 'Fit to be sold', *Apparel Ind Mag*, Feb., 1984 24–26.
36. Markee N L, Carey I L S and Pedersen E L, 'Body cathexis and clothed body cathexis: Is there a difference?', *Percept Motor Skill*, 1990 **70**(3) 1239–1244.
37. Fan J, Newton E, Lau L and Liu F, 'Garment sizes in perception of body size', *Percept Motor Skill*, 2003, **96** 875–882.
38. Eicher J B, Evenson S L and Lutz H A, *The visible self: Global perspectives on dress, culture, and society*, 2nd ed, New York, Fairchild Publications, 2000.
39. Davis M L, *Visual design in dress*, 3rd edn, Upper Saddle River, NJ, Prentice Hall, 1996.

2

Subjective assessment of clothing appearance

J F A N

2.1 Introduction

Clothing appearance or aesthetics is one of the most important aspects of clothing quality. Aesthetics is a very complicated subject because what is appealing to one person may not necessarily be regarded as appealing by the next person. It is therefore almost impossible to universally define garment aesthetics. Nevertheless, people do have a reasonably common notion or concept of what is good or bad appearance. With the exception of some deliberate use of 'puckered' or 'wrinkled' surfaces, a nicely smooth and curved garment surface is regarded as desirable.[1] Clothing is often discarded because of an unacceptable deterioration or change in appearance, including loss of shape or fit, surface degradation, colour change, change in handle and pilling.

The evaluation of clothing appearance is critical to product development and quality assurance. Subjective visual assessment is still the industrial norm because of the limitations of the many objective measurement systems. Visual assessments can be carried out on the materials and components of clothing as well as on the overall appearance of the clothing. In this chapter, the suitability and limitations of various subjective testing methods and past research on the related issues are reviewed and discussed.

2.2 Assessment of fabric surface smoothness

2.2.1 Assessment of fabric wrinkle recovery

A large number of techniques and methods exist for assessing fabric wrinkle appearance and recovery.[2] One of the factors which influences clothing appearance is the ability of fabrics to recover from induced wrinkles or to retain a smooth surface appearance after wear and repeated laundering. The method often used in industry to evaluate the wrinkle recovery of a fabric is AATCC Test method 128 'Wrinkle Recovery of Fabrics: Appearance Method'.[3] The principle of the method is to induce wrinkles in the fabric under standard atmospheric conditions in a standard wrinkling device under a predetermined

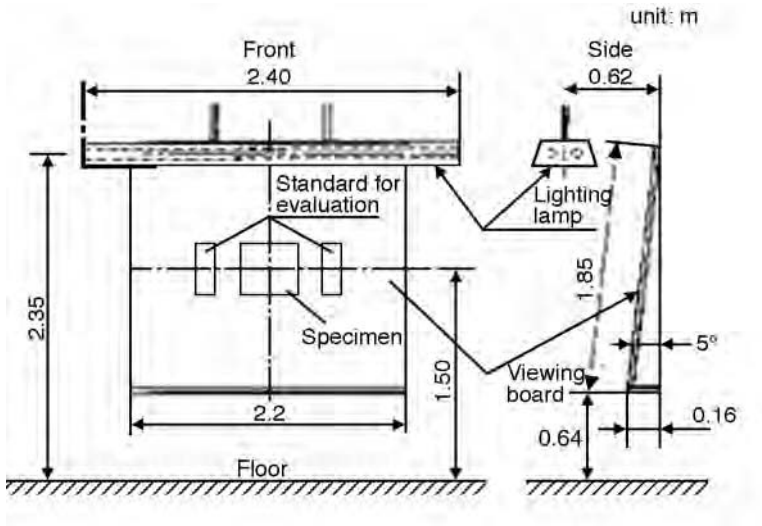


Figure 2.1 Lighting equipment for viewing test specimens. Source: JIS L 1905:2000.[23]

load for a prescribed period of time. The specimen is then reconditioned and rated for appearance by comparing it with three-dimensional reference standards (AATCC Wrinkle Recovery Replica). The viewing condition is shown in Fig. 2.1. At least three trained observers are required to independently rate the degree of wrinkles. The same method has been adopted by the International Organisation for Standardisation[4] and Japanese Industry.

It is generally accepted and experimentally proven that fabric colour and pattern have a significant effect on the perception of wrinkles. Abbott[5] found that a darker fabric will appear less wrinkled than a lighter fabric, as the darker fabric absorbs more light and makes the perception of wrinkles difficult. Salter *et al*.[6] found that the subjective perception of a wrinkle is strongly influenced by the fabric pattern. Check and black-figure fabrics appeared to obscure the extent of wrinkling.

2.2.2 Assessment of pilling propensity

The appearance and aesthetic quality of clothing are also influenced by the fabric propensity to surface fuzzing and pilling. Pills are developed on a fabric surface in four main stages: fuzz formation, entanglement, growth and wear-off.[7] The formation of pills and other related surface changes (e.g. fuzzing) on textile fabrics during garment wear can create an unsightly appearance. This is a particularly serious problem with some synthetic fibres, where the strong synthetic fibres anchor the pills to the fabric surface, not allowing them to fall off as is the case with the weaker natural fibres.



Figure 2.2 View device for pilling assessment.

The pilling resistance of fabrics is normally tested by simulated wear through tumbling, brushing or rubbing on a laboratory testing machine. The specimens are then visually assessed by comparison with visual standards (either actual fabrics or photographs) to determine the degree of pilling on a scale ranging from 5 (no pilling) to 1 (very severe pilling). Figure 2.2 shows a viewing device for pilling assessment. The observers are guided to assess the pilling appearance of a tested specimen on the basis of a combined impression of the density and size of pills and the degree of colour contrast around the pilled areas.

Several test methods (ASTM, ISO, BS and JIS) have been established for the assessment of pilling propensity. They differ in the way the specimens are treated to simulate wear conditions and create a 'pilled' appearance. In ISO 12945-1[8] and BS 5811,[9] specimens are mounted on polyurethane tubes and tumbled randomly, under defined conditions, in a cork-lined box, such as the ICI pilling box (see Fig. 2.3) for an agreed period of time (say 5 hours).

In ASTM D4970[10] and ISO 12945-2,[11] pilling formation during wear is simulated on the Martindale Tester. The face of the test specimen is rubbed, under light pressure for a specific number of movements, against the face of the



Figure 2.3 ICI Pilling Box Tester.

same mounted fabric in the form of a geometric figure, that is, a straight line, which becomes a gradual widening ellipse, until it forms another straight line in the opposite direction and traces the same figure again. Figure 2.4 shows a Martindale Tester.



Figure 2.4 Martindale Tester.

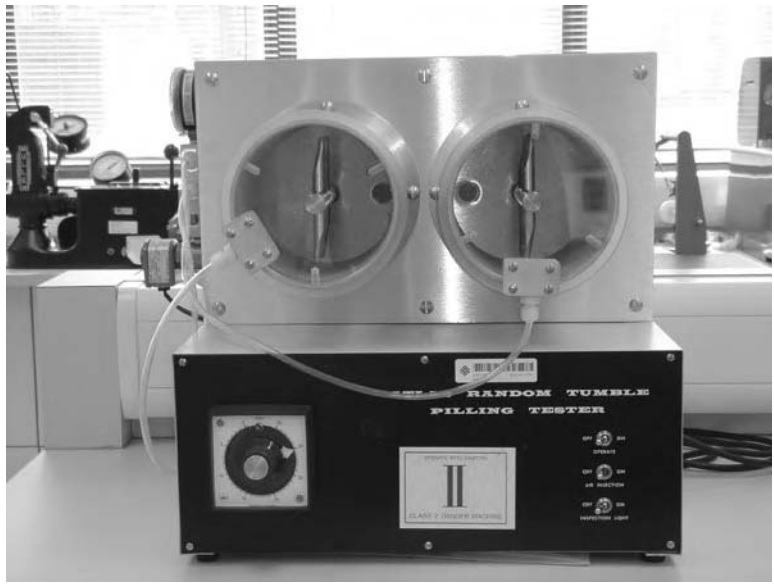


Figure 2.5 Random Tumble Pilling Tester.

In ASTM D3511,[12] D3512[13] and D3514,[14] pilling and other changes in surface appearance which occur in normal wear, are simulated by brushing the specimens to free fibre ends, by random rubbing action produced by tumbling specimens in a cylindrical test chamber lined with mildly abrasive materials, and by controlled rubbing against an elastomeric pad having specifically selected mechanical properties, respectively. Figure 2.5 shows a Random Tumble Pilling Tester. The Japanese standard JIS L1076[15] covers six types of testers, similar to those in the ISO, BS and ASTM standards.

The kind of pilling tester used has a significant effect on the test results. Cooke and Goksoy[16] compared the results of the pilling box, Martindale and Accelerotor testers and found that the Martindale and Accelerotor gave more reliable results, while the results from the pilling box might be misleading. Goktepe[17] investigated the pilling performance of fabrics in the wet state on the Martindale Tester, the ICI pilling box and the pilling drum. He found that use of the Martindale Tester resulted in worse pilling grades than the other two testers, and different pilling testers have different sensitivities for various fibre, yarn and fabric parameters. The chosen tester for the performance evaluation should best simulate the actual wear condition.

The subject of fabric pilling has been reviewed by Ukponmwan.[18]

2.2.3 Surface smoothness after repeated laundering

AATCC Test Method 124[19] is designed for evaluating the appearance, in terms of smoothness, of flat fabric specimens after repeated home laundering. The test

procedure and evaluation method are almost the same as in the two methods mentioned above, except for the difference in specimen preparation and standard replicas.

2.3 Assessment of seam appearance

Visual assessment of seam appearance is conducted by comparing the seams with photographic standards under standard viewing conditions. The American Association of Textile Chemists and Colorists (AATCC), American Society for Testing Materials (ASTM), International Organisation for Standardisation (ISO) and Japan Industrial Standard (JIS) have established respective standards and procedures for visual assessment.

2.3.1 AATCC standard

AATCC Test Method 88B[20] is perhaps the most commonly practised test method in the industry for the assessment of seam appearance. The test method was designed for evaluating the appearance of seams in wash and wear fabrics, but is also applicable to the assessment of seams in both unfinished and finished garments or items.

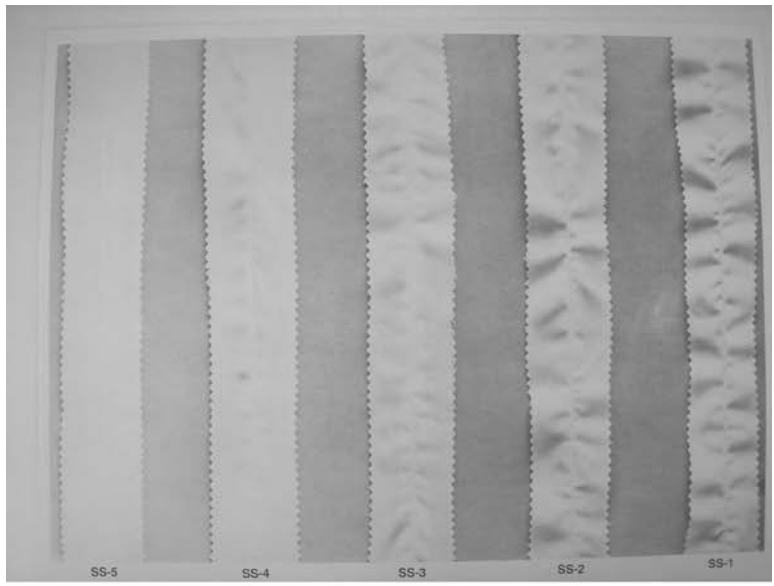
The principle of this test method is to compare the appearance of the specimen seams with the standard photographs, applying the standard overhead lighting procedure. The test specimen is mounted on the viewing board as shown in Fig. 2.1 with the appropriate photographic standard placed alongside. All lights are switched off, except the overhead fluorescent light from two 8 inch F96 CW (Cool-White) preheat rapid start fluorescent lamps. It is also recommended that the side walls of the viewing chamber are painted black, and that black curtains be mounted on either side of the viewing board to eliminate any reflective interference.

Two standard photographic seam smoothness replicas are available, one for single needle seams and one for double needle seams (see Fig. 2.6). The appearance of the seams is graded in five classes.

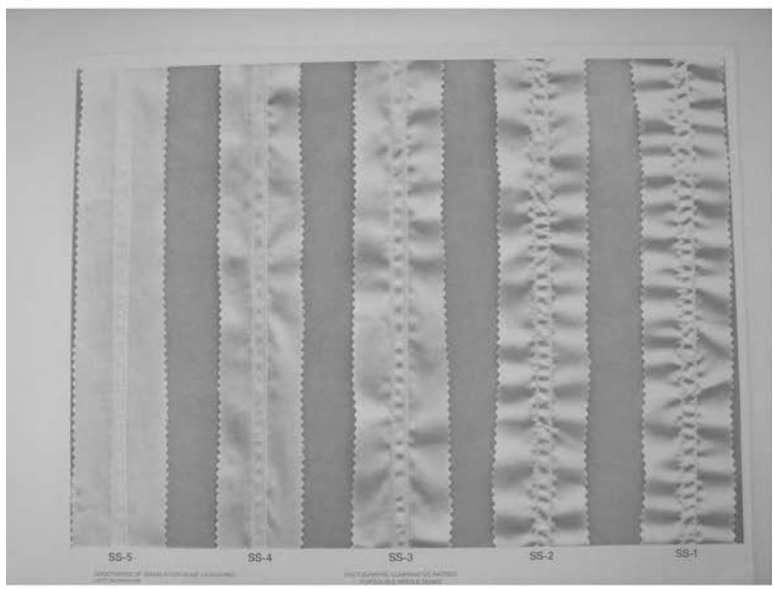
Class 5: Seam appearance equivalent to Standard 5.
Class 4: Seam appearance equivalent to Standard 4.
Class 3: Seam appearance equivalent to Standard 3.
Class 2: Seam appearance equivalent to Standard 2.
Class 1: Seam appearance equivalent to Standard 1.

At least three experienced observers are required, each independently rating at least three test specimens. The average ratings of the observations are reported to the nearest 0.1.

The test specimens could be seamed fabrics, garment parts or finished garments. The samples may be subjected to procedures simulating home



(a)



(b)

Figure 2.6 Photographic Comparative Ratings for Single and Double Needle Seams. Source: AATCC 88B Seam Smoothness Photo Standard. Originally published in the *2001 AATCC Technical Manual*, p.115.[20] Reprinted with permission from AATCC.

laundry practices, e.g. hand or machine washing with appropriate wash cycles, temperatures and drying procedures, so as to evaluate the effect of laundering.[21]

2.3.2 ASTM standard

ASTM D4231-83 (re-approved 1989)[22] provides a standard practice for the evaluation of men's and boys' home launderable woven dress shirts and sports shirts. The standard covers seam failure, shade difference, dimensional change and appearance. With regard to shirt appearance, it extends the method described in AATCC 88B[20] for assessing the appearance of seams, pockets, collars and front plackets, etc. For different parts of garments, it is recommended that users establish appropriate photographic standards. The acceptable level shall be as agreed between the purchaser and supplier.

2.3.3 ISO and JIS standard

JIS L1905[23,24] describes a Japanese Industrial Standard for assessing the appearance of seam pucker in accordance with ISO 7770.[25] The standard is similar to AATCC 88B[20] except that it has a clearer and more detailed description of the testing condition, procedure and rating standard. It defines the viewing board to be at least 1.85 m in length and 1.20 m in width, with the angle of its surface inclined 5^{o} from the vertical and the colour of the surface equal to b_2 of the grey scale. The design of the viewing board is the same as that shown in Fig. 2.1. In assessing garments, however, the viewing board may not be used. Figure 2.7 shows the arrangement for assessing the appearance of garments. The observers should stand 1.2 m away from the garment portion, and the garment portion should be 1.5 m above the floor level (approximately at eye level).

When standard three-dimensional replicas are used for rating, half grades are allowed, but when photographic standards are used, no half grade is allowed. The rating standards are defined in Tables 2.1 and 2.2.

2.3.4 Visual rating standard

The standard three-dimensional replicas or photographic standards may present difficulty in the visual assessment of garment seams, as the seams in the standards may be very different from those in the garments. The garment seams may be curved (e.g. armhole seam) and shaped following the natural drape. The reliability of the visual assessment was found to be a major problem.[26] To circumvent this, visual standards for different garment seams should be established before visual assessment.

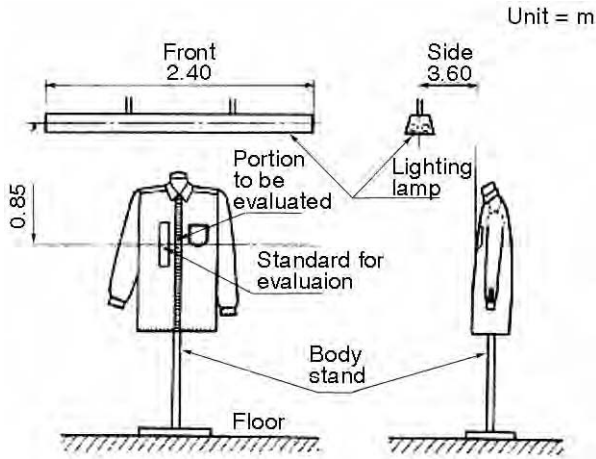


Figure 2.7 Viewing Apparatus for Garments. Source: JIS L 1905:2000.[23]

Table 2.1 Rating standard based on standard three-dimensional replicas

Grade	Rating standard
Grade 5	Appearance showing to be equivalent to, or better than, standard for grade 5
Grade 4.5	Appearance showing to be intermediate between standards for grade 4 and 5
Grade 4	Appearance showing to be equivalent to standard for grade 4
Grade 3.5	Appearance showing to be intermediate between standards for grade 3 and 4
Grade 3	Appearance showing to be equivalent to standard for grade 3
Grade 2.5	Appearance showing to be intermediate between standards for grade 2 and 3
Grade 2	Appearance showing to be equivalent to standard for grade 2
Grade 1.5	Appearance showing to be intermediate between standards for grade 2 and 2
Grade 1	Appearance showing to be equivalent to, or worse than, standard for grade 1

Table 2.2 Rating standard based on photographic standards

Grade	Rating standard
Grade 5	Appearance showing to be equivalent to, or better than, standard for grade 5
Grade 4	Appearance showing to be equivalent to standard for grade 4
Grade 3	Appearance showing to be equivalent to standard for grade 3
Grade 2	Appearance showing to be equivalent to standard for grade 2
Grade 1	Appearance showing to be equivalent to, or worse than, standard for grade 1



Figure 2.8 Grade scale of yoke position. Source: Pang, 2000.[25]

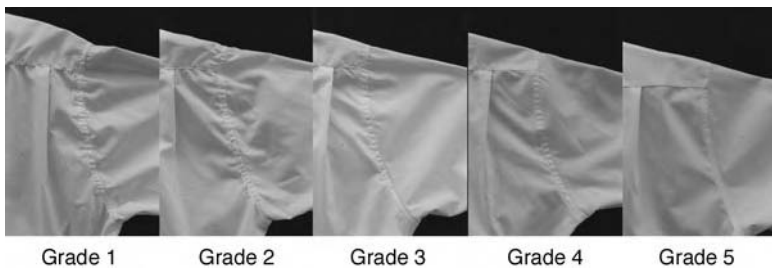


Figure 2.9 Grade scale of armhole position. Source: Pang, 2000.[25]

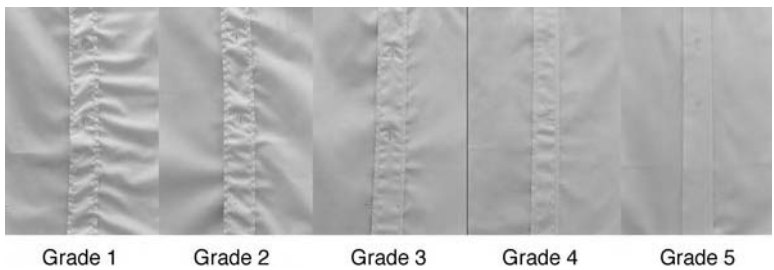


Figure 2.10 Grade scale of buttonhole placket position. Source: Pang, 2000.[25]

Pang[26] established photographic standards of five different garment seams for men's shirts (Yoke seam, armhole seam, buttonhole placket seam, button placket seam and pocket seam) with reference to the photographic standards in AATCC 88B[20] and the ASTM D4231-83.[22] Ten experienced judges were invited to choose a seam from a pool of seams to represent Grades five, four, three, two and one, respectively. The seam that most of the judges ranked as Grade 5 was taken as the Grade five standard. The same procedure was applied to determine Grades 4, 3, 2 and 1. The photographic standards for the seams are shown in Figs 2.8 to 2.12.

2.4 Assessment of crease retention

To maintain good garment appearance, the pressed-in creases in garments (especially in trousers) should be retained after repeated home laundering.

AATCC Test Method 88C[27] is designed for evaluating the quality of crease retention in the fabric. The principle of the method is to subject creased fabric

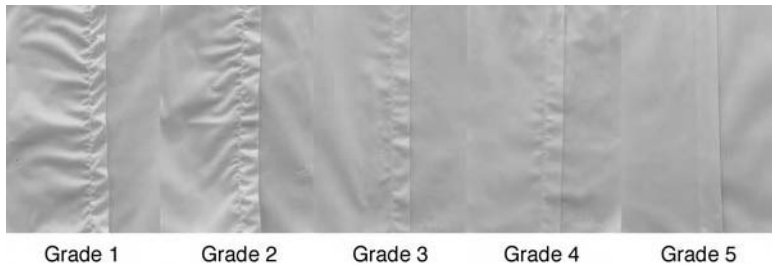


Figure 2.11 Grade scale of button placket position. Source: Pang, 2000.[25]

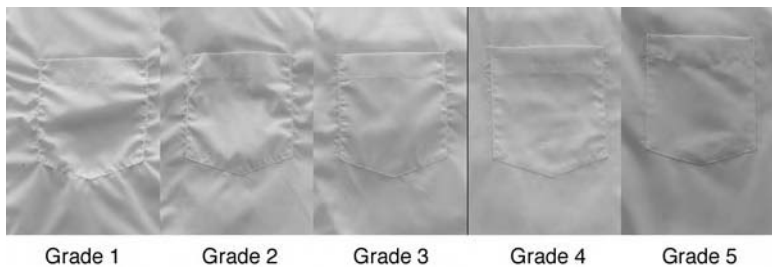


Figure 2.12 Grade scale of pocket position. Source: Pang, 2000.[25]

specimens to standard home laundering practices and then rate the appearance of specimens in comparison with appropriate reference standards under a standard lighting and viewing area.[21] A choice is provided of hand or machine washing, alternative machine wash cycles and temperatures, and alternative drying procedures. Three representative fabric specimens (38 × 38 cm) cut parallel to the fabric length and width, are prepared, pressed and rated, respectively. The AATCC crease retention replicas are in five grades. The viewing condition is the same as that shown in Fig. 2.1.

2.5 Assessment of appearance retention of finished garments

Garment appearance may deteriorate due to poor fabric dimensional stability and pressing performance, poor workmanship during garment manufacture and unfavourable conditions during transport. This problem is especially acute for wool garments. Consequently, the International Wool Secretariat, Japanese branch[28] proposed a test method for assessing the appearance retention of men's suits after final pressing and prior to sale.

The principle of the test is to expose garments to certain temperature and humidity conditions for a period of time and then to check the changes in appearance afterwards. During testing, garments are firstly hung in a testing room at 20ºC and 65% RH (standard temperature and humidity conditions) for 24 hours,

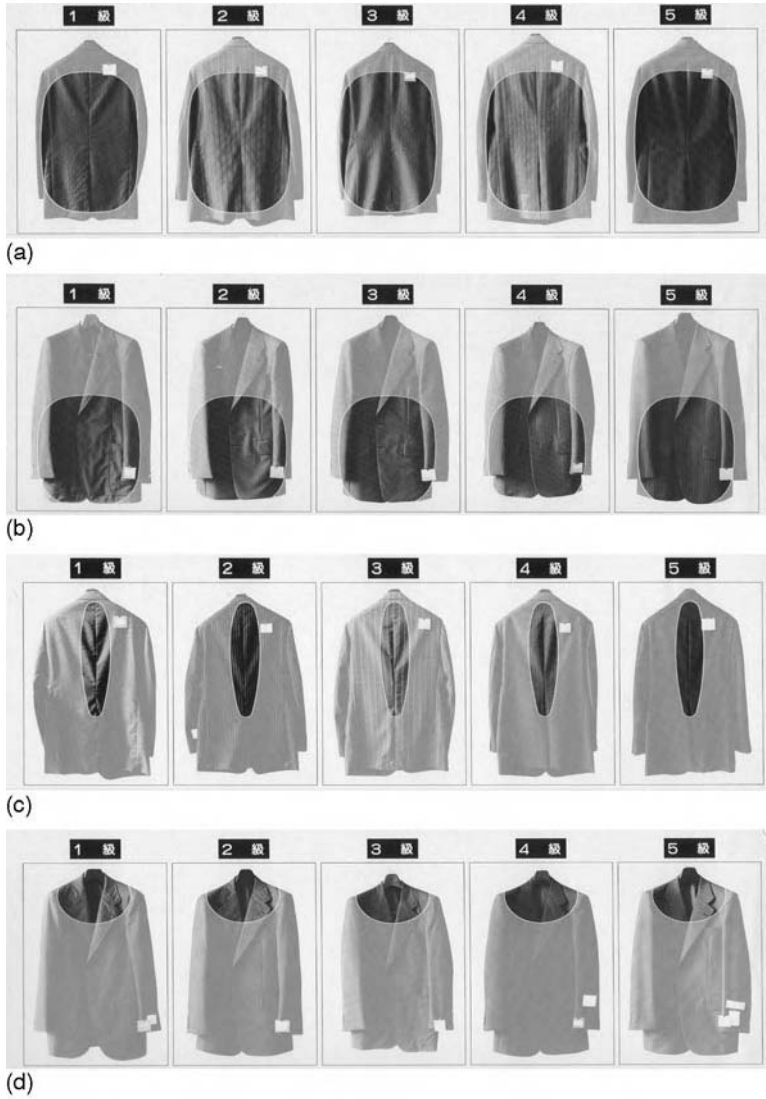


Figure 2.13 Rating Scale for the Appearance of Wool Suits. Source: Mitsuo Hori, IWS Ichinomiya Technical Centre, 1 May 1984.

after which the appearance of each garment part, e.g. collar, shoulder, front, back, side body and sleeve, is inspected and rated according to the photographic standards (Fig. 2.13 shows an example of the standards). The temperature and humidity of the testing room are then changed to 30ºC and 90% RH (high temperature and high humidity) or 20ºC and 40% RH (standard temperature and low humidity) for a period of time (normally 6 hours). Thereafter, the conditions of the testing room are changed back to the standard conditions of 20ºC and 65%



Figure 2.13 Continued.

RH, where the garments are hung for at least 24 hours before being inspected and rated again using the photographic standards. If any part of a garment is rated grade 3 or less (grade 5 = no deterioration, grade 1 = severe deterioration), the garment is considered as unacceptable in terms of appearance retention.

2.6 Reliability of subjective assessment

In carrying out subjective assessments, Slater[29] pointed out that the results may be influenced by many factors outside the control of the person doing the experiment. The subject's personality, state of mind or health, and internal assessment scaling may affect the results in a totally unpredictable manner. It is also crucial to avoid any invalid analysis techniques. To ensure the maximum reliability of the subjective assessment results, the quality of the assessors, the assessment procedure, assessment scaling as well as analysis methods should be considered very carefully.

2.6.1 Training of assessors

The assessors doing the subjective assessment may have different internal assessment scales to rate an observation. Therefore the training of the assessors is very important so as to bring each member of the panel as near to an identical scale as possible.

According to Park and Lee,[30] well-trained expert assessors can give more reliable grading of the seam appearance. Yick *et al.*,[31] in their study of the handle of men's shirting fabrics, compared two groups of assessors, one consisted of members with less experience and the other with more experience. They found that the results from the more experienced group were more consistent. In the AATCC Technical Manual, it is therefore stated that the assessors should be trained well enough to rate the test specimen independently.

2.6.2 Number of assessors in subjective assessment

Increasing the number of assessors can generally improve the validity of the average rating by cancelling out any individual differences in terms of health, state of mind, etc. However, it has been pointed out[32] that, beyond a certain point, it is impossible to increase the reliability of assessment further by increasing the number of assessors. The reliability of the average rating can be evaluated by calculating the 95% confidence interval of the average rating.[33] Three independent assessors are required in terms of the AATCC standards.

2.6.3 Assessment procedure

The assessors may be biased in trying to give what they perceive to be 'appropriate' results or, in the worst case, may deliberately sabotage the experiment. To prevent this problem, blind testing was applied in the evaluation of tactile sensation.[34] Blind testing is obviously not possible for the assessment of garment appearance, although the principle can be applied. It is advisable that the assessors are not aware of the purpose of the assessment and therefore do not appreciate what effect a response will have on the investigation.

2.6.4 Assessment scale and rating technique

The scale for subjective assessment should be devised carefully. Ideally, the intervals between the grades should be equidistant. If possible, objective confirmation of the uniformity of the intervals is useful in ensuring the validity of the scale.

Due to the uncertainty in deriving a valid scale and whether all assessors follow the same scaling during the assessment, several other rating techniques have been developed. The simplest, perhaps, is that of asking for a 'yes' or 'no' answer to a question.[29] The next simplest one is rank ordering. In this technique, each respondent is asked to rate a number of test specimens, in order, from best

to worst, according to the property being assessed. A points system is used (1 for best, 2 for the next, and so on). If an assessor is unable to differentiate between two or more specimens, they can be given the mean rating for those which they declared equal. Once all the specimens have been ranked by all the observers, the specimen with the lowest number of total points is then rated 'best'. This technique was used by Fan and Leeuwner[35] to assess the seam appearance.

Another technique aimed at reducing the bias caused by the problem of scaling is paired comparison assessment. With this technique, a pair of specimens is compared in each assessment. The 'better' specimen of the pair is given a value of 1 and the other a value of 0. Once all possible pairs of specimens have been compared, the sum of all 1 and 0 values for each specimen is calculated, and all the samples are then ranked according to the sum of these totals from all the assessors. This technique was used by Thompson and Whiteley[36] to assess the lightness and yellowness of wool samples and by Ukponmwan[18] to compare the handle of a range of fabrics. Fan *et al*.[37] used the technique to assess the effect of garment size on the perception of body size.

2.7 References

1. Fan J, 'Assessing the quality of garment appearance', *J Asia Text Apparel*, Jun/Jul, 1998 88–90, also *China Text Apparel*, (Aug./Sept.) 1998 84–85.
2. Smuts S, 'A review of the wrinkling of wool and wool/polyester fabrics', *South African Wool & Text Res Inst CSIR TexReport No. 1*, July, 1989.
3. AATCC 128, *Wrinkle Recovery of Fabrics: Appearance Method,* American Association of Textile Chemists & Colorists, 1999.
4. ISO 9867, *Textiles – Evaluation of the Wrinkle Recovery of Fabrics – Appearance Method*, International Organisation for Standardisation, 1991.
5. Abbott N J, 'Wrinkled fabrics, optical illusions and the FRL topometer' *Text Res J*, 1970 **40**(11) 1026–1034.
6. Salter C J, Stephens L G, Higgerson G J and Samuelsdorff M J, 'The perception of wrinkling – the effects of fabric pattern', *J Text Inst*, 1996 **87**(1) 166–171.
7. Cooke W D, 'Pilling attrition and fatigue', *Text Res J*, 1985 **55**(7) 409–414.
8. ISO 12945-1, *Textiles – Determination of Fabric Propensity to Surface Fuzzing and to Pilling – Part 1: Pilling Box Method*, International Organisation for Standardisation, 2000.
9. BS 5811, *Method for Determination of the Resistance to Pilling and Changes of Appearance of Fabrics*, BSI, 1986.
10. ASTM D4970, *Standard Test Method for Pilling Resistance and Other Related Surface Changes of Textile Fabrics: Martindale Tester*, ASTM International, 2002.
11. ISO 12945-2, *Textiles – Determination of Fabric Propensity to Surface Fuzzing and to Pilling – Part 2: Modified Martindale Method*, International Organisation for Standardisation, 2000.
12. ASTM D3511, *Standard Test Method for Pilling Resistance and Other Related Surface Changes of Textile Fabrics: Brush Pilling Tester*, ASTM International, 2002.
13. ASTM D3512, *Standard Test Method for Pilling Resistance and Other Related Surface Changes of Textile Fabrics: Random Tumble Pilling Tester*, ASTM

International, 2002.
14. ASTM D3514, *Standard Test Method for Pilling Resistance and Other Related Surface Changes of Textile Fabrics: Elastomeric Pad Tester*, ASTM International, 2002.
15. JIS L1076, *Testing Methods for Pilling of Woven Fabrics and Knitted Fabrics*, Japanese Standards Association, 1992.
16. Cooke W D and Goksoy M, 'Problem of predicting pilling performance using laboratory test method', *Mell Textilber, Eng. Ed.* 1988 **69**(4) 250–254 (E134–135).
17. Goktepe O, 'Fabric pilling performance and sensitivity of several testers', *Text Res J*, 2002 **72**(7) 625–630.
18. Ukponmwan J O, 'Appraisal of woven fabric performance', *Text Res J*, 1987 **57**(8) 445–462.
19. AATCC 124, *Appearance of Fabrics after Repeated Home Laundering*, American Association of Textile Chemists & Colorists, 2001.
20. AATCC 88B, *Smoothness of Seams in Fabrics after Repeated Home Laundering*, AATCC Technical Manual, 2001.
21. AATCC 143 *Appearance of Apparel and Other Textile End Products after Repeated Home Laundering*, American Association of Textile Chemists & Colorists, 1996.
22. ASTM D4231, *Standard Practice for Evaluation of Men's and Boys' Home Launderable Woven Dress Shirts and Sport Shirts*, ASTM International, 1989.
23. JIS L1905, *Methods for Assessing the Appearance of Seam Pucker on Textiles*, Japanese Standards Association, 1994.
24. JIS L1905, *Methods for Assessing the Appearance of Seam Pucker on Textiles*, Japanese Standards Association, 2000.
25. ISO 7770 *Textiles – Method for Assessing the Appearance of Seams in Durable Press Products after Domestic Washing and Drying*, International Organisation for Standardisation, 1985.
26. Pang Y T, *A Study on the Evaluation of Seam Pucker in Garments*, MA Dissertation, The Hong Kong Polytechnic University, 2000.
27. AATCC 88C, *Retention of Creases in Fabrics after Repeated Home Laundering*, American Association of Textile Chemists & Colorists, 2001.
28. IWS Japan 'Shape retention test method, clothing service information No. 10', International Wool Secretariat (Aug., 1978).
29. Slater K, 'Subjective textile testing', *J Text Inst*, 1997 **88** Part 1(2) 79–91.
30. Park C K and Lee D H, 'A new evaluation of seam pucker and its application', *Int J Cloth Sci Technol*, 1997 **9**(3) 252–255.
31. Yick K L, Cheng K P S and How Y L, 'Subjective and objective evaluation of men's shirting fabric', *Int J Cloth Sci Technol*, 1995 **7**(4) 17–29.
32. Tezer L, Luning R and Bohland K H, 'Evaluation of carpet surfaces by means of image analysis', *Chemiefasern/Textilindustrie*, 1994 **44/96**(3) 153–156 (E12–13).
33. Fan J and Liu F, 'Objective evaluation of garment seams using 3-D laser scanning technology', *Text Res J*, 2000 **70**(11), 1025–1030.
34. Sweeney M M and Branson D H, 'Sensorial Comfort. I. A psychophysical method for assessing moisture sensation in clothing', *Text Res J*, 1990 **60**(7) 371–377.
35. Fan J and Leeuwner W, 'The performance of sewing threads with respect to seam appearance', *J Text Inst*, 1998 **89** Part 1(1) 124–154.
36. Thompson B and Whiteley K J, 'Visual perception of the colour of scoured wool', *J Text Inst*, 1986 **77**(4) 284–287.
37. Fan J, Newton E, Lau L and Liu F, 'Garment sizes in perception of body size', *Percept Motor Skill*, 2003 **96** 875–882.

3

Subjective assessment of clothing fit

W YU

3.1 Definition of fit

Clothing fit has long been regarded as the single most important element to customers in clothing appearance. The principles of fit are, however, not clearly understood, and the definitions of fit vary from time to time, and depend on the fashion culture, industrial norm and individual perception of fit. Some general definitions are introduced here for basic reference purposes:

> 'Fit is directly related to the anatomy of the human body and most of the fitting problems are created by the bulges of the human body' – Cain.[1]
>
> Clothing that fits well, conforms to the human body and has adequate ease of movement, has no wrinkles and has been cut and manipulated in such a way that it appears to be part of the wearer' – Chamber and Wiley.[2]
>
> 'Fit is defined as a combination of five factors; ease, line, grain, balance and set' – Erwin and Kinchen.[3]
>
> 'Clothing fit is a complex property which is affected by fashion, style and many other factors' – Efrat.[4]
>
> 'Clothing should fit the body smoothly with enough room to move easily and be free from wrinkles' – Hackler.[5]
>
> 'Clothing which fits, provides a neat and smooth appearance and will allow maximum comfort and mobility for the wearer' – Shen and Huck.[6]
>
> '[Fit is defined as] the ability to be the right shape and size' – *The Oxford Dictionary*.[7]

These divergent definitions of fit reflect the lack of agreement within the industry on the features which are responsible for a good fit. Therefore, a more detailed understanding of the factors contributing to clothing fit is necessary.

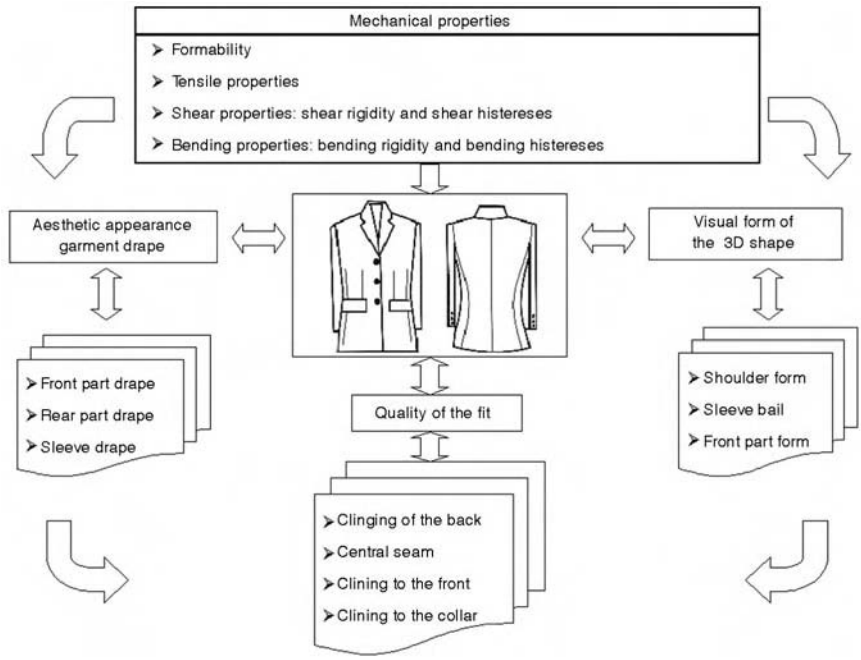


Figure 3.1 Criteria for qualitative evaluation of clothing fit. Source: J Geršak, 2002.[10]

3.2 Influences on clothing fit

Physical comfort, psychological comfort and appearance all play a part in the consumer's perceived satisfaction of fit.[8] Ashdown[9] noted several factors impacting on decisions to understand fit within the research framework. Geršak[10] illustrated the elements determining the quality of clothing fit, which are directly linked to the mechanical properties of fabric which affect the aesthetic drape and 3-D shape, as shown in Fig. 3.1.

Understanding fit from a consumer's perspective is complex. LaBat and DeLong[11] suggested two external influences (social message of the ideal body and fashion figure in the industry) impacting and two personal influences (body cathexis and physical dimensional fit of clothing) impacting on the consumer's satisfaction with clothing fit.

3.2.1 Social message of the ideal body

The satisfaction of fit is affected by a societal message concerning the ideal body. The balance of body proportion and symmetry of body segments are all important. For example, Armstrong defined a lady's ideal figure as one where the shoulder width equals the hip width, with the waist (measurement) girth 10 to 12.5 inches smaller than that of the bust and hip.[12]

3.2.2 Fashion figure in the industry

The fashion industry's portrayal of an idealised figure, for example taller and slimmer in proper proportion and balance, is always presented through fashion illustrations, photography and catwalk models. Wacoal has compiled several indices of beauty based on their research findings: 'Golden Proportions' (1955); 'Beautiful Proportions' (1979); and 'Golden Canon' (1995).[13]

3.2.3 Body cathexis

Body cathexis is defined as positive and negative feelings toward one's body. Various scales evaluating body cathexis have been used to examine attitudes toward the body. Secord and Jourard's original body cathexis scale[14] consisted of 46 physical characteristics used to measure satisfaction and dissatisfaction on a seven-point Likert scale. LaBat and DeLong[11] selected a scale developed by Rosen and Ross[15] to measure body cathexis on a nine-point Likert scale. Hwang[16] studied the relationship between body cathexis, clothing benefits sought and clothing behaviour for 19 body parts.

Wenger[17] and Frederick[18] have examined the fit preferences from a consumer's viewpoint. They revealed that women who were satisfied with a particular body part preferred a definite fit at that area. The overweight group reported much less satisfaction with their bodies and the fit of their clothing. An understanding of the fit preferences of consumers allows designers better to define fit for individuals and target markets.[19]

3.2.4 Physical dimension fit of clothing

The physical dimension of clothing is a key element of fit evaluation in numeric form. The clothing size can also significantly affect customer satisfaction. The next section will describe, in detail, various methods of testing fit.

3.3 Testing methods for dimensional fit

To verify whether a garment fits the dimensional specifications, it can be tested by using different standards, such as live models and dress forms. Advantages and disadvantages of these different standards are listed in Table 3.1.

3.3.1 Live models

Live models, although expensive, are commonly used for evaluating clothing fit because real human bodies are involved and their comments on the clothing are sensible. However, they tend to make judgements based on subjective and qualitative preferences, which vary from one person to another and from time to

Table 3.1 Advantages and disadvantages of fitting standards

Fitting standard	Advantage	Disadvantage
Live model	Real body shape Real movement	Subjective and qualitative Psychological interruption
Dress form	Static and convenient to use High repeatability	Subjective and qualitative Personal assessment of tension

time. Moreover, the way in which the live models are selected and how the fit is defined and evaluated, could affect the results significantly.

Several studies examined the fit satisfaction of consumers and their perception of fit of various clothing items at specific areas. However, due to the complexities involved, studies based on live models were confined to a limited sample size.

In order to standardise the fit scenario, reference procedures have been developed to perform the subjective evaluation of clothing that fits a live model. Huck *et al*,[20] who evaluated protective overalls, asked each subject to complete an exercise routine, consisting of a series of body movements which represented the physical movements, as defined in Table 3.2, which might be required in a work environment where the garments under investigation are worn and stretched. The researchers recorded their visual observations of the movements of the subjects, and each subject was asked to complete a wearer acceptability scale after completing the exercise protocol.

Table 3.2 Exercise protocol

Exercise order	Procedure
1	Kneel on left knee, kneel on both knees, kneel on right knee, stand. Repeat exercise four times.
2	Duck squat, pivot right, pivot left, stand. Repeat exercise four times.
3	Stand erect. With arms at sides, bend body to left and return, bend body forward and return, bend body to right, and return. Repeat exercise four times.
4	Stand erect. Extend arms overhead in the lateral direction, then bend elbows. Repeat exercise four times. Extend arms overhead in the frontal direction, then bend elbows. Repeat exercise a total of four times.
5	Stand erect. Extend arms perpendicular to sides of torso. Twist torso left and return, twist torso right and return. Repeat exercise four times.
6	Stand erect. Reach arms across chest completely to opposite sides. Repeat exercise a total of three times.
7	Walk a distance of 100 yds (91m) (or walk on the spot for at least 3 min).
8	Crawl on hands and knees for a distance of 20 ft (6 m) (or crawl on the same spot for a minimum duration of 1 min).

Source: ASTM F1154-99a 'Standard Practices for Qualitatively Evaluating the Comfort, Fit, Function, and Integrity of Chemical-Protective Suit Ensembles'.

The National Association of Hosiery Manufacturers (NAHM) Standard also describes a live model testing procedure for women's pantyhose.[21] It suggests that the models do standing, sitting and walking exercises. The clothing of each model is then evaluated for reasonable tension, tendency to slide down and to wrinkle. Merchandise testing Labs (MTL) suggested live models should wear the clothing for a reasonably long period and rank preferences relative to good/poor fit.[22]

3.3.2 Dress form

Fashion designers and pattern makers must have their customers' specified dress forms which represent the average size and shape of the target market. They may develop the silhouette on the dress form by direct fabric draping, or fit the prototype on the dress form for evaluation. As dress form is very important to ensure the fit of the clothing, its quality is always of concern both to industrialists and academics. However, commercial dress standards are still unsatisfactory due to their limitations in terms of size and shape accuracy. Companies tend to make their own dress forms which represent the body figures of their target customers.

Cascini *et al*.[23] has patented a range of mannequins, FORMAX®, based on all body conformations extracted from anthropometrical statistics obtained from a low-cost body shape silhouetter 'ScanFit system'. CAD Modeling is a company providing a complete set of such mannequins representing realistic models for the target population to which the garments are dedicated.[24]

Based on research on 3-D human morphology and garment engineering, Alvanon[25] sells tailor-made dress forms and a platform for objective and subjective assessment of a garment's fit, so as to reduce sample making costs, raise efficiency in production and increase accuracy of fit.

The Digital Human Laboratory[26] in Japan, in collaboration with the Bunka Fashion College, has since 1996 developed a series of new dress forms (Fig. 3.2a) which looks more real than the conventional dress form (Fig. 3.2b). The conventional dress form is handmade from clay, hence its shape is artificial. The new dress form represents the average dimensions of the target population measured by an optical 3-D body scanner, and the 3-D data were modelled using about 500 data points which are defined and based on anatomical landmarks (Fig. 3.3). The average form was calculated using an FFD technique, and was manufactured by rapid prototyping. A dress form is made by modifying the average form by reducing the unnecessary curves, but is still very close to the actual human body shape. Bunka Fashion College started selling the new dressmaking dummies from September 2000. A Japanese company Taninaka[27] also provides information on the web, but now refuses to sell the dummy overseas (Fig. 3.4).

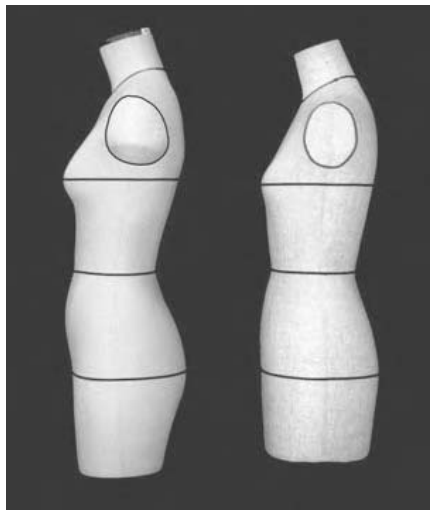


Figure 3.2 Difference between the (a) new and (b) conventional dress form. Source: Makiko Kouchi, Masaaki Mochimaru and Yumiko Ito, 2001: Development of a new dressmaking dummy based on a 3-D human model. Proceedings of Numerisation 3-D Scanning 2001.

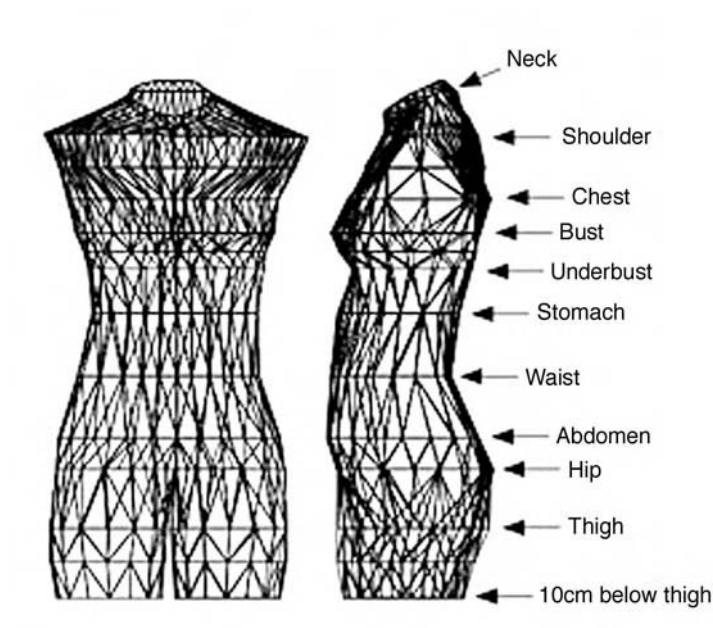


Figure 3.3 Digital human body model based on anatomical landmarks. Source: Makiko Kouchi, Masaaki Mochimaru and Yumiko Ito, 2001: Development of a new dressmaking dummy based on a 3-D human model. Proceedings of Numerisation 3-D Scanning 2001.

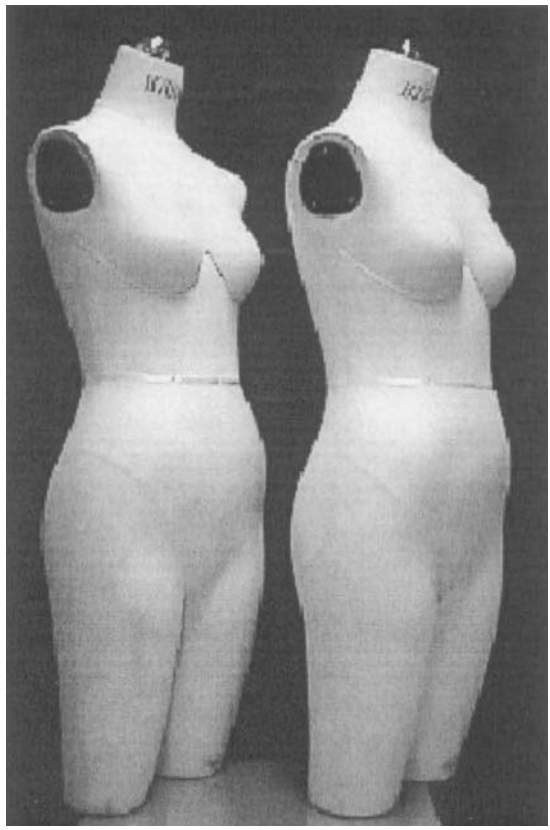


Figure 3.4 Taninaka's Dress stand. Source: http://www2.nsknet.or.jp/~taninaka/main-page.html

3.4 Subject rating scales

3.4.1 Likert type scale

Likert scaling[28] presents a set of attitude statements. Subjects are asked to express agreement or disagreement on a five-point scale. Each point of agreement is given a numerical value from one to five. Thus a total numerical value can be calculated from all the responses.

3.4.2 Wearer acceptability scale

Huck *et al*[20] designed a wearer acceptability scale (Fig. 3.5) after completing a range of body movements. The nine-point scale consisted of a series of descriptive adjective sets to determine how subjects felt and also how they perceived the fit and comfort of their clothing.

Place a check (tick) between each pair of adjectives at the location that best describes *how you feel:*

1.	Comfortable	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1*	Uncomfortable
2.	Acceptable	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Unacceptable
3.	Tired	1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9	Rested

Place a check (tick) between each pair of adjectives at the location that best describes *the clothing you are wearing:*

4.	Flexible	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Stiff
5.	Easy to put on	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Hard to put on
6.	Freedom of movement of arms	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Restricted movement of arms
7.	Easy to move in	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Hard to move in
8.	Satisfactory fit	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Unsatisfactory fit
9.	Freedom of movement of legs	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Restricted movement of legs
10.	Freedom of movement of torso	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Restricted movement of torso
11.	Dislike	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Like
12.	Loose	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Tight
13.	Crotch of overall right distance from body	9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1	Crotch of overall too close or too far from body

*Number added for reader reference only

Figure 3.5 Wearer acceptability scale. Source: Huck *et al.,* 1997.[20]

3.4.3 Fit evaluation scale

In 1993, Shen and Huck[6] developed a subjective scale which contained 25 items in three categories: overall fit, bodice front fit and bodice back fit. For each item, nine responses were possible, ranging from 'much too tight' to 'much too loose'. The middle position for each fit criterion indicated a 'good' fit. Yu *et al*. have applied this scale for the fit evaluation of men's jackets as shown in Fig. 3.6.

3.5 Subjective fitting guide

Clothing fit is influenced by fashion trends, personal preference and the intended end-use of the clothing. The overall fit generally contains five elements: grain, set, line, balance and ease. The lengthwise grain runs parallel to the centre front and centre back of the clothing. The crosswise grain runs horizontally at the bust/chest and hip levels. Good set refers to a smooth fit with no undesirable wrinkles. The lines of the clothing follow the silhouette and circumference lines



Figure 3.6 Fit evaluation scale. Source: Yu *et al.*, 'Assessment of Garment Fit', Proceedings of the HKITA & CTES Conference on Hand-in-hand Marching into 21st Century, April 1998, 125–129.

of the body. Clothing that is balanced appears symmetrical from side to side and front to back. It also requires adequate fitting ease to provide comfort and allow room for movement. Additional ease for style reasons is called 'design ease'. A complete checklist of clothing fit observations can be found in the book by Brown and Rice.[29]

For conventional fit of formal wear, Rasband[30] has given a comprehensive guideline of clothing fit. For example, the neckline should sit on the curve

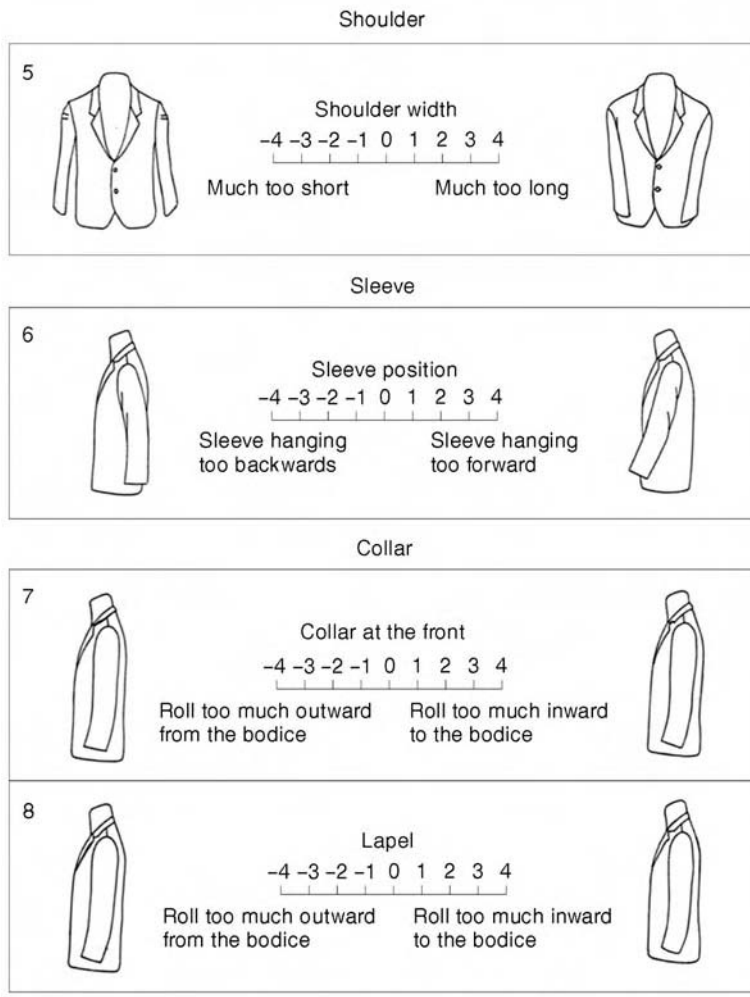


Figure 3.6 Continued.

around the neck base without wrinkling or gaps. A suit collar reveals about half an inch of the shirt collar at the centre back, whereas the outer edge of the suit collar just covers the neckline seam. Lapels should lie symmetrical and flat without gaps. Armholes should be large enough to allow for easy movement without cutting into the arm, binding or gaps. Upper back areas must lie smooth, with no wrinkles or strain at the armhole seam when arms are moved forward; as well as the absence of horizontal wrinkles, bubbles or bulges below the collar.

Centre front and back seams should be centred on the body and fall straight down, perpendicular to the floor. The side seams should intersect the waistline at

a 90º angle. Set-in cap sleeves should lie at the end of the shoulder and curve smoothly around the armhole, without puckers or wrinkles. Fullness is evenly distributed along the front and back. Ease at the elbow should be sufficient to allow the arm to bend without binding or discomfort. Long sleeve cuffs should end at the wrist when the arm is bent upward at the elbow. When arms are down at the sides, the cuffs of the long sleeves should hang no longer than the wrist joint. The shirt sleeve cuff should be about half an inch longer than the jacket sleeve.

3.6 Conclusions

Clothing fit is a complex issue and has been defined in divergent ways. Aspects of fit do not just involve the 3D body shape and the fabric properties which affect clothing drape and appearance but also include a social message, fashion, body cathexis and clothing physical dimensions. Live models and dress forms represent common standards used to test clothing fit through wear trials and judged by experienced assessors. The assessors would subjectively judge the fit in qualitative terms or grade the quality of fit in terms of quantitative scales. Fitting guides and checklists are well provided to assess whether clothing can fit the figure smoothly and accurately, and whether clothing seams follow the natural line of the figure. However, the subjective approach is still not very precise for communication purposes. It has been generally agreed that clothing fit is a critical feature of the effectiveness of clothing appearance. Research work has been carried out to rationalise the problems of fit and explain its complexities using a logical approach and understanding.

3.7 References

1 Cain G, *The American way of designing*, New York, Fairchild Publications, 1950.
2 Chamber H and Wiley E, *Clothing selection*, New York, 1967.
3 Erwin M D and Kinchen L A, *Clothing for modern*s, 4th edn, New York, Macmillan, 1969.
4 Efrat S, *The development of a method of generating patterns for clothing that conform to the shape of the human body*, PhD thesis, School of Textile and Knitwear Technology, 1982, Leicester Polytechnic, 234–235.
5 Hackler N, 'What is good fit?', *Consumer Affairs Committee*, May, 1984, 2 (1).
6 Shen L and Huck J, 'Bodice pattern development using somatographic and physical data', *Int J Cloth Sci Technol*, 1993, **5**(1) 6–16.
7 *The Oxford Dictionary*, Oxford, Oxford University Press, 2002.
8 Frost K, *Consumer's perception of fit and comfort of pants*, Washington State University, Pullman, 1988.
9 Ashdown S, 'Introduction to sizing and fit research', The Fit Symposium, Clemson Apparel Research, South Carolina, Clemson, 2000.
10 Geršak J, 'Development of the system for qualitative prediction of clothing appearance quality', *Int J Cloth Sci Technol*, 2002, **14**(3/4) 169–180.

11 LaBat K L and DeLong M R, 'Body cathexis and satisfaction with fit of apparel', *Cloth Text Res J*, Winter 1990, **8**(2) 43–48.
12 Armstrong H J, *Patternmaking for fashion design,* New York, Harper and Row, 1987.
13. URL: http://www.wacoal.co.jp/company/aboutcom_e/ningen/index_e.html
14 Secord P F and Jourard S M, 'The appraisal of body-cathexis: Body-cathexis and the self', *J Counseling Psycho*, 1953, **17**(5) 343–347.
15 Rosen G and Ross A, *The relationship of body image to self concept*, thesis, University of Pittsburgh, Pittsburgh, Pa., 1973.
16 Hwang J, *Relationships between body-cathexis and clothing*, Virginia Polytechnic Institute and State University, Blacksbury, VA, 1996.
17 Wenger J, C*lothing fit and body attitudes*, Colorado State University, Fort Collins, 1969.
18 Frederick N, *The relationship between body cathexis and clothing market satisfaction of overweight women*, unpublished MSc thesis, Washington State University, Pullman, 1977.
19 Anderson L J, 'Understanding fitting preferences of female consumers: Development of an expert system to enhance accurate sizing selection', *Annual Rep - Nat Text Center*, 2001, Sect. 4, (Nov. 2001).
20 Huck J, Maganga O and Kim Y, 'Protective overalls: Evaluation of clothing design and fit', *Int J Cloth Sci Technol*, 1997, **9**(1) 45–61.
21 AFNOR, *Textiles hosiery articles – determination of the dimensions of stretched stockings, tights and other hosiery articles,* NF G 32-104, 1995.
22 Pechoux B L and Ghosh T K, 'Apparel sizing and fit', *Text Progr*, 2002, 27.
23 Cascini G, Pieroni N and Quattrocolo S, 'Development of a low cost body scanner for garment construction', *12th ADM Int Conf*, Rimini, Italy, Sept., 2001, 5-7, A4-1~8.
24 CAD Modeling', URL: http://www.cadmodelling.it/english/home.htm.
25 Alvanon, *Fit conformance for the apparel industry*, URL: http://www.alvanon.com/home.html.
26 Digital Human Laboratory, *Development of a dress making dummy based on digital human body models for Japanese women*, URL: http://www.dh.aist.go.jp/NIBH/indexcontents/j4reseachperformance/j401contents/press000405-e.html.
27 URL: http://www2.nsknet.or.jp/~taninaka/main-page.html.
28 Likert R, *A Technique for the measurement of attitudes*, New York, New York University, 1932.
29 Brown P and Rice J, *Ready-to-wear apparel analysis,* 3rd edn, Upper Saddle River, NJ, Merrin Prentice Hall, 2001.
30 Rasband J, *Fabulous fit*, New York, Fairchild Publications, 1994.

4

Objective evaluation of clothing appearance

J FAN, L HUNTER AND F LIU

4.1 Introduction

Subjective methods of evaluating clothing appearance, discussed in Chapter 2, tend to be inconsistent and inaccurate as the results are influenced by the personality, experience, background and state of mind of the assessors. For several decades, researchers have therefore attempted to develop objective methods for evaluating clothing appearance. In this chapter, the different objective methods for assessing fabric wrinkling, pilling, seam pucker and overall garment appearance are reviewed.

4.2 Objective evaluation of fabric wrinkling

Objective evaluation of fabric wrinkling has long been of interest to researchers in the textile and related industries. According to the way in which the wrinkled appearance is detected and measured, these systems can be classified into two main categories: contact and non-contact methods. Furthermore, the non-contact methods may be classified into two main types, namely laser scanning and image processing.

4.2.1 Contact methods for objective evaluation of fabric wrinkling

An early instrument, designed and used by Hebeler and Kolb[1] in the 1950s for tracing the surface of a wrinkled sample, is an example of the contact objective method. The instrument, named 'Wrinklometer', consisted of a movable platform, a variable-speed motor, a small counterbalanced probe linked to a shutter, a light source, a photovoltaic cell and a signal recorder. The contour of the wrinkled fabric was recorded on the recorder paper. There was a one-to-one correlation between each wrinkle in the fabric and a peak in the curve on the recorder paper. The area under the traced curve was proportional to the product of the mean wrinkle height and the length of the trace on the fabric, which was converted into the mean

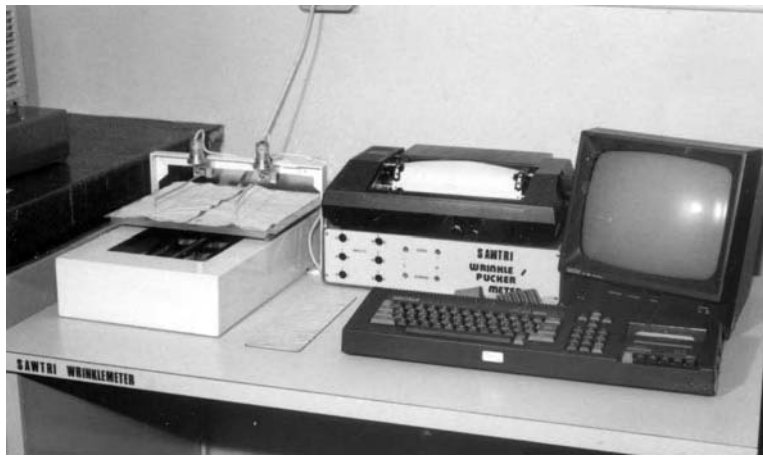


Figure 4.1 SAWTRI Wrinklemeter.

wrinkle height of the fabric. The instrument also had an electronic integrator which simplified the calculations of mean wrinkle height. To demonstrate its reproducibility and ranges of applicability, Kaswell[2] used the 'Wrinklometer' to measure the mean profile heights of some randomly wrinkled samples.

Shiloh[3] designed and built an instrument, called the Sivim Wrinklemeter, to be followed by the SAWTRI Wrinklemeter (Fig. 4.1), to measure the contours of fabric surfaces automatically. The instrument consisted of two major parts:

1. A tracing system, which includes an electro-mechanical device which translates contour variations into voltage; the tracing element has a frictionless-core suspension so that the fabric is traced under conditions of minimum constant pressure and wrinkle deformations are largely avoided.
2. An analogue computer with an operational amplifier, integrators, differentiators, multipliers, squares and control circuits.

The analogue computer processes the input voltage according to the required equations to give a value of wrinkle height $H(\theta)$, wrinkle slope$T(\theta)$, the density of zero points $N_0(\theta)$ and the density of extreme points $N_1(\theta)$ in real time.

The wrinkled surface of the fabric is regarded as a random rigid surface. Its mathematical representation is $z = f(x,y)$.

For a particular cross-section of the fabric at a given direction, θ to the axes, the following wrinkle parameters have been suggested:[3,4]

1. The wrinkle height

$$H(\theta) = \sqrt{\overline{f(x)^2}} \tag{4.1}$$

where $\overline{f(x)^2}$ is the mean square height of the section curve from its regression line.

2. The wrinkle slope

$$T(\theta) = \sqrt{\overline{f'(x)^2}} \tag{4.2}$$

where $\overline{f'(x)^2}$ is the mean square of the first derivative of the above-mentioned curve.

3. The density of zero points

$$N_0(\theta) = \frac{1}{\pi} \cdot \frac{T(\theta)}{H(\theta)} \tag{4.3}$$

the cross-sectional line being assumed to be a random curve.

4. The density of extreme points

$$N_1(\theta) = \frac{1}{\pi} \cdot \frac{K(\theta)}{T(\theta)} \tag{4.4}$$

a random curve again being assumed. Here $K(\theta) = \sqrt{\overline{f''(x)^2}}$, where $\sqrt{\overline{f''(x)^2}}$is the mean square of the second derivative of the curve.

These parameters were considered necessary for adequately representing the severity of wrinkling quantitatively.

It was suggested the wrinkle parameters be measured within the following ranges:

1. Wrinkle heights should be greater than 0.2 mm and smaller than 10 mm.
2. Wrinkle wavelengths should be longer than 0.5 mm and shorter than 50 mm (or wrinkle densities not exceeding 2 per mm and not less than 0.02 per mm).

The Sivim Wrinklemeter was capable of measuring wrinkle parameters of fabrics quickly and non-destructively.

Contact instruments, such as the 'Wrinklometer', 'Sivim Wrinklemeter' and SAWTRI Wrinklemeter, use a stylus or other similar device which comes into contact with the fabric surface and which to a certain degree can disturb the fabric wrinkle and, depending on the type and size of the 'stylus', can miss certain wrinkle signals, which could result in an error in the assessment of fabric wrinkles. Along with the emergence of the laser and the development of new opto-electronic devices, such as the CCD camera, non-contact methods have been developed to evaluate fabric wrinkling objectively.

4.2.2 Laser scanning system

Laser has been defined as light amplification by stimulated emission of radiation. A simple definition for a laser would be 'a light-emitting body with feedback for amplifying the emitted light'.[5] Since its first demonstration in

1962, the laser has become a fascinating technology, and one which has attracted enormous interest across a wide range of industries. Thus, a large variety of lasers has been developed by scientists. With the gradual improvement in laser design and promising laser materials and processing research results in the early 1980s, the laser was no longer treated as laboratory research equipment or a scientific curiosity. Laser technology has been widely applied in the textile and clothing industries too.

Ramgulam *et al.*[6] used a laser sensor to measure the distance between itself and the object, using a laser triangulation technique. A beam of light, 25-micron in diameter, was projected from a laser diode onto the object, and part of the light was reflected back onto a photosensitive detector, which then signalled the position of the image from it. As the reflected light strikes the detector at different locations depending on its distance from the surface under examination, the location of the reflected light can be converted into the distance. The sensor used was capable of measuring the distance (and hence the height of the object) with a resolution of 10 microns. The fabric sample was placed and fixed on a dialed stage which was mounted on an X-Y table. The X-Y table was equipped with stepping motors and the whole system, except for the dialled stage, was interfaced with a microprocessor. The stage, and hence the bias angle of the sample with respect to either an X or Y movement, could be rotated and fixed manually.

Amirbayat and Alagha[7] used Ramgulam *et al.*'s[6] laser scanning system to measure heights at different points of the replica plates within a base of 100 × 100 mm at intervals of 1 mm which produced 10 000 readings for each replica. With the obtained heights, Amirbayat and Alagha[7] calculated the following geometrical parameters by applying simple numerical algorithms:

- Mean length of the paths over the wrinkled surface along X and Y directions, L_1, L_2;
- Surface area, A;
- Volume under the surface, V;
- Mean principal curvature, K_1, K_2;
- Mean maximum twist, T.

The results showed that mean twist, T, which has the dimension of the inverse of length, was a main factor in evaluating the severity of fabric wrinkles. The following equation was derived to relate the grade of wrinkle recovery (WR) to the mean twist T:

$$\mathrm{WR} = 0.73 + 7.73e^{-T\sqrt{A/10}} \tag{4.5}$$

The most important advantage of laser triangulation, in addition to the accuracy and the fact that it is non-contact, is its ability to measure the height of any surface regardless of the colour and pattern, which affects image analysis methods employing an ordinary light source.

The three-dimensional scanning device developed by Park and Kang[8] to measure wrinkle shape consisted of a laser scanner, an A/D converter and a personal computer. The laser was composed of a laser sensor to detect the magnitude of a wrinkle, a system to control the movement of the laser sensor and an amplifier to amplify the sensor signal. The laser sensor had a reference distance of 50±1 mm and could measure within the range of ±5 mm at the reference position with a resolution of 10 μm.

With the developed instrument, Kim[9] scanned wrinkled fabric specimens generated according to AATCC 128. There were 64 × 64 points of sampling data, with an interval of 1.5 mm in the X and Y directions in an area at the centre of the specimen. Neural networks were used to construct a generalised delta rule[10] to quantify wrinkle evaluation. A Windows program was developed to control the operation, perform calculations and display the degree of wrinkles. The study revealed a linear relationship between objectively and subjectively evaluated wrinkle severity, the correlation coefficient being 0.95. Nevertheless, the correlation coefficients for dark coloured or checked patterned fabrics were less than those for bright single colour fabrics.

Kang and Lee[11] proposed measuring the severity of the fabric surface wrinkles using fractal dimensions. The surface contours of wrinkled fabrics or puckered seams were first scanned using a laser scanning system, and the fractal dimensions of the surface were then counted using a box-counting method.[12] Fractal dimensions in the X and Y directions have proved to be closely related to the severity of wrinkles or puckers.[11]

In all laser scanning systems, the surface profile of a fabric specimen is scanned using a laser probe to measure surface height variation.[6–9,11] Such devices have excellent resolution in the order of microns. Nevertheless, because a laser makes one measurement at a time, a mechanical stage has to be used to move the sample in the X and Y directions to obtain a surface map and, as a result, the scanning process tends to be too slow to be suitable for industrial applications.

In order to improve the scanning speed of laser scanning systems, Xu *et al.*[13] developed a system, in which a laser stripe line was projected onto the fabric specimen to obtain a line of data simultaneously. A motorised stage was used to rotate the sample, a video camera to grab images at certain rotational angles of the stage and a computer to process the acquired data.

To make the instrument suitable for a broad range of fabric types, in terms of colour and designs, Xu *et al.*[13] took into account three practical issues during the development:

1. The necessity to obtain measurements insensitive to the orientation of the fabric wrinkles, such as wrinkles which follow one main direction or are randomly oriented. Cameras or laser scanning mechanisms may produce different surface data when the orientation of the wrinkles is dominant in

one direction or when a fabric is placed at different angles relative to the light source.
2. The need to obtain measurements unaffected by the colour of a fabric, its construction, pattern or any printed design.
3. The need to discern differences in smoothness appearance between AATCC replicas SA-3 and SA-3.5. SA-3.5 was added to the AATCC Test Method 124 to describe a fairly smooth, non-pressed appearance.

Xu *et al.*[13] used three geometric factors to characterise wrinkle appearance: wrinkle roughness, wrinkle sharpness and wrinkle density.

1. *Wrinkle roughness* is a measure of the size of the wrinkles, with no consideration of their shape, and is characterised by four different quantitative measures.
   - *Arithmetic average roughness*:

$$R_a = \frac{1}{n}\sum |Z_i - m| \tag{4.6}$$

   - *Root mean square roughness*:

$$R_q = \sqrt{\frac{1}{n}\sum (Z_i - m)^2} \tag{4.7}$$

   In these two equations, Z_i is the height of the profile at the ith point, n is the number of points selected, and m is the height of the mean line which fits in the middle of the profile. Both these measures compute the average height of the wrinkles from the mean line.
   - *Ten-point height* R_z: The average distance between the five highest peaks and the five lowest valleys on the curve.
   - *Bearing length ratio* t_p: A measure obtained by establishing a reference line parallel to the mean line at a predetermined height between the highest peak and the lowest valley of the profile. The line intersects the profile, generating one or more subtended lengths; t_p is the ratio of the sum of the subtended length to the sampling length of the curve.
2. *Wrinkle sharpness k* represents the shape of the wrinkle, describing the top point of the wrinkle which forms a definite peak. The ratio of the height to the width of the wrinkle is used to quantify sharpness.
3. *Wrinkle density* can be quantified by the peak-and-valley count (PVc), which is the number of peaks and valleys along the selected bandwidth symmetrical to the mean line of the profile. The selection of bandwidth is important to avoid tiny peaks and valleys which may correspond to noise signals.

In addition to being quantitative and automated, Xu *et al.'s*[13] instrument was not influenced by whether the fabrics were uni-directionally wrinkled or not, owing to the rotation of the sample during the test. It was also not influenced by

colour differences in the fabric, due to the use of a laser stripe in scanning. It was capable of distinguishing between replicas SA-3.5 and SA-3.

4.2.3 Image processing systems

Xu and Reed[14] proposed a computer image system and testing procedure for automated grading of fabric wrinkling. The system consisted of a Dell 486/M compatible computer, an HP colour scanner and the self-developed software. The main benefit of using the colour scanner was that an identical environment of image capturing, such as illumination conditions and background, can be easily maintained for separate tests. Two wrinkling descriptors, surface area and shaded area, were derived from the measured image intensities. They were used to measure two perspectives, wrinkle depth and wrinkle size. *Wrinkle ratio* was defined as the ratio of the surface area to the image square area of the image. Obviously, the larger the wrinkle ratio, the more wrinkled the fabric appears to be. *Shade ratio* was defined as the ratio of the shaded area to the image size. A large shade ratio suggests a highly wrinkled appearance.

Seven fabrics, varying in fibre content and other structural characteristics, were tested for wrinkling by subjective evaluation and image analysis. The results showed that the grades assigned by the subjective AATCC method were not linearly, but exponentially related to the above objective parameters (i.e. the wrinkle ratio and the shade ratio) obtained from image analysis. The computer predicted grades, using two exponential equations, were close to the visual grades.

Mori and Komiyama[15] used a grey scale image analysis method to evaluate the visual features of wrinkles in plain fabrics made from cotton, linen, rayon, wool, silk and polyester. Colour images of each wrinkled sample were scanned into the computer, using a colour scanner (Epson GT-9500). When scanning a wrinkled sample, the cover of the scanner was supported by a separator, which creates a space large enough for the sample to be placed in the scanner without any pressure on the wrinkled surface. The obtained colour image contains RGB colour coordinates for all pixels. From the RGB value of a pixel, the grey level at that point can be calculated by the following equation:

$$L = 0.177R + 0.813G + 0.011B \tag{4.8}$$

where L is the grey level of a pixel, the RGB value of which is *(R,G,B)*. A colour image was converted into a grey level image using this equation.

Four parameters characterising the visual features, based on a matrix $M(d,\theta)$, were used in their research. The co-occurrence matrix $M(d,\theta)$ consists of probability $P_\delta(i,j)$, $(i = 1,2,\cdots,n)$, in which the pixel of the grey level i appears separated a distance $\delta = (d,\theta)$ from the pixel of grey level j, where the parameters d and θ are the distance and positional angle between a certain grey-level pair. The four parameters and fractal dimension D were defined as follows:

- Angular second moment (*ASM*)

$$ASM = \sum_{i=0}^{n=1}\sum_{j=0}^{n-1}\{P_\theta(i,j)\}^2, i = 1,2,\cdots,n-1; j = 1,2,\cdots,n-1 \tag{4.9}$$

- Contrast (*CON*)

$$CON = \sum_{k=0}^{n-1} k^2 P_{x-y}(k), |i-j| = k, k = 1,2,\cdots,n-1 \tag{4.10}$$

where

$$P_x(i) = \sum_{i=0}^{n-1} P_\delta(i,j)$$

$$P_y(j) = \sum_{j=0}^{n-1} P_\delta(i,j)$$

$$P_{x-y}(k) = \sum_{i=0}^{n-1}\sum_{j=0}^{n-1} P_\delta(i,j)$$

- Correlation (*COR*)

$$COR = \left\{\sum_{i=0}^{n-1}\sum_{j=0}^{n-1} i\cdot j\cdot P_\delta(i,j) - \mu_x\cdot\mu_y\right\}/\sigma_x\sigma_y \tag{4.11}$$

where

$$\mu_x = \sum_{i=0}^{n-1} i\cdot P_x(i), \mu_y = \sum_{j=0}^{n-1} j\cdot P_y(j)$$

$$\sigma_x^2 = \sum_{i=0}^{n-1}(i-\mu_x)^2\cdot P(i), \sigma_y^2 = \sum_{j=0}^{n-1}(j-\mu_y)^2\cdot P_y(j)$$

- Entropy (*ENT*)

$$ENT = \sum_{i=o}^{n-1}\sum_{j=0}^{n-1} P_\delta(i,j)\cdot\log\{P_\delta(i,j)\} \tag{4.12}$$

- Fractal dimension D

$$D = \frac{\log c - \log(N(r))}{\log(r)} \tag{4.13}$$

where c is a positive constant, r is the side length of the cube and $N(r)$ is the number of cubes which cover the image.

The Kalman filter algorithm was implemented in the procedure for training a neural network to evaluate the grade of wrinkled fabrics, using the above five parameters (*ASM, CON, COR, ENT* and *D*) as input and the mean sensory value presenting the grade of wrinkled fabrics as output. The calculated values obtained by the trained neural model for the unknown data indicated very good agreement with the sensory values, especially for cotton, linen and rayon fabrics. For evaluating the grade of wrinkled fabrics, the method using the colour scanner provided better accuracy than that using the digital camera. But in this research, the colour of the samples of the wrinkled fabrics used was only close to white. Their method was strongly influenced by colour and pattern of the fabric.

Dobb and Russell[16] also reported on an objective and quantitative method for measuring fabric wrinkles which was based on image analysis. The principle was based on the measurement of differential intensities across the wrinkled specimen under constant illumination. To facilitate intensity measurements, a Leica-Cambridge Quantimet 570 image analyser, coupled to a video camera, was used for recording the fabric images. Dobb and Russel[16] commented that, in order to make meaningful measurements of fabric wrinkles, the following points should be taken into consideration:

- Lighting conditions should be adjusted to prevent either completely black (grey level 0) or peak-white (grey level 255) regions occurring in the video image.
- Fabrics can only be meaningfully compared if the illumination conditions are kept constant.
- The steepness factor (i.e. the difference in light intensity between neighbouring pixels) is an arbitrary value depending on the lighting conditions.
- Only plain fabrics can be evaluated using this method; patterned fabrics will give rise to anomalous steepness factors.

Na and Pourdeyhimi[17] described a system of grading fabric wrinkle recovery through the application of digital image processing techniques. The image capture system consisted of a Sony CCD camera, a True Vision Targa 64 Plus 32-bit capture card and an IBM 80486 microcomputer. Degrees of fabric wrinkling, in accordance with AATCC replicate standards, were analysed in terms of texture and profile. From the data obtained, Na and Pourdeyhimi derived a number of geometric parameters to characterise wrinkle appearance, including wrinkle density, profile, sharpness, randomness, overall appearance, surface area, normalised relief and fractal dimension. The results showed that wrinkling could be analysed and quantified successfully and accurately using these parameters. The method was simple and could apply to the analysis of

wrinkling in plain fabrics. For woven fabrics with large patterns or prints, additional steps were required for differentiating wrinkles from the patterns or prints.

Kang *et al.*[18] deployed a projecting grid technique for objectively evaluating fabric wrinkling. A parallel light source in a dark room illuminated the wrinkled surface through the aligned grid panel, creating uniform grid lines and a CCD camera was used to capture the deformation of grid lines. From the deformation ratios of the grid lines projected onto the wrinkled surface, the technique reconstructed the 3D shape of the wrinkles and quantified the degree of wrinkling using a number of derived parameters, including the roughness ratio, surface area ratio, wrinkle density and power spectrum density of the Fast Fourier Transform.

- *Roughness ratio*. Roughness ratio (W_R) was defined as:

$$W_R = \sqrt{\frac{1}{n}\sum_{i=1}^{n} \Delta Z_i^2} \tag{4.14}$$

  where ΔZ_i is the difference of the ith height of an X direction in an X-Y plane coordinate from the mean height $(\bar{Z})$, $|Z_i - \bar{Z}|$, and n is the total number of data points in the X direction. In general, the larger the roughness ratio, the more wrinkled the fabric appears to be.
- *Surface area ratio*. Surface area depends mainly on the shape of the specimen. The more complex the surface shape, the larger the surface area of wrinkled space appears to be. The normalised surface area was obtained as follows. Three points were selected from the vertex of a rectangular facet on the 3D shape to make two vectors. The cross-product of the two vectors represents a triangular area. The total surface area was obtained by summing individual triangular areas. The summation results were divided into normalised areas by the orthogonal projection area of the surface area.
- *Wrinkle density*. Wrinkle density was defined as the number of wrinkles per unit area, assuming uniform wrinkle distribution, a turning point representing a wrinkle in the fabric. In this research, they counted the number of turning points instead of counting the number of wrinkles per unit area, by scanning the 3D projected grid lines horizontally.

The work demonstrated that there was good correlation between the four parameters and the wrinkle recovery grade of a wrinkled surface. This method could predict the fabric wrinkle grades without the influence of fabric colours and patterns but has limitations for sharply contrasting coloured fabrics.

Matsudaira *et al.*[19] described a method to evaluate objectively the appearance of fabric wrinkling replicas by image processing. The image processing system consisted of a light source, which allowed the incident lighting angle to be adjusted so as to adjust the light power intensity, a camera, a digitisation capture

board and a computer. At first, the image captured from the fabric wrinkling replicate was filtered using a 7 × 7 weighting and smoothing filter to remove the noise produced from illumination reflection, camera imperfections, surface texture and fabric structure. Then the parameters were defined and the FFT was applied based on the grey level.

- Standard deviation of grey level (G_{sd}). G_{sd} is defined as:

$$G_{sd} = \sqrt{\frac{\sum_i \sum_j (Z(i,j) - \bar{Z})^2}{m \times n}} \tag{4.15}$$

  where *Z(i,j)* is the grey level of point *A(i,j)*, $\bar{Z}$ is the mean of data points and *m, n* are the pixels in the *X* and *Y* directions, respectively.
- Ratio of surface area R_A. R_A is defined as Kang *et al.*'s[18] surface area ratio.
- Ratio of X direction length and Y direction length of surface profiles (R_{Lx} and R_{Ly}). R_{Lx} and R_{Ly} were defined as follows:

$$R_{Lx} = \frac{\sum_i \sum_j L_{A'B'}}{n(x_m - x_1)} \tag{4.16}$$

$$R_{Ly} = \frac{\sum_i \sum_j L_{A'C'}}{m(y_n - y_1)} \tag{4.17}$$

  where A', B' and A', C' are adjacent pixels on the image, respectively. $L_{A'B'}$ and $L_{A'C'}$ are the lengths of the lines A', B' and A', C' on the fabric surface, respectively.

The results showed that all the parameters of the fabric wrinkle grades fell into good logarithm functions, which meant that this method can objectively evaluate fabric wrinkling. The results of the FFT analyses showed that the spectra of surface profiles could quantify the wrinkle grades.

Recently, Hu and Xin[20] proposed a new method for measuring fabric wrinkling based on integrating photometric stereo and image analysis techniques. Their 3D wrinkling measurement system consisted of a colour digital camera, a lighting box, a frame grabber and a personal computer. Parallel lighting was controlled in four directions in their special lighting box, and they designed special equipment to generate calibrated parallel light sources from common fluorescent tubes. The dedicated image analysis software calculated two parameters, *P* and *Q,* for measuring wrinkling in the *X* and *Y* directions, respectively. *P*+*Q* was used to describe the wrinkling of the whole fabric surface. Their work showed that the effective feature, *P*+*Q,* can give a good measure of the degree of wrinkling. Here

$$P = \frac{1}{N} \sum_{1}^{N} |p(i)| \tag{4.18}$$

and

$$Q = \frac{1}{N}\sum_{1}^{N} |q(i)| \tag{4.19}$$

where, *p(i)* and *q(i)* are the first partial derivatives of *z* with respect to *X* and *Y* of the surface element *i*, and *N* is the number of surface elements (pixels) of each image.

Yang and Huang[21] proposed an approach to reconstruct the fabric 3D surface shape from multiple illuminated images of the pattern, based on a photometric stereo method. They then measured the degree of wrinkling of an AATCC standard wrinkle pattern using four index values to indicate the variation of the surface height value.

The basic system of a photometric stereo method consists of multiple light sources, a CCD digital camera and other control systems. This photometric stereo method transfers the multiple grey level signals obtained from the multiple light sources into the height signal at any point on the 3D surface, producing the reconstruction of the 3D surface shape.[21] The research[21] applied four feature indices to measure the degree of wrinkling of the pattern. They were coarseness,[22] fractal dimension,[11] surface area[17] and average offset.[23] The results showed that there was a good linear correlation between the index value and the subjective grade, which meant that the photometric stereo method can possibly be used to reconstruct the 3D wrinkled surface shape of a fabric, and the index value to indicate the degree of wrinkling of the fabric.

Generally speaking, image processing methods are much faster in capturing the profiles of the wrinkled surface than the laser scanning method, but may be less accurate. They also tend to have difficulties in evaluating checked fabrics as the grey-value intensity cannot reveal the height of every position on the fabric surface since it is bound to change with the colour of the fabric, intensity and location of the light source, and even with the camera lens settings, contrast and brightness.

4.3 Objective evaluation of fabric pilling

Pilling of fabrics is a well-known phenomenon, and can seriously compromise a fabric's acceptability. Pilling is a fabric surface effect caused by wear and tear which considerably spoils the original appearance of the fabric. It begins with the migration of fibres to the outside yarn surface causing fuzz to emerge on the fabric surface. Due to friction, this fuzz becomes entangled, thus forming pills which remain attached to the fabric by long fibres.

Considerable research has been undertaken on the objective evaluation of fabric pilling. The research can be divided into two categories according to the

method of acquiring the surface data from the fabric specimen. One is the laser scanning method,[24–26] and the other is the image processing method.[27–32]

Ramgulam and co-workers[24,25] applied the laser triangulation technique (see Fig. 4.4) to evaluate fabric pilling objectively.[24,25] Their system involved the following steps:

1. Measurement of height at different locations on the sample, using laser triangulation.
2. Elimination of the noise and excessive detail in the image by averaging the height measurements at any point.
3. Use of image segmentation, each sample surface being segmented into two separate zones, namely pills and background, according to height.
4. Counting the number of pills.
5. Measuring the total projected area and height of the pills.
6. Using information from 4 and 5 as point coordinates to relate it to the known pilling grade of a particular sample.

Based on the correlation analysis between the subjective grades and the objective parameters, they concluded that improved data analytical techniques were necessary in order to develop an effective objective evaluation method based on the triangulation technique.

Sirikasemlert and Tao[26] also adopted the laser triangulation technique to study fabric surface characteristics. The objective measurement system developed for fabric surface mapping, shown in Figs 4.2(a) and 4.2(b), consisted of a laser scanner from CyberScan Cobra, an X-Y position controller with a sample stage and a PC for controlling the laser scanner and collecting and processing the data. The experimentally determined surface profile was described as an array of independent profile height values as a function of the coordinates in the fabric plane (X, Y). The data were used to derive a number of surface texture parameters by statistical, fractal, Fourier and wavelet analyses. They derived eleven objective parameters for pilling: mean profile height, mean roughness CLA, mean roughness RMS, skewness, kurtosis, fractal dimension of pills, fractal dimension of pills and fuzz, wavelet energy, number of wavelet coefficients, ratio of the total area of pills and the number of pills and change in total power in the pill zone, which were defined as follows:

- *Mean roughness CLA*. Mean roughness central-line average (CLA) $\bar{R}_a$ was the average value of the integration of the heights deviating from the calibrated line:

$$\overline{R_a} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{L}\int^{L} z\,dx \tag{4.20}$$

  where L is the scanned length and z is the profile height (X, Y).



(a)



(b)

Figure 4.2 (a) The measuring system using laser triangulation; (b) The laser scanner from CyberScan.

- *Mean roughness root-mean-square (RMS)* $\overline{R_q}$. This is given by:

$$\overline{R}_q = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\frac{1}{L}\int^{L} z^2 dx} \tag{4.21}$$

- *Skewness and kurtosis*. The probability density function $p(z)$ may offer useful information about surface texture in terms of its height-ordered moments.[33] The third moment, skewness (SK), a measure of distribution symmetry, is defined as:

$$SK = \frac{1}{\sigma^3}\int_{-\infty}^{\infty} z^3 p(z) dz \tag{4.22}$$

where σ is the standard deviation of $p(z)$.

The fourth moment, kurtosis (K), indicates Gaussian similarity, in simplified words, the peakedness of the distribution:

$$K = \frac{1}{\sigma^4}\int_{-\infty}^{\infty} z^4 p(z) dz \tag{4.23}$$

- *Fractal dimension of pills and fractal dimension of pills with fuzz*. Based on the binary image, by implementing a box-counting algorithm,[34] the fractal dimension D was defined as:

$$D = -\frac{\log(N(r))}{\log(r)} \tag{4.24}$$

where r is the side length of the squared box and $N(r)$ is the number of boxes which cover the image.

The fractal dimension of pills (D_p) and the fractal dimension of pills with fuzz (D_{pf}) were then determined based on the binary images of pills and pills with fuzz, respectively. The binary image of pills with fuzz was the image converted from an original image based on the selected threshold.

- *Change in total power in the pill zone*. The total power in the pill zone before and after wear (P_p) is described as:

$$P_p = \int_{\lambda_p \min}^{\lambda_p \max} (P_b - P_a) d\lambda \tag{4.25}$$

where P_b and P_a are the power spectrums before and after simulated wear, respectively. The wavelength λ can be expressed in terms of the position of a pixel by:

$$\lambda = \frac{1}{\sqrt{u^2 + v^2}}$$

where u and v are two frequency spectrum variables of the 2D Fourier transform.

- *Wavelet energy and number of wavelet coefficients*. From the image after thresholding, the wavelet energy of the pills (E_p) is calculated, based on the remaining wavelet coefficients (c_w), using the following equation:

$$E_p = \sum c_w^2(n) \tag{4.26}$$

  The number of wavelet coefficients (Wn) is the number of pixels with a wavelet coefficient higher than the selected threshold, which these pixels represent as pills on the fabric surface.

In all these parameters, wavelet energy and the number of wavelet coefficients represent the best and the second best single parameter offering the highest and the second highest correlation coefficients with the subjective grade, respectively.

The laser scanning technique, however, is a much slower process than the camera-capturing technique, since it requires an X-Y stage to move the sample mechanically.[27] Digital image processing techniques have therefore been preferred for the objective evaluation of fabric pilling.

Konda *et al*.[28] developed a method of comparing images of pilled samples taken by a video camera with the corresponding images of standard photographs, thus determining a fabric pilling grade. Home video lights VZ-LS35 and an OLYMPUS TE-II were used as the light source for the standard photographs in JIS L1076 and the actual fabric samples, respectively. The images of the sample surface captured with a TV camera, NATIONAL VY7000, were displayed graphically and the feature values of pilling were calculated using a minicomputer. Konda *et al*.[28] discussed in detail the threshold values in the binary transformation. The threshold values were different for different categories of standard photographs, but nearly constant for different grades in the same category. The distribution curve of pill sizes, the total number and area of pills, and the mean area of pills could be calculated from the images of a pilling sample. The pilling grade of a given sample was determined by comparing its total number and area of pills with those of the standard photographs of different grades in the group. The judgement of pilling grade by two feature values, namely the total number and area of pills, was found better than that by any single feature value.

The method of determining fabric pilling grades, developed by Konda *et al*.,[28] was one of the early objective measurement techniques based on image processing. This method was good for grading the pilling of plain-coloured fabrics, but was unsuitable for patterned fabrics because the video camera cannot distinguish between the images produced from pills under the incident light and the dark regions of the fabric surface.

Xu[30] and Xu and Ting[35,36] developed an image-analysis system to evaluate fabric appearance. The system consisted mainly of a CCD camera, a colour scanner, an imaging board, a computer and the self-developed software. Two

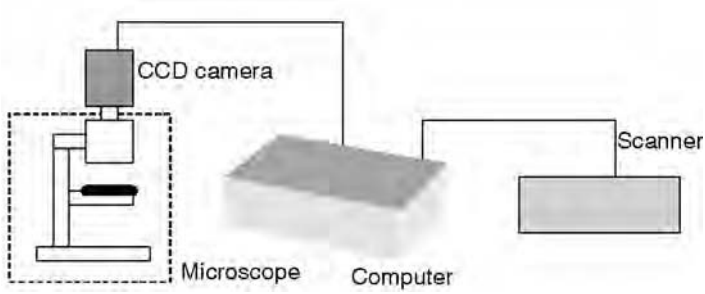


Figure 4.3 Schematic set-up of the image-analysis system.

different devices can be chosen as image-input devices. One is a JVC TK1070U CCD camera and the second is an HP Scanjet IIC scanner. The basic set-up of the system is shown in Fig. 4.3.

To accommodate differences in fabric colour, an auto-iris lens was used so that constant brightness could be maintained over dark and bright samples. A three-chip colour CCD camera was used to provide accurate colour information for removing the pattern in the imaging analysis. Since the pills observed in worn garments vary appreciably in size and appearance, the system was designed to be capable of capturing and analysing multi-frame images of the samples at various locations to generate reliable statistical data. To avoid human interference, a stage, driven by a DC motor, was designed to automatically transport the sample under the camera. The number of positions and the interval between two positions could be set from the computer interface. The stage moved from one end and stopped at each position to let the camera capture a still image.

Since the development of pills may be accompanied by other surface phenomena, such as a loss of cover, colour change, or the development of fuzz, the image of a tested fabric often contains a non-uniform background, varying contrast and other defects. It is necessary to correct or reduce the image defects to facilitate pill identification. For example, floating-yarn points in the image are a barrier to identifying pills, because such points often have similar sizes and intensities to the pills. FFT techniques were applied by Xu[30] to separate pills from floating-yarn points. Other methods of enhancing images for pill identification have also been suggested.[27,35,36]

Xu[30] characterised pills using three parameters: pill density, pill size and contrast between a pill and its surrounding area. In order to make the rating results generated by the pilling-evaluation system consistent with the visual standards, the ASTM photographic pilling standards were first analysed by using the system, and the rating equations were built on the basis of the measurements of the pill properties from these photographs. The experimental results showed that the density, size and contrast were the important properties of pills which describe the degree of pilling and were used as independent variables in the grading equations for pilling.

Xin and Hu[32] presented an objective evaluation method of pilling in knitted fabrics by image analysis techniques. They developed a special lighting box which illuminated fabric samples uniformly, simulating day-time lighting conditions. With the captured image, pilling was evaluated by template training, template matching, image segmentation, feature extraction and grade rating. The pill template was trained by using actual pill images and the two-dimensional Gaussian fit theory. In total, five parameters were extracted: pill number, mean area, total area of pills, contrast and density. Except for contrast, the other parameters have high correlations with the subjective grades, and four rating formulae were derived by means of these four parameters. This method was effective for fabrics of a uniform colour, but could not be used for printed fabrics of multiple colours, which not only contain shape information, but also colour space information.

Jensen and Carstensen[37] presented an automatic and objective method for reproducible image acquisition and evaluation of fuzz and pills in knitted fabrics. A new sensor technology was used for the measurements and acquired all the images of the samples by means of a Videometer camera system. This system was a highly precise device to measure colour, texture and shape using a calibrated 3CCD colour camera. The system was designed as a high-intensity, integrating sphere illuminator, which delivers well-defined and diffuse illumination in a closed environment. Images were captured as an average over ten frames to eliminate single-frame noise. In order to recognise more clearly fuzz and pills and remove the knitted stitch pattern, images were filtered first using the Fourier 'mask' which consisted of a circular centered area excluding smaller circular areas centered over the positions of the peaks characterising the knitted structure.

They defined a fuzz and pill feature (FP) as follows:

$$FP = \sum_{(u,v)\epsilon M} |F(u,v)|^2 \tag{4.27}$$

where M was the mask region in the Fourier power spectrum and $F(u,v)$ was the frequency domain function of the image signal.

Results showed that the fuzz and pill evaluation method was consistent with results obtained from expert evaluations.

4.4 Objective evaluation of seam pucker

During the past five decades, considerable efforts have been directed towards developing objective methods for the evaluation of seam pucker. Techniques for the objective characterisation of seam pucker may be classified into two main categories, namely 'contact' and 'non-contact' methods. Most of the non-contact type instruments involve optical methods. The non-contact type testers have advantages over the contact type, as a device which contacts the fabric may

disturb the fabric surface and provide an inaccurate assessment of geometric roughness. The non-contact type of test tends to have high accuracy, good resolution and high reproducibility.

4.4.1 Contact methods for the objective evaluation of seam pucker

Shiloh[38] used the Wrinklemeter, originally developed to detect and measure fabric wrinkling, to evaluate seam pucker by tracing the seam contour curve. The trace was made on two contour curves, parallel to the seam, at a distance of 2 mm from the sewing thread on both sides. The first trace provided height, the second trace provided the slope and the third trace, the curvature. From the curvature, density was easily calculated. Finally, the means of the measurements obtained from the two contours along the seam were calculated to represent the extent of puckering.

The samples were prepared on a set of seven cotton seam specimens, sewn with cotton threads. These were washed and then selected to represent a wide variation in puckered appearance. Shiloh[38] gave the results of the measurements, which included AATCC visual rating, ranking score, seam height, seam slope and 'puckering-severity index' (the product of height and slope, *HT*, was suggested as a 'puckering-severity index'). From these results, significant correlations were found between the puckering-severity index and both the scores and the AATCC visual ratings. The densities of zero points and extreme points were also calculated. These were found to be related to the stitch length used in preparing the seamed specimens.

Galuszynski[39,40] developed the SAWTRI puckermeter, which measured pucker by comparing the length of the puckered seam with that of the seam without puckers. The puckermeter enabled one to evaluate the contribution to seam pucker of such factors as differential shrinkage of seam components, fabric displacement during seam formation, sewing thread tension and inherent puckers. The degree of seam pucker was expressed in terms of a 'pucker index'.

4.4.2 Non-contact methods for the objective evaluation of seam pucker

Owing to the fact that direct contact between the sensor and the seam specimen can undermine the accuracy and reproducibility of the measurements, Belser *et al.*[41] designed a photo-electric device to quantitatively evaluate seam pucker by examining the magnitude of the seam pucker profile. They used the ratio of the length of the curve on the seam surface to the length of the straight centre-line as a measure of seam pucker. The total length of the curve from beginning to end was measured with a Stadimeter. The results obtained showed good agreement between visual assessments made in accordance with the AATCC standards,

except for fabrics with complex patterns and colours. Bertoldi and Munden[42] used a similar apparatus to assess the shadow pattern created by light falling on the puckered surface. It assessed the darkness and shadow areas of the undulations in the case of an angular light beam. The ratio of the length of the recorded curve to the seam length was used as an index. Nevertheless, they did not compare their values with the grading according to the AATCC method.

Recently, the quantitative evaluation of seam pucker has been made by more advanced non-contact technologies, such as the Moiré measurement method, CCD camera, laser scanning technology and ultrasonic wave technology.

CCD camera

Stylios and co-workers[43–45] developed a so-called Pucker Vision System, comprising a CCD camera, to replace the human eye, and a software program simulating the human cognitive process. The system was designed to capture the images of two groups of seam stripes produced from the same fabric, one an unstitched seam and the other sewn with puckers. Using the mean reflection of the unstitched seams as a reference, the system assessed the configuration of the pucker by identifying the pucker wavelength and pucker amplitude to develop a pucker severity index. The consistency of the light source and the influence of the pattern and colour of the fabric were the major limitations of the system.

Forschungsinstitut für Textiltechnologie Chemniz GmbH Germany (FIFT)[46] also developed a system using a special camera. Seam pucker was evaluated by photogrammetric interpretation of photographs taken of the seams using this camera.

Richard[47] developed a computer-based seam pucker measurement system (SPMS) for quantifying seam surface irregularities using digital image analysis. A video camera was used to capture seams in the immediate vicinity of the seam formation area. The measurement of the pucker index on a scale of 1 to 5 was very rapid and the results were incorporated into a fabric sewability report, together with the measurement of the dynamic force of the sewing process.[47, 48]

Ultrasonic wave technology

Ultrasonic wave technology was used by Shigeru and Atsuo[46] as a non-contact method for measuring seam pucker with high precision. It collects information about the surface shape of seam pucker through an ultrasonic image scanner. The ultrasonic waves are narrow beams and the intensity of reflection was related to the slope of the surface. The seam pucker surface was measured by the ultrasonic wave reflection and the intensity of reflection. Seam pucker was related to various waves of the surface of the seam. In ultrasonic wave technology, data values relate to the slant angle (slope) of the surface. The data were used for the variables of surface shape and also improved the performance of discrimination under optimum conditions in terms of the length or pitch of the measurement. They found that the measurements were not affected by surface colour.

Laser scanning

Shigeru and Atsuo[46] applied laser scanning technology for the objective evaluation of seam pucker. The laser technology system consisted of a laser displacement meter, a moving stage with two axes, magnetic displacement meters, controllers and a computer. The laser scanner detected the reflection from the puckered surface by a light-detecting semi-conductor. With the output of the height of the reflecting point, which is calculated by the principle of triangulation, the data on the lines, with respect to the wave and power spectra of each line, were calculated by means of Fast Fourier Transform (FFT).

Logarithmic power spectra were used to emphasise the wave power at a small frequency because the wave power at a high frequency is very small compared with the power wave at a low frequency and the high frequency wave is important for evaluation. The frequency band of the power spectra was divided into three band segments and all lines were divided into three groups. The nine areas were defined by a division of frequency and position. With these nine values and the division of five grades, the relationship was analysed with discriminate analysis. It was difficult to discriminate slight pucker values with the data from objective measurements.

Park and co-workers[49,50] and Park[51] also used laser technology to capture seam pucker and evaluate it using artificial intelligence. A displacement meter, consisting of a laser diode, can accurately measure the surface profile of the seam regardless of changes in colour or surface condition. The data obtained along the seam line were transformed into power spectra at a frequency domain using FFT. The power spectra created the specified patterns for neural networks, which evaluated the seam pucker by simulating the AATCC rating of well-trained human experts. They found that the prediction and optimisation of seam pucker were possible using the approach developed in their research with material properties and processing parameters.

Kawabata[52] and Kawabata *et al*.[23] used the laser scanning method to measure seam pucker and analysed the sensory evaluation of seam pucker using the Weber-Fechner law. In their work, the geometrical shape of pucker was measured by a scanning laser beam to obtain a height profile. The height signal passed through a low-pass filter with a cut off frequency of 1 Hz (1 Hz is equivalent to 4 cm of the wavelength at a scanning velocity of 4 cm/s) to eliminate the influence of a longer wave on the pucker evaluation. From the height signal, they calculated a surface roughness parameter and found that sensory evaluation of seam pucker follows the Weber-Fechner law, which states that a sensory value is proportional to the logarithm of the magnitude of the quality of the physical stimulation. Based on the above theory, they developed an equation for the objective prediction of seam pucker. It was a very important contribution, discovering an almost linear relationship between the subjective pucker grade and physical quantity.



Figure 4.4 The 3D Model Maker laser scanner.

In 1997, Fan and co-workers[22, 53–57] developed an objective method for the evaluation of seams on a 3D garment surface through the application of laser scanning technology. For this experiment, a commercial 3D laser scanning system, which consisted of a laser scanning head, robot arm, computer and some special software for data acquisition, was used to scan garment seams. The 3D laser scanning system, called 3D Model Maker, is shown in Fig. 4.4.

2D Digital filters were used to obtain pucker profiles by removing the high-frequency components in the seam profiles, which might be contributed by the individual threads of the fabric or noise, as well as the lower frequency components, which might be contributed by the garment surface. They considered the following four geometrical parameters calculated from the pucker profile:

- The average displacement from the mean magnitude (R_a)

$$R_a = \frac{1}{N}\sum_{i=1}^{N}\left(|z(i) - \overline{z(i)}|\right). \tag{4.28}$$

  where $z(i)$ is the height of the ith measurement, and N is the number of measurement points.
- The variance, given by:

$$\sigma^2 = \frac{1}{N}\sum_{i=1}^{N}\left(z(i) - \overline{z(i)}\right)^2 \tag{4.29}$$

- The skewness of the distribution of the heights of the pucker profile, given by:

$$S = \frac{1}{N}\sum_{i=1}^{N}\left(z(i) - \overline{z(i)}\right)^3 / \sigma^3 \tag{4.30}$$

- The pointedness (kurtosis) of the distribution of the height of the pucker profile given by:

$$K = \frac{1}{N}\sum_{i=1}^{N}\left(z(i) - \overline{z(i)}\right)^4 / \sigma^4 \tag{4.31}$$

It was found that the logarithm of the average displacement from the mean magnitude (log R_a) and logarithm of variance (log σ^2) were linearly related to the severity of seam pucker. The addition of the logarithm of skewness (S) and pointedness (K) of the height distribution hardly improved the correlation. Log R_a and log σ^2 were therefore recommended as objective measures of seam pucker.

In their research, Fan and Liu used ten men's shirts, made from two different fabrics of similar weight and density, one a white polyester/cotton and the other a red-and-white cotton check, as samples. They discussed the relationship between the logarithm of variance (log σ^2) and the subjective grade of seam pucker close to four parts on the sample garment, which were yoke seam, pocket seam, placket seam and armhole seam. The relationships are shown in Figs 4.5(a), 4.5(b), 4.5(c), and 4.5(d), respectively.

Based on this investigation,[53] the following conclusions were drawn:

1. The 3D laser scanning system is effective for capturing the garment surface with sufficient accuracy and reproducibility for the objective evaluation of garment appearance.
2. The reported 2D band-pass digital filter is effective for extracting the pucker profiles from the scanned garment surfaces by removing the 'high frequency' components from the fabric surface texture and the 'low frequency' components representing the garment silhouette and drape.
3. The subjectively assessed pucker grades of garment seams are linearly related to log (σ^2), which can be calculated from the pucker profiles.
4. The pucker grades of garment seams can be objectively evaluated through the measurement of log (σ^2). The objective evaluation is more accurate and reproducible than the subjective assessment.
5. The objective evaluation method is not affected by the colour and pattern of the fabric, from which the garment is made.

Although the objective method had been proven through this investigation, further work was still considered necessary. The system consisted of expensive hardware and software. It might still be too expensive for routine industrial application, although it was practically feasible when only a small number of samples were required for testing. Future efforts were needed to reduce the cost of the system and make it more robust for industrial use.

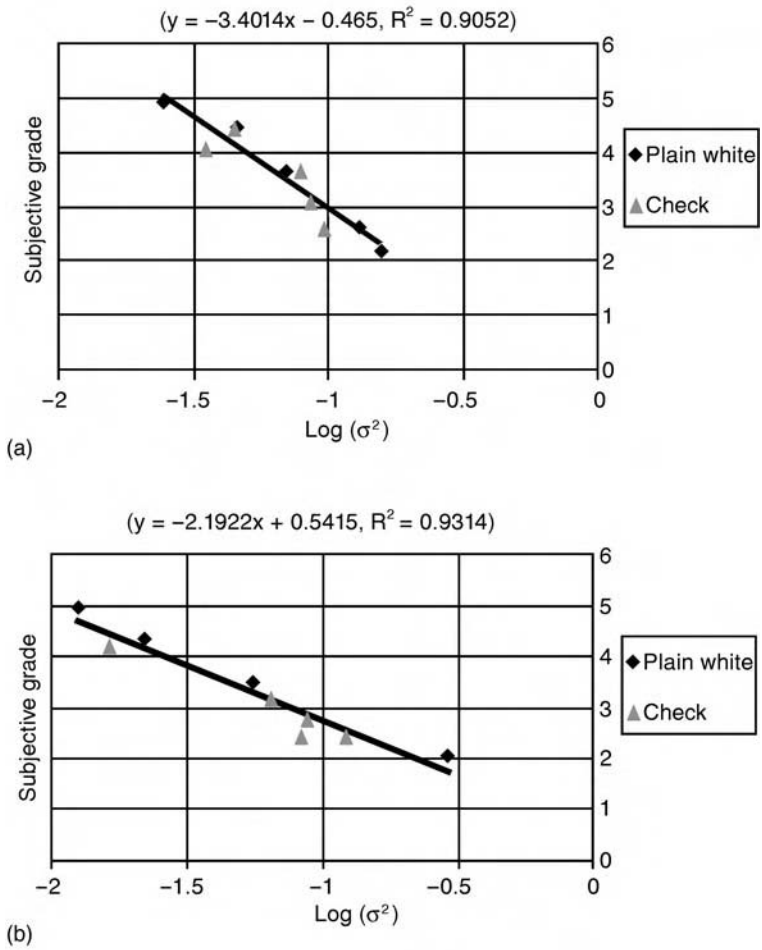


Figure 4.5 (a) Subjective Grade vs Log(σ^2) for Yoke seam; (b) Subjective Grade vs Log(σ^2) for Pocket seam; (c) Subjective Grade vs Log(σ^2) for Placket seam; (d) Subjective Grade vs Log(σ^2) for Armhole seam.

4.5 Objective evaluation of overall garment appearance

Attempts are being made to capture the 3D garment surface profile using a 3D laser scanner, such as Cyberware and a 3D Model Maker, and to analyse garment appearance profiles using image processing techniques. Figure 4.6 shows an image of a shirt captured by a Cyberware laser scanner. The following procedure was used to analyse the image:

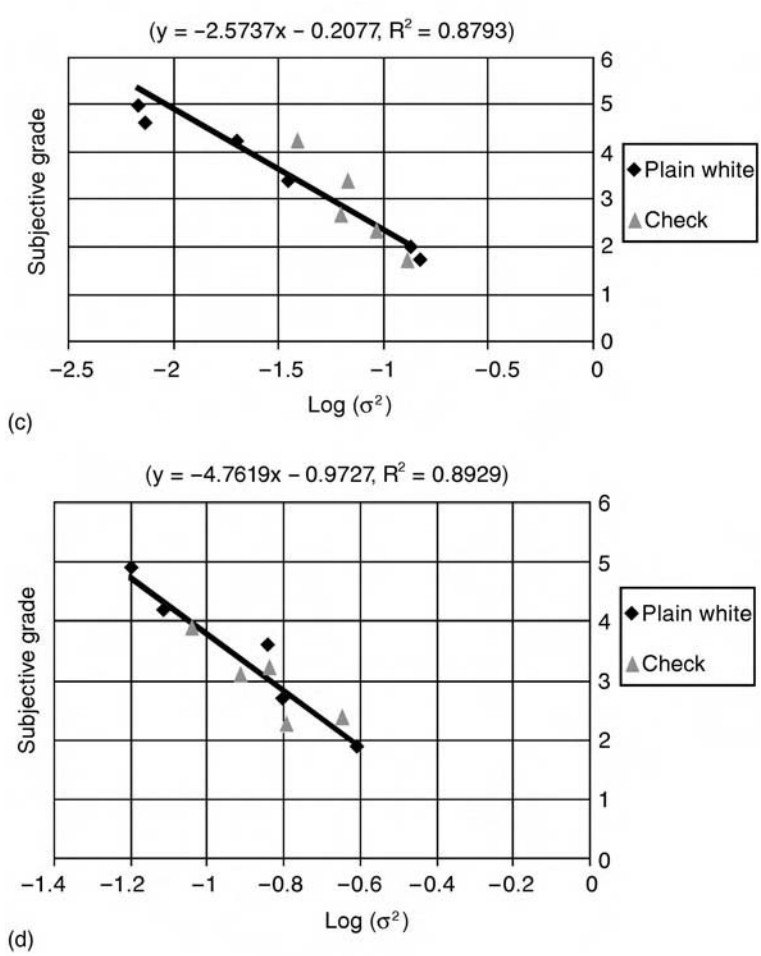


Figure 4.5 Continued.

(1) Selection of a particular portion of 3D garment appearance for analysis
Using a specialty software, Surfacer Version 3.0, run in a UNIX platform, a portion of area was selected.

(2) Segmentation of a particular portion
Using the segmentation technique, curves which are separated by the same distance along the X-Y axis of a particular portion were determined with the same direction as for the scanning of the garment surface.

(3) Digital filtering
2D Digital filtering techniques were applied to remove the high frequency components, due to fabric surface texture, and the low frequency components,

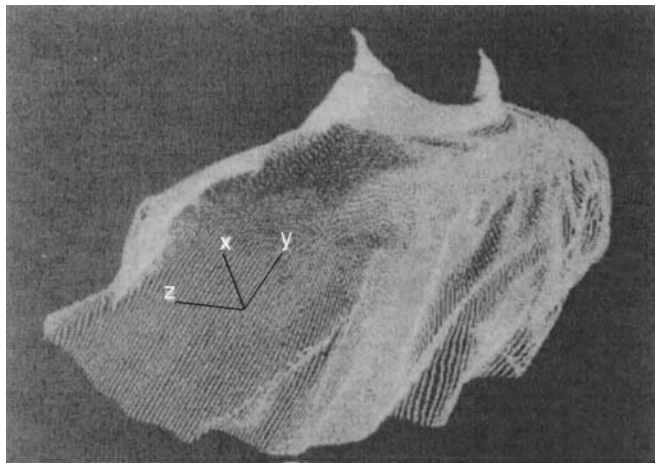


Figure 4.6 Objective evaluation of overall garment appearance.

due to the garment silhouette and drape, so as to obtain surface profiles representing the roughness, and wrinkling or puckering of the surface.

(4) Evaluating surface roughness
The degree of the roughness, wrinkling or puckering of the garment surface was measured using the physical parameters as was done with garment seams.

Current work on the objective evaluation of overall garment appearance still has considerable limitations in the following areas:

1. A large 3D laser scanner is required to scan the garment surface, which is too expensive for use in apparel production.
2. The time required to scan the entire garment surface is too long to be feasible for on-line application.
3. The accuracy of scanned data could be a problem, particularly in areas of large curvature.
4. Three independent software packages are used for data analysis. Further work is required to integrate these software packages.

4.6 References

1. Hebeler H H and Kolb H J, 'The measurement of fabric wrinkling', *Text Res J*, 1950 **20**(9) 650.
2. Kaswell E R, 'Evaluation of the celanese wrinkle tester', *American Dyestuff Rep,* 1959 **48**(7) 56.
3. Shiloh M, 'The effect of fabric structure on wrinkling, studies in modern fabrics', *Text Inst,* 1970 **61** 14.
4. Shiloh M and Grill A, 'The evaluation of wrinkles in textile fabrics', *Text Res J*, 1966 **36**(10) 924.

5. Muncheryan, and Hand M, *Laser Technology*, Indianapolis: H. W. Sams, 1979.
6. Ramgulam R B, Amirbayat J and Porat I, 'Measurement of fabric roughness by a noncontact method', *J Text Inst,* 1993 **84**(1) 99–106.
7. Amirbayat J and Alagha M J, 'Objective assessment of wrinkle recovery by means of laser triangulation', *J Text Inst,* 1996 **87**(2) 349–355.
8. Park C K and Kang T J, 'Objective rating of seam pucker using neural networks', *Text Res J*, 1997 **67**(7) 494–502.
9. Kim E H, 'Objective evaluation of wrinkle recovery', *Text Res J,* 1999 **69**(11) 860–865.
10. Freeman J A and Skapura D M, *Neural Networks Algorithms, Applications and Programming Techniques*, New York, Addison-Wesley, 1992.
11. Kang T J and Lee J Y, 'Objective evaluation of fabric wrinkles and seam puckers using fractal geometry', *Text Res J*, 2000 **70**(6) 469–475.
12. Peitgen H O, Jurgen H and Saupe D, *Fractals for the classroom, part one, introduction to fractals and chaos*, New York, Springer-Verlag, 1992.
13. Xu B, Cuminato D F and Keyes N M, 'Evaluating fabric smoothness appearance with a laser profilometer', *Text Res J*, 1998 **68**(2) 901–906.
14. Xu B and Reed J A, 'Instrumental evaluation of fabric wrinkle recovery', *J Text Inst,* 1995 **86**(1) 129–135.
15. Mori T, and Komiyama J, 'Evaluating wrinkled fabrics with image analysis and neural networks', *Text Res J*, 2002 **72**(5) 417.
16. Dobb M G and Russell S J, 'A system for the quantitative comparison of wrinkling in plain fabrics', *J Text Inst,* 1995 **86**(3), 495–497.
17. Na Y G and Pourdeyhimi B H, 'Assessing wrinkling using image analysis and replicate standards', *Text Res J*, 1995 **65**(3) 149–157.
18. Kang T J, Cho D H and Whang H S, 'A new objective method of measuring fabric wrinkles using a 3-D projecting grid technique', *Text Res J*, 1999 **69**(4) 261–268.
19. Matsudarai M, Han J, and Yang M, 'Objective evaluation method for appearance of fabric wrinkling replica by image processing system', *J Text Eng,* 2002 **48**(1) 11.
20. Hu J L and Xin B J, 'Measuring and modeling 3-D wrinkles in fabrics', *Text Res J*, 2002 **72**(10) 863.
21. Yang X B, and Huang X B, 'Evaluating fabric wrinkle degree with a photometric stereo method', *Text Res J*, 2003 **73**(5) 451.
22. Fan J, Lu D, MacAlpine M and Hui P, 'Objective evaluation of pucker in 3-dimensional garment seams', *Text Res J,* 1999 **69**(7) 467–472.
23. Kawabata S, Mori M and Niwa M, 'An experiment on human sensory measurement and its objective measurement of seam pucker level', *Int Cloth Sci Technol*, 1997 **9**(2-3) 203–206.
24. Ramgulam R B, Amirbayat J and Porat I, 'The Objective Assessment of Fabric Pilling, Part I: Methodology', *J Text Inst,* 1993 **84**(2) 221–226.
25. Ramgulam R B and Alagha M J, 'The objective assessment of fabric pilling, part II: experimental work', *J Text Inst,* 1994 **85**(3) 397.
26. Sirikasemlert A and Tao X, 'Objective evaluation of textural changes in knitted fabrics by laser triangulation', *Text Res J*, 2000 **70**(12) 1076–1087.
27. Xu B G, 'An overview of applications of image analysis to objectively evaluate fabric appearance', *Text Chem Colourage*, 1996 **28**(5) 18–23.
28. Konda A, Xin L C, Takadera M, Okoshi Y and Toriumi K, 'Evaluation of pilling by computer image analysis', *J Text Mach Soc Japan*, 1990 **36**(3) 96–107.

29. Hector C A, Millan M S, Torres Y and Navarro R, 'Automatic method based on image analysis for pilling evaluation in fabrics', *Optic Eng*, 1998 **37**(11), 2937.
30. Xu B, 'Instrument evaluation of fabric pilling', *J Text Inst,* 1997 **88** Part 1(4) 488.
31. Wang B, and Associates, 'Development of an image analysis algorithm for assessing pilling', *TAPPI Nonwovens Conf*, 1999 305.
32. Xin B J and Hu J L, 'Objective evaluation of fabric pilling using image analysis techniques', *Text Res J*, 2002 **72**(12) 1057–1064.
33. Thomas T R, *Rough Surface*, New York, Longman, 1982.
34. Mori T, Endou Y and Nakayama A, 'Fractal analysis and aesthetic evaluation of geometrically overlapping patterns', *Text Res J*, 1996 **66**(9) 581–586.
35. Xu B and Ting Y L, 'Fiber-image analysis, part I: fiber-image enhancement', *J Text Inst*, 1996 **87**(2) Part 1 274.
36. Xu, B. and Ting, Y.L., 'Fiber-image analysis, Part II: Measurement of general geometric properties of fibers', *J Text Inst,* 1996 **87** Part 1 284.
37. Jensen K L, and Carstensen J M, 'Fuzz and pills evaluated on knitted textiles by image analysis', *Text Res J*, 2002 **72**(1) 34.
38. Shiloh M, 'The evaluation of seam-puckering', *J Text Inst,* 1971 **62**(3) 176.
39. Galuszynski S, *Seam Pucker*, SAWTRI Special Publication, May, 1986.
40. Galuszynski S, 'Objective measurement of seam pucker', *Proc Symp New Technol Text*, South African Wool and Textile Research Institute, Port-Elizabeth, July, 1986 100–113.
41. Belser R B, Kwon C T and Conrad J M, 'Instrument for grading seam pucker', *Text Res J*, 1968 **38**(3) 315.
42. Bertoldi A M and Munden D L, 'The effects of sewing variables on fabric pucker', *Cloth Res J*, 1974 **2**(1) 68.
43. Stylios G and Parsons Moore R, 'Seam pucker prediction using neural computing', *Int Cloth Sci Technol*, 1993 **5**(5) 24.
44. Stylios G and Sotomi J O, 'Investigation of seam pucker in lightweight synthetic fabric as an aesthetic property part II: model implementation using computer ''vision'' ', *J Text Inst*, 1993 **84**(4) 601.
45. Stylios G and Sotomi J O, 'Investigation of seam pucker in lightweight synthetic fabric as an aesthetic property, part I: a cognitive measurement of seam pucker', *J Text Inst*, 1993 **84**(4) 593.
46. Shigeru I and Atsuo S, 'Objective evaluation of seam pucker', *Int Cloth Sci Technol*, 1992 **4**(5) 24.
47. Richard C, 'Pucker as fabric-thread machine mechanical instability phenomenon', *J Fed AsianProf Text Assoc*, 1996 **3**(2) 69.
48. Richard C, 'Sewability in the dynamic environment of the sewing process', *J Fed Asian Prof Text Assoc,* 1995 **3**(1) 83.
49. Park C K, Lee D H and Kang T J 'A new evaluation of seam pucker and its application', *Int J Cloth Sci Tech*, 1997 **9**(3) 252.
50. Park C K and Kang T J, 'Objective rating of seam pucker using neural networks', *Text Res J*, 1997 **67**(7) 494–502.
51. Park C K, 'Objective evaluation of seam pucker using artificial intelligence', *J.S.N. Int*, Sept., 1997 43.
52. Kawabata S, 'Fibre science to apparel engineering', *Text Asia*, Nov., 1998 51–56.
53. Fan J and Liu F, 'Objective evaluation of garment seams using 3-D laser scanning technology', *Text Res J*, 2000 **70**(11) 1025–1030.

54. Fan, J., 'Assessing the quality of garment appearance', *ATA Journal*, 76 (Jun./July, 1998).
55. Fan J, MacAlpine J M K and Lu D, 'The use of a 2-D digital filter in the objective evaluation of seam pucker as 3-D surface', *J Text Inst*, 1999 **90** Part 1 (3) 445.
56. Fan J, Hui C L P, Lu D and MacAlpine J M K, *Latest Development of Objective Evaluation of Garment Appearance*, Hong Kong Polytechnic University, 1998.
57. Fan J, Hui C L P and Lu D, 'Towards the objective evaluation of garment appearance', *Int Cloth Sci Technol*, 1999 **11**(2/3) 151.

5

Objective evaluation of clothing fit

W YU

5.1 Introduction

Clothing fit is generally assessed by qualitative methods. Although a quantitative method is more desirable, it is difficult to achieve. The main drawback of the qualitative approach is the lack of precision in subjective assessment and ineffective communication. Kohn and Ashdown[1] first used video-captured images of slashed test jackets for the analysis of fit for women aged between 55 and 65. Expert analysts and this image analysis method were both found capable of defining the complex interactions of the garment/body interface. The standardisation of clothing fit remains a complex and controversial subject.[2] This chapter introduces five main approaches to the objective evaluation and computation of clothing fit, namely the use of moiré optics, an algebraic mannequin, waveform, pressure mechanics and computer fit modelling.

5.2 Moiré optics

For the measurement of unstable soft objects, such as clothing, contact methods are not applicable because the objects deform readily. Shadow moiré topography[3] is an effective non-contact technique for capturing a 3D form on a 2D fringe pattern. It is a well-known technique, commonly used in the analysis of spinal deformities in the human body.

For clothing applications, Japanese researchers in the 1980s attempted to measure and evaluate clothing drape,[4] bagging,[5] wrinkling[6] and body shape[7] by means of moiré topography (Fig. 5.1). During the 1990s, further applications of the moiré technique were found in the area of pattern construction. Tomita *et al*.[8] brought out several publications dealing with investigations on basic dress patterns for the figures of older women. Yu *et al*.[9] have applied moiré topography for evaluating the fit of various clothing types. Examples are given in the following sections.

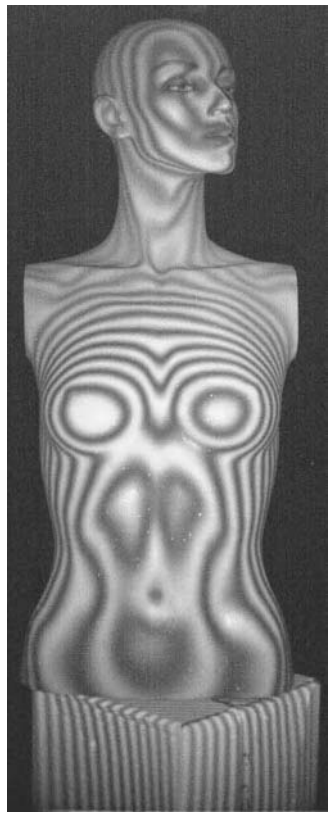


Figure 5.1 Moiré measurements of the human body.

5.2.1 Shape conformity of bra cup

Regarding the objective assessment of clothing shape, Yu[10] was the first to develop a moiré system for the measurement of bra cups, employing a special instrumental design[11] and technique to enhance the fringe visibility.[12] A metallic frame was constructed for controlling the position of the light source, the camera and the specimen with precise alignment (Fig. 5.2). To produce a moiré picture with a clear image, Yu developed a grid plate using photo-chemical processing and a pneumatic grid translation system for removing background 'noise'. The moiré picture was then digitised and the coordinates of the sectional profiles were quantified, using third-order polynomial functions (Fig. 5.3). Several measures of the shape characteristics were also derived.[13]

5.2.2 Moiré evaluation of clothing fit

For the non-contact shape measurement of a jacket, Yu *et al.*[14] developed another moiré topographic system (Fig. 5.4). The jacket worn by a mannequin

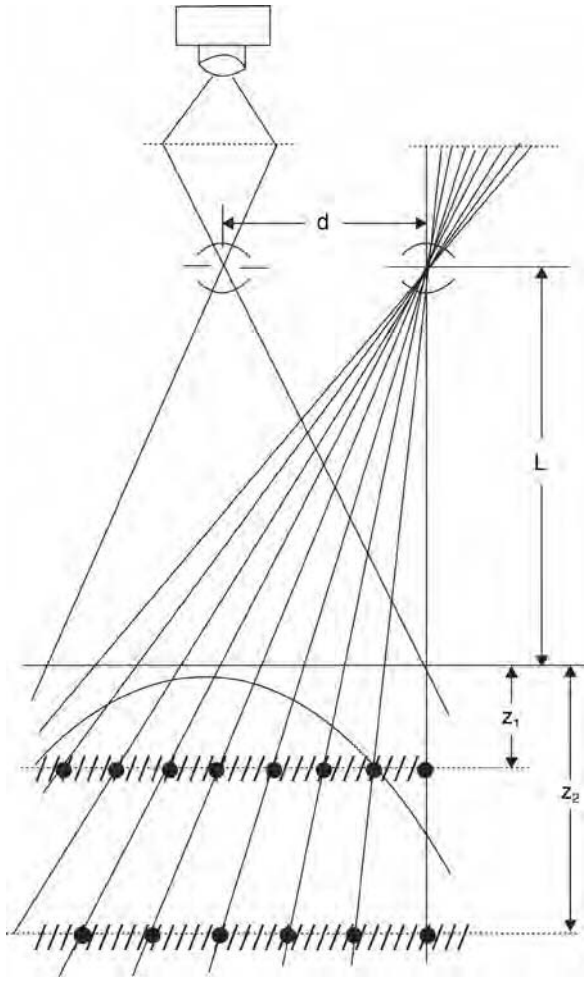


Figure 5.2 Schematic setup of the moiré system.

was placed close to the grid, enabling a sharp image of the moiré fringes to be obtained (Fig. 5.5).

For capturing the full size of the human figure, a vertical frame 605 mm (L) $\times$ 570 mm (W), was designed to mount the grid lines in an exact parallel manner. The grid plane was translated perpendicularly to the grid lines in its own plane, the movement being controlled by an electrical device, for the elimination of 'background noise' fringes.

Based on Pirodda's approach,[15] equation (5.1) was used for the computation of the distance between the object surface and the grid at a given position of the moiré fringe.

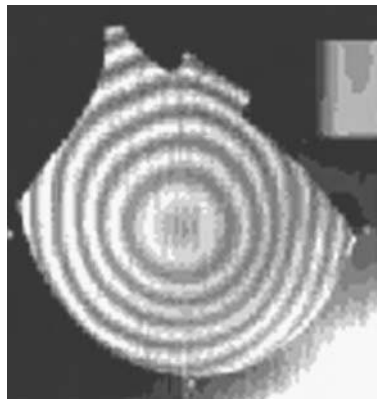


Figure 5.3 Moiré image of bra cup.

$$z = \frac{ngL}{d - ng} \tag{5.1}$$

where z corresponds to the fringe depth of the object surface measured from the grid plane, and the absolute fringe number $n = 0, 1, 2 \ldots$ for bright fringes, or $n = \frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots$, for dark fringes. L is the distance between the grid and the light source, g is the grid line spacing and d represents the distance between the light source and camera.

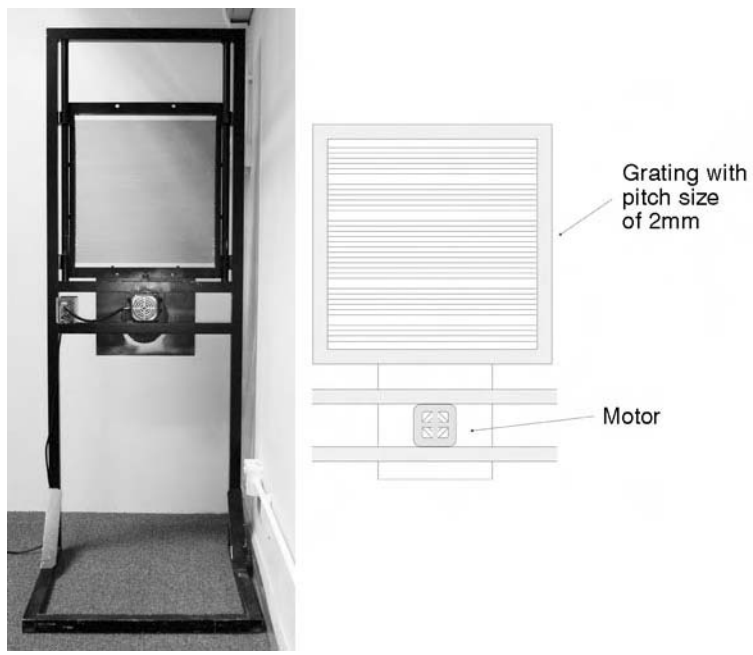


Figure 5.4 Moiré system for jacket measurement.

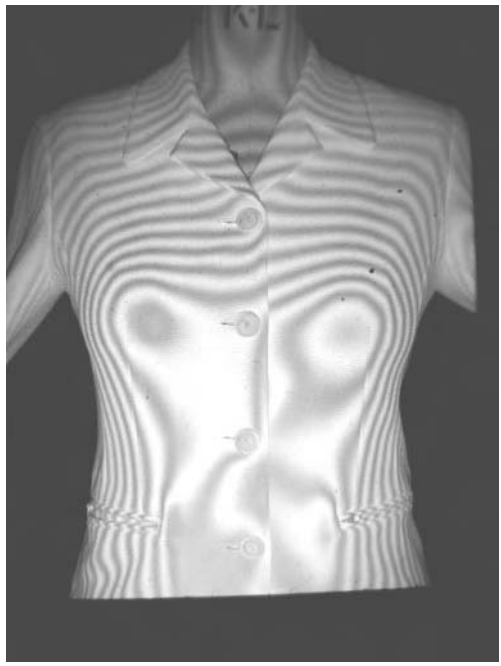


Figure 5.5 Moiré image of jacket.

The contour map of the moiré fringes generates the required shape information across the clothing surface. A visual interpretation of the fringe pattern is a good means for assessing the shape conformity of a three-dimensional clothing sample. If the clothing fits well, the contour lines appear round and symmetrical (Fig. 5.6). On the other hand, if it does not fit precisely, the fringe pattern will be distorted.

For the objective measurement of the jacket shape, a digital analysis of different sections of the front, back and side view was performed. The fringe pattern was then digitised and the co-ordinates of the sectional profiles were quantified using fourth-order polynomial functions, and root-mean-square measures of the shape characteristics were derived (Fig. 5.7).

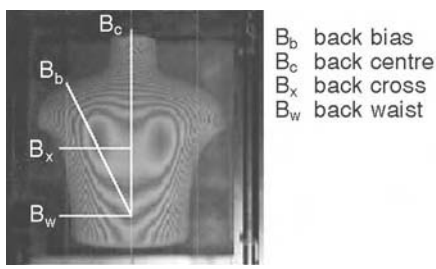


Figure 5.6 Sectional analysis of clothing fit.

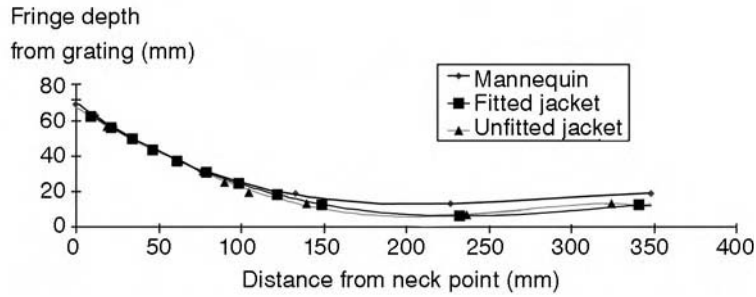


Figure 5.7 Polynomial curves of centre back profile.

To have a perfect fit, the depth of any point on the clothing sample should be the same as that on the mannequin. For outer-clothing, such as a jacket, it is generally agreed that the clothing should fit nicely from the neck to the cross-back level, from where it should hang naturally and parallel to the body. The depth deviation can therefore determine the fit. A single measure of the overall clothing fit is provided by a root mean square value.

If the depth deviation $D(x)$ represents the difference between a point on the mannequin and a point on the jacket corresponding to the same x-value, its mean value can be calculated by integrating $D^2(x)$ over the total investigated length. The square root of this mean value is calculated in order to obtain the root-mean-square (rms) of the depth deviation, i.e.:

$$\text{rms} = \sqrt{\mu_{D^2}} \tag{5.2}$$

Obviously, when the clothing shape fits the mannequin perfectly, the rms value is zero.

The above provides an objective technique for industry to compare differences in clothing appearance resulting from various pattern constructions and methods of assembly, and for monitoring variations in clothing shape in a production batch. The moiré system so developed, provides a quick and reliable device to evaluate the complex clothing shape and to assess the quantitative shape conformity in the critical area, with less reliance on experience and personal assessment.

Extending the above research, a new 3D body scanning system 'Cubicam', using modified projection moiré topography, was developed (see Chapter 8). This method of objective evaluation was then applied in the assessment of the 'shaping up' effects of foundation garments, such as push-up bras, girdles, maternity supports as well as outer suits (see Figs 5.8 and 5.9). In previously mentioned studies, mathematical analysis was essentially made on arbitrarily defined sectional profiles of the moiré fringes. Further research is required to study the overall measurement of the complex clothing shape and appearance.

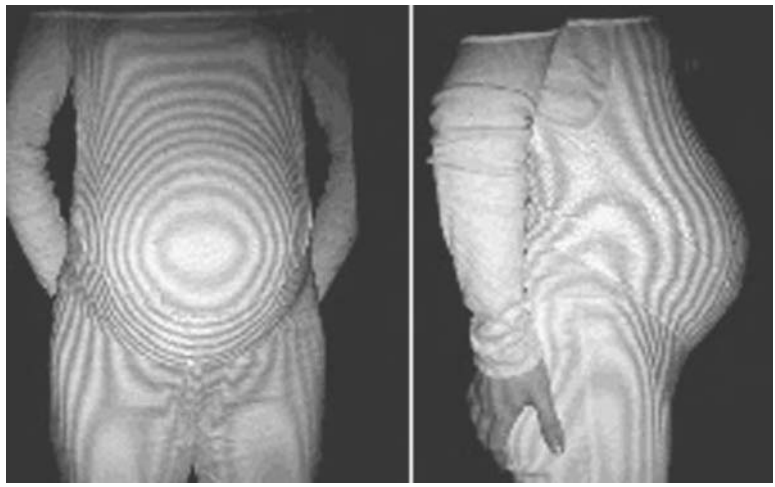


Figure 5.8 Maternity support.

5.3 Algebraic evaluation of clothing fit

Based on the mathematical concept of an 'algebraic mannequin', Ng *et al*.[16] rationalised a framework of fit measurements at four levels, namely linear dimension, sectional area, volume and overall. This provided simple indices to measure the distance, area or space between the body and the garment, the indices being the linear index, the cross-sectional index, the volume index and the signature curve index, respectively.

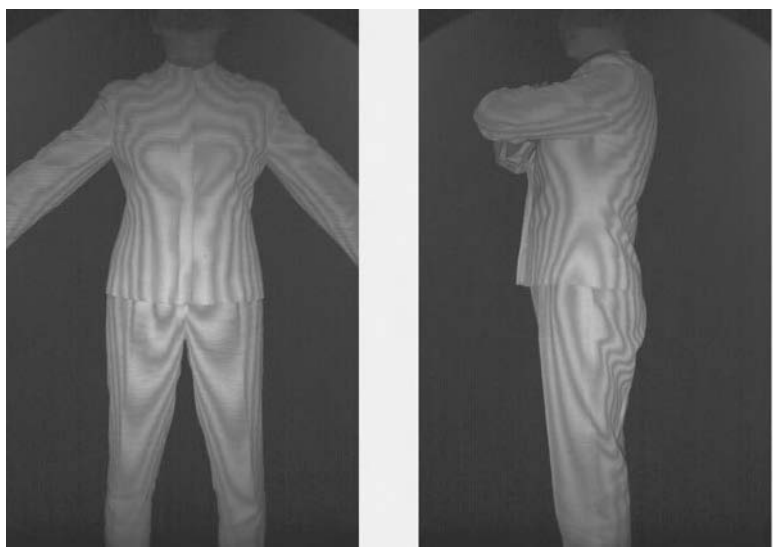


Figure 5.9 Outer suit.

5.3.1 Linear index

The Linear Index measures the difference in the linear measurements. It is the difference in the linear measurement between the garment and the body, representing an 'ease allowance' for breathing and other body movements and is calculated as follows:

$$\text{linear index (LI)} = (\text{LM}_{\text{Garment}} - \text{LM}_{\text{Body}})/\text{LM}_{\text{Body}} \tag{5.3}$$

where LM stands for linear measurement. There is no upper limit for such an index, while the minimum value is -1.

5.3.2 Cross-sectional index

The cross-sectional index measures the area between the garment and the body. It is the total cross-sectional area on the transverse plane. If there is an opening, a straight line connecting the endpoints is used to close the area for computational purposes. This is a more precise measure than the linear index in terms of the 'ease allowance' for body movement. The cross-sectional index can be further divided into regional areas, such as front and back. Since the lungs expand more at the front than the back during inhaling, the front part has a greater 'ease allowance'. The front cross-sectional index can be expected to be greater than that of the back. The formula is:

$$\text{cross-sectional index (XI)} = (\text{XA}_{\text{Garment}}\text{XA}_{\text{Body}})/\text{XA}_{\text{Body}} \tag{5.4}$$

where XA stands for the cross-sectional area. The XI value is typically greater than or equal to zero. XI is equal to zero only in the case of a stretchable garment. If the elasticity of the muscles is considered, the index may be negative.

5.3.3 Volume index

The volume index measures the total volume trapped between the garment and the dummy. This index is an indication of any jump in size. For example, the volume index of an overcoat must be greater than that of underwear. Volume is meaningful only for an enclosed surface, so the volume is measured as if the opening of the garment is closed and covered by a minimal surface. Since the opening lies on the same transverse plane as in the algebraic mannequin, the volume integral is taken up to such a plane. The general formula is:

$$\text{volume index (VI)} = (\text{volume}_{\text{Garment}} - \text{volume}_{\text{Body}})/\text{volume}_{\text{Body}} \tag{5.5}$$

VI is usually positive, being equal to zero when the garment is close fitting, like a second skin. If the elasticity of the muscle is considered, the index may be negative.

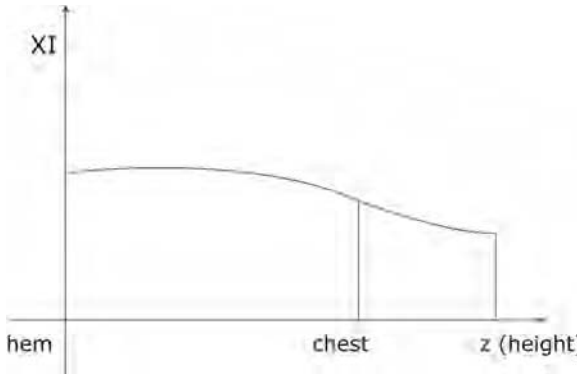


Figure 5.10 Example of a Signature Curve on the bodice.

5.3.4 Signature curve

The signature curve is a measure of the overall fit, referred to as a fit-spectrum diagram. It is a function of the cross-sectional index versus the height of the transverse plane. The curve reveals the characteristics of the garment. For example, the signature curve of a tight fitting garment appears relatively flat with consistently low values of XI (see Fig. 5.10).

Another type of signature curve, called the absolute signature curve, measures the actual trapped cross-sectional area versus the height. It is useful when reconstructing the surface of the garment,[17] since absolute measurements, instead of percentages, are needed for calculation.

In practice, the cross-sectional index is calculated at crucial levels. Therefore, the signature curve can be generated by fitting polynomials, Hermite, Bezier or B-spline, to the data points, the Lagrange polynomial not being recommended.

5.4 Clothing waveform

Taya *et al.*[18] published a series of papers which proposed various methods for evaluating clothing fit. In part 1, they digitised the 3D co-ordinates of measuring grids marked on the dummy, using a Vectron measuring apparatus. Three types of fabric were used for evaluating the clothing fit of a certain dress style. The cross-sectional profile at every altitude and the 3D shape of the body and clothing were reconstructed (Fig. 5.11). With the data obtained, the space between the body and clothing was then quantified as an index of fit (FI):

$$FI = F_i/F_o \tag{5.6}$$

where F_i is the apparent clothing space and F_o is the maximum clothing space. The results of fitting at the bust, waist and hip were presented on the basis of this evaluation index.

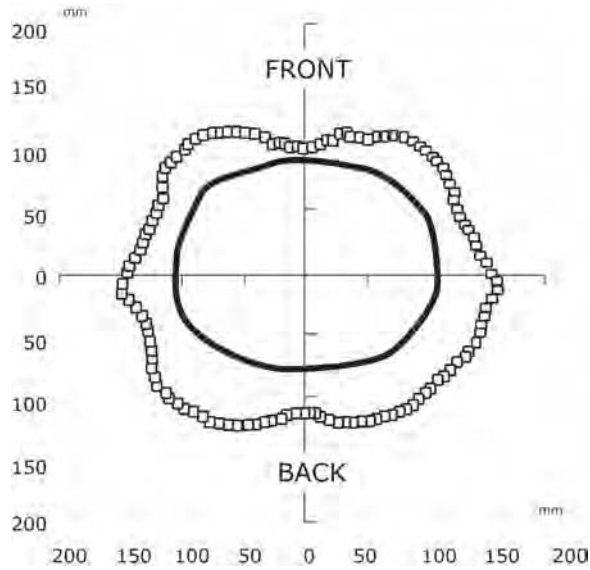


Figure 5.11 Cross-sectional profile of body and clothing at the waist line; body shape, clothing shape, calculated clothing shape. Source: Taya *et al.*, 1995.[18]

In part 2, Pickover's acoustic theory and symmetrised dot pattern (SDP) were applied to capture the subtle difference in clothing shape, which could be shown as an ellipse, rectangle, rhombus, dumbbell, or an ellipse combined with a cosine curve and a sine curve (Fig. 5.12). The amplitude of the clothing waveform was analysed for the detection and characterisation of the significant features of any clothing shape.[19]

In part 3, Taya *et al*.[20] studied the relationship between clothing size and shape. The amplitude of the clothing waveform was analysed using the probability density spectra and the new SDP method (Fig. 5.13).

In part 4, Taya *et al*.[21] found that the clothing waveform depended greatly upon physical size and the mechanical properties of the material. The best conditions showed a uniform distribution of the touch points and the space (Fig. 5.14).

As revealed in part 5 of Taya *et al*.'s paper,[22] it was difficult to extract local and detailed information from the clothing waveform because the clothing shape is localised and it has directional waves with different angles. The wavelet transform was therefore applied to extract a characteristic of clothing waveform for the fit evaluation. The clothing waveform is considered to be a periodic function of angle θ and amplitude $f(\theta)$, where $f(\theta)$ is defined as a distance to the outside surface of the clothing from the centre of the human body. The magnitude of the wavelet transform of the wave data at the angle offers detailed information of clothing waveform at each frequency (Fig. 5.15).

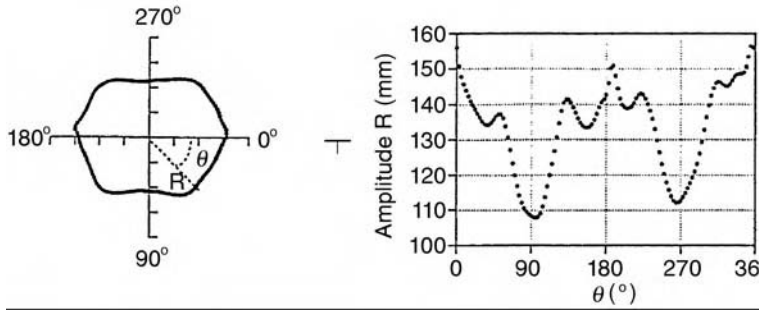


Figure 5.12 Cross-sectional shape of clothing at the waistline and its derived waveform. Source: Taya *et al.*, 1995.[19]

In part 6, Taya *et al*.[23] further investigated the influence of clothing size and material on clothing waveform. The experimental clothing waveform was compared to the standard. The contour colour figure of the wavelet transform can detect a small variation of clothing waveform at the bust line due to a

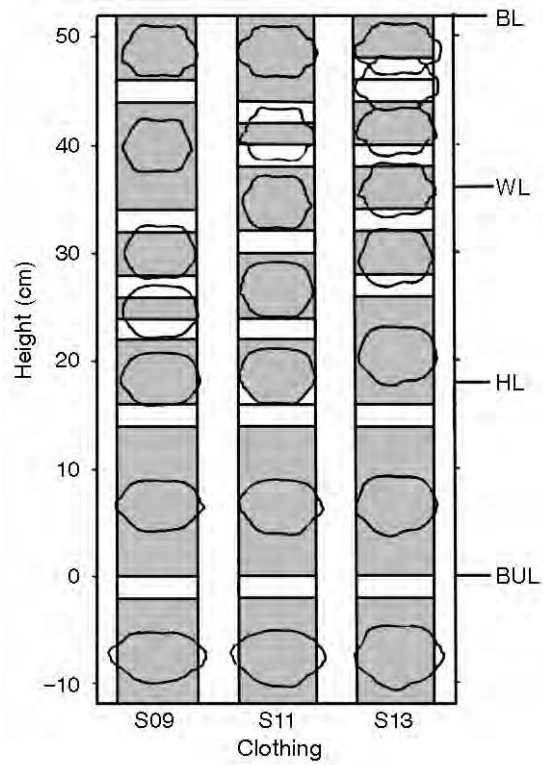


Figure 5.13 Clothing waveform of different sizes: 9, 11 and 13. Source: Taya *et al.*, 1995.[20]

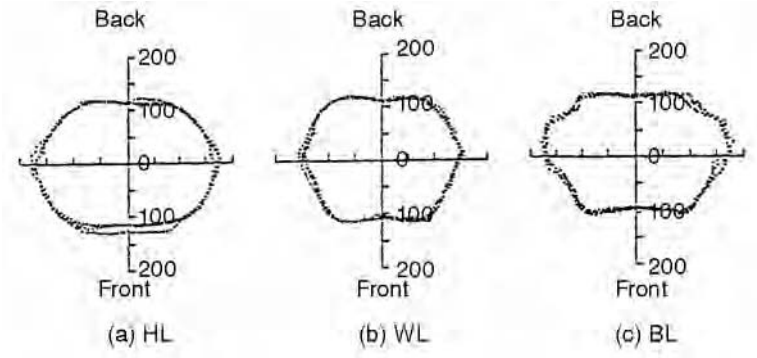


Figure 5.14 Cross-sectional waveforms of various clothing materials at (a) the hip level, (b) the waist level and (c) the bust levels for a body size no. 9. Source: Taya *et al.*, 1995.[21]

defined change in material and size. These can provide a good measure of clothing fit. It showed that material type significantly affects clothing fit. When the clothing material varied, the change of waveform was larger than that caused by a change in size.

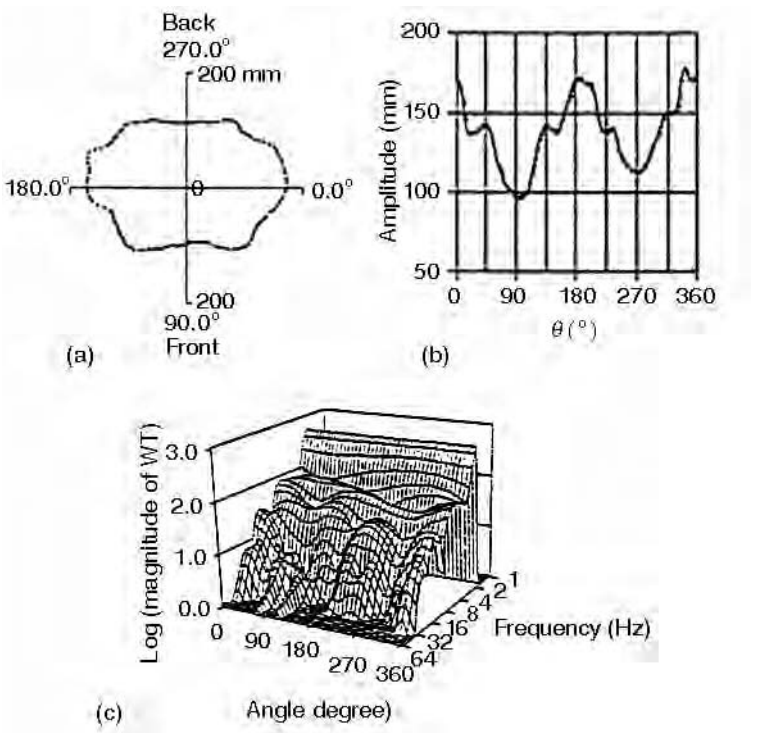


Figure 5.15 Magnitude of the wavelet transform at the bust line waveform of a body size no.9: (a) cross-sectional clothing shape, (b) amplitude of waveform, (c) magnitude of the wavelet transform. Source: Taya *et al.*, 1996.[23]

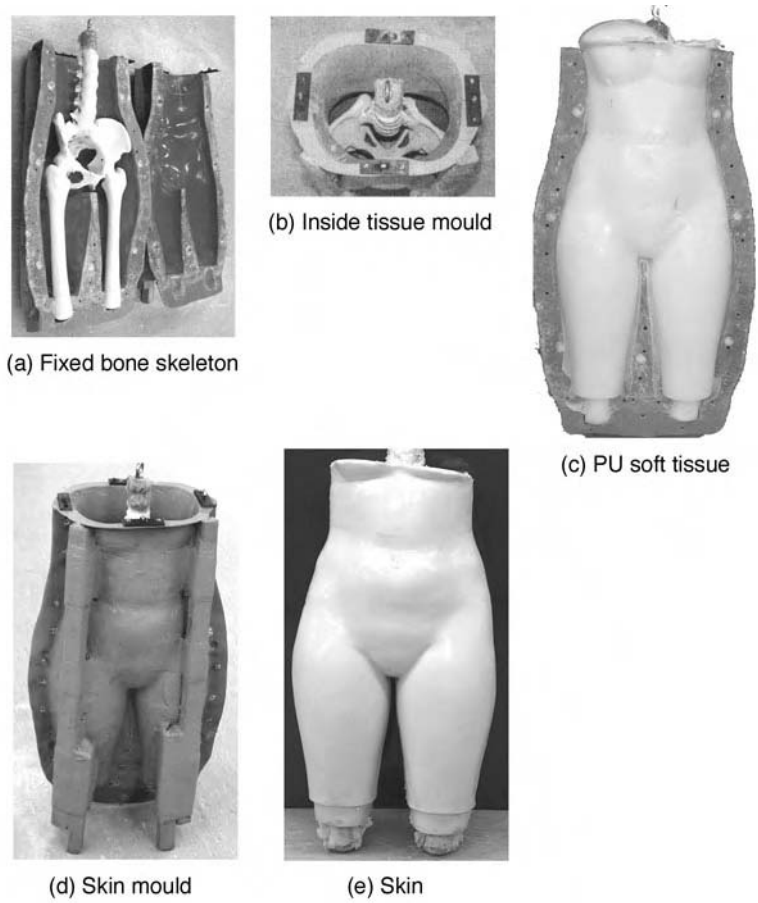


Figure 5.16 Manufacture of soft mannequin. Source: Yu *et al.*, 2001.[24]

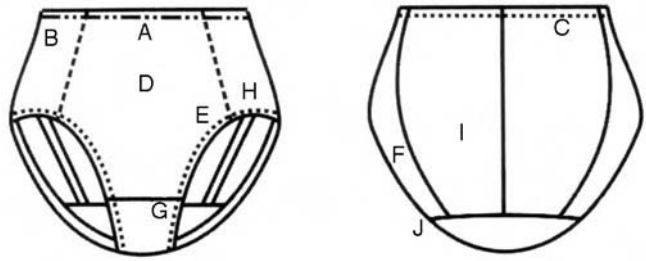
5.5 Pressure evaluation of clothing fit

5.5.1 Soft mannequin

Apart from the algebraic indices of clothing fit and the geometric presentation of clothing shape, the pressure acting on the body's soft tissue also plays an important role in the evaluation of fit. In 2002 Yu *et al.*[24] developed a soft mannequin to simulate the human body for measuring contact pressure. It was developed with the exact dimensions of the lower torso of a female body, containing a full-size bone skeleton, also imitating soft tissue and skin. The imitated soft tissue is comprised of flexible polyurethane foam of different moduli. Silicone rubber is used to simulate the human skin. Figure 5.16 shows the different layers required in the manufacture of the soft mannequin. It was found that the clothing pressure on a live model can be predicted by using linear

equations which correlate the relationship between the measurements obtained from the soft mannequin with those of the human body.

The pressure values *Pm* obtained from the soft mannequin are correlated with the contact pressure *Ps* imposed on the subject, at different body positions:



Point A:	$Ps = 0.72$	$Pm\ -320.65$	$R = 0.82$	
Point B:	$Ps = 3.08$	$Pm\ -1098.13$	$R = 0.87$	
Point C:	$Ps = 3.17$	$Pm\ -397.51$	$R = 0.88$	
Point D:	$Ps = 0.18$	$Pm\ -111.19$	$R = 0.88$	
Point E:	$Ps = 3.37$	$Pm\ -628.55$	$R = 0.94$	
Point F:	$Ps = 2.31$	$Pm\ -75.54$	$R = 0.71$	
Point G:	$Ps = 0.16$	$Pm\ +13.80$	$R = 0.47$	
Point H:	$Ps = 0.98$	$Pm\ -36.75$	$R = 0.77$	
Point I:	$Ps = 0$			
Point J:	$Ps = 0.33$	$Pm\ +81.65$	$R = 0.80$	(5.7)

5.5.2 Stretch test

People think that a stretch garment will automatically fit in the right places and provide ease of movement. This is a fundamental misunderstanding of stretch characteristics. Watkins[25] divided contour fit into three categories: form fit, action fit and power fit. Form fit exerts no pressure on the body; action fit holds and supports the body; and power fit moulds the body into the desired shape. A grid system was used as an aid to visualise the fabric curvilinear distortion in the study of stretch characteristics in relationship to the sculptural form of the body.

Stretch clothing presents unusual difficulties in the evaluation of fit. An appropriate stretch fit is essential to secure certain functionality, comfort and appearance. The clothing measurements have to be adjusted and usually made smaller than the body measurements by a percentage because wear will stretch the material. Therefore, the stress-strain behaviour of the material essentially influences the clothing fit. For intimate apparel, stretch tests contribute an essential part of fit testing. The fabric and/or elastic bands are stretched to actual body dimensions, and the force level is measured by a tension spring. Marks &

Spencer has also introduced a simple bra sensor to measure the pressure fit at several positions, such as the shoulder and rib cage around the body.

CETME equipment[26] is widely used by US hosiery manufacturers and testing laboratories in checking rise and 'in-seam' lengths (panty and lengths). MTL recommends cross-stretch tests in the waistband and thigh areas, as well as area/volume stretching in the leg section, and the lateral and lengthwise directions of the panty. The pantyhose were fitted on 2D sliding flat forms, each clamped at the top and bottom jaws of a tensile testing machine. The force level required to stretch to the actual body dimensions was then recorded.

5.6 3D modelling of pressure fit

The National Institute of Materials and Chemical Research[27] in Japan developed a system using computer simulation to predict how clothing fits a person. In this system, clothing is divided into hundreds of small triangular finite elements. Each element is viewed as an elastic material. The formulation of the stress-strain relationships in terms of mechanical properties of the material will allow the measurement of potential energy and prediction of the 3D configuration of ease, the wearing silhouette and distribution of pressure without actually producing the clothing. Using computer graphics, technology enables the results to be shown on a 3D display. Thus the construction of apparel CAD software, including an evaluation of fit sensitivity, can be expected.

Using the finite element method, Zhang *et al*.[28] have simulated the garment-body dynamical interactions during wear in a 3D bio-mechanical model. They computed the 3D distribution of pressure, stress and deformation of the garment and body.

5.7 Conclusions

Objective evaluation of clothing fit is necessary but difficult to achieve, hence the limited number of researchers working in this area. The technologies are mainly based on optical methods, such as somatometry and moiré topography, which capture the clothing images using a non-contact approach. After image analysis, the three-dimensional fit of clothing can be calculated in quantitative terms. Objective techniques are valuable for the industry in comparing differences in clothing appearance obtained from various pattern constructions and methods of assembly, with less reliance on experience and personal assessment. More importantly, the quantitative approach of fit assessment is useful for the construction of basic block pattern.

Mathematically, clothing fit can be expressed in terms of the linear ratio and geometric index. The curved shape of the clothing surface and human body is illustrated in symmetrical shapes, while the clothing drape, generalised as

different kinds of waveforms, may change with different clothing materials. The theory was developed using wavelet transformation.

At present, various technologies have been developed for the presentation of clothing appearance in a simulated 3D form. It is envisaged that these novel systems can provide a remote communication tool for industrial partners to discuss the 3D clothing fit, based on the clothing image. This may lead to more efficient and effective decision making in the process of product development and quality control.

5.8 References

1. Kohn I L and Ashdown S P, 'Using video capture and image analysis to quantify apparel fit', *Text Res J*, 1998 **68**(1) 17–26.
2. Peterson E A, 'Standardization of industrial garment fit', *Industrial Launderer*, Oct., 1980, **31** 81–89.
3. Patorski K, *Handbook of the Moiré Fringe Technique*, Amsterdam, New York, Elsevier, 1993, 220–253.
4. Suda N and Takahashi T, 'Evaluation of drapability by moiré topography', *J Japan Res Asso Text End Uses*, 1983, **24** 209–214.
5. Matsuoka H, Nagae S and Niwa M, 'Evaluation methods for bagging of garment', *J Japan Res Assoc Text End-Uses*, 1984, **25** 502–509.
6. Matsuoka H, Niwa M and Nagae S, 'On evaluation methods for wrinkling for using moiré topography', *J Japan Res Assoc Text End-Uses*, 1984, **25** 34–42.
7. Tanaka M and Doi S, 'Classification of partial body shape by moiré topography', *J Japan Res Assoc Text End-Uses*, 1982, **23** 255–261.
8. Tomita A, Kazuyo I and Nakaho Y, 'An experiment on basic dress pattern for aged women, Part2: The characteristics of the arm form for drawing the flat pattern of the sleeve', *J Japan Res Assoc Text End-Uses*, 1992, **33** 434–441.
9. Yu W M, Ng K P, Yan M C and Gu H B, 'Body scanner' Chinese patent no. ZL01269653.6, granted on 2 October, 2002.
10. Yu W M, *The effect of polyurethane properties and moulding conditions on the shape characteristics of brassiere cups*, PhD Thesis, The University of Leeds, UK, April, 1996.
11. Yu W M, Harlock S C, Leaf G A V and Yeung K W, 'Instrumental design for capturing three-dimensional moiré images', *Int J Cloth Sci Technol*, 1997, **9**(4) 301–310.
12. Yu W M, Harlock S C, Leaf G A V and Yeung K W, 'Enhancement of fringe visibility for three-dimensional moiré measurement', *Proc 78th Textile Inst World Conf*, 23–26 May 1997, **2** 361–370.
13. Yu W M, Harlock S C and Yeung K W, 'Contour measurements of moulded brassiere cups using a shadow moiré technique', *Proc Third Asian Text Conf*, Hong Kong, 1995, **1** 300–308.
14. Yu W M, Yeung K W and Lam Y L, 'Assessment of garment fit', *Proc of the HKITA and CTES Conf on Hand-in-Hand Marching into 21 Century*, Shanghai, China, April 1998, 125–129.
15. Pirodda L, 1982, 'Shadow and projection moiré techniques for absolute or relative mapping of surface shapes', *Opti Eng*, **21** 640–649.

16. Ng R, Chan C K, Pong T Y and Au R, 'Objective measurement of the 'fit' of an apparel', *Proc 77th Text Inst World Conf*, May, 1996, Tampere, Finland.
17. Ng R, Chan C K, Pong T Y and Au R, 1995, 'Shape reconstruction using linear measurements', *J China Text University* (English Edition), **12** 30–35.
18. Taya Y, Shibuya A and Nakajima T, 'Evaluation method of clothing fitness with body – Part 1: Evaluation index of clothing fitness', *J Text Mach Soc Japan*, 1995, **48**, 2 T48–T55.
19. Taya Y, Shibuya A and Nakajima T, 'Evaluation method of clothing fitness with body – Part 2: Application of symmetrized dot patterns to the visual characterization of clothing wave form', *J Text Mach Soc Japan,* 1995, **48**, 6 51–60.
20. Taya Y, Shibuya A and Nakajima T, 'Evaluation method of clothing fitness with body – Part 3: Evaluation by cross-sectional shape of clothing', *J Text Mach Soc Japan*, 1995, **48**(9) T225–234.
21. Taya Y, Shibuya A and Nakajima T, 'Evaluation method of clothing fitness with body – Part 4: Evaluation by waveform spacing between body and clothing', *J Text Mach Soc Japan*, 1995, **48**(11) T261–269.
22. Taya Y, Shibuya A and Nakajima T, 'Evaluation method of clothing fitness with body – Part 5: Application of wavelet transform to analysis of clothing waveforms', *J Text Mach Soc Japan*, 1996, **48**, 11 41–49.
23. Taya Y, Shibuya A and Nakajima T, 'Evaluation method of clothing fitness with body – Part 6: Evaluation of clothing waveforms by wavelet transform', *J Text Mach Soc Japan*, 1996, **49**, 6 46–58.
24. Yu W, Fan JT, Qian XM and Tao XM, 'Development of a mannequin for garment pressure evaluation', *Proc Text Edu Res*: Strategies for the New Millennium, 1st AUTEX Conference, Portugal, 26–29 June, 2001,**1** 452-457.
25. Watkins P., 'Analysis of Stretch Garments', *Proceedings of the 80th World Conference of the Textile Institute*, 16–19, April, 2000. Manchester, UK.
26. Pechoux B L and Ghosh TK, 'Apparel sizing and fit', *Text Progr*, The Textile Institute, Manchester, UK, **32**(1), 31.
27. NIMC, *Evaluation of size fitness of garments*, www.aist.go.jp/NIMC/overview/v17.html.
28. Zhang X, Yeung K W and Li Y, 'Numerical simulation of 3-D dynamic garment pressure', *Text Res J*, 2002, **72**(3) 245–252.

6

Fabric properties related to clothing appearance and fit

L HUNTER AND J FAN

6.1 Introduction

Discerning and quality conscious consumers require that their clothing satisfy their requirements and expectations in terms of appearance, fit and comfort, both when new and for an acceptable wear period thereafter. The clothing manufacturer, on the other hand, requires that the fabric is easy to tailor, passes through the making-up (garment manufacturing) process easily and without undue problems and that the finished garment has a good appearance (see Table 6.1[1]).

Table 6.1 Assessment of fabric performance in apparel

For Consumer		
Aesthetic impression	visual	colour and pattern * drape
	tactile	* feel
	audible	rustle etc
Cover	light transmission body shape (obscure or enhance)	
Comfort	permeability, heat, moisture, air skin contact	* feel (local and distributed)
Strength and durability	breakage and loss of fibre * damage-prone sharp folds	
Appearance retention	* wrinkling and creasing change of aesthetics ease-of-care	
For Clothing Manufacturer		
Handling characteristics	* laying down, cutting, * transporting, * sewing manipulation, needle and stitch action, * forming and pressing	

* all involve complex buckling of fabrics related to fabric hand.
Source: Hearle, 1993.[1]

Many aspects, notably garment type, style, cut and sizing are involved in 'fit', but this chapter will basically cover changes in fit, and the fabric properties which play a role in such changes, notably dimensional stability and deformation, as well as fabric appearance and those fabric properties which affect garment appearance, quality and performance during cutting, sewing and making-up. Appearance, within the context of this chapter, chiefly refers to the visual appearance of the garment *per se*, as opposed to that of the fabric, covering aspects such as puckering, bagging and fit. Fabric-specific appearance factors, such as wrinkling, pilling, abrasion (also shine), fuzzing and colour changes, as well as aspects relating to garment comfort, are therefore not covered. These aspects are well covered in other chapters or relevant reviews (see section 6.2).

Essentially the wear behaviour, performance and appearance of a garment depend upon the following factors:

- fibre structure and properties
- yarn structure
- fabric structure
- garment construction and fit
- wear conditions

Traditionally, the quality of fabrics and 'fitness for purpose', including their performance during making-up (tailoring) and in the garment, were assessed subjectively in terms of the fabric handle (referred to as fabric handle or hand), by experts (judges) in the clothing industry (see Fig. 6.1).[3] In assessing the fabric, these experts used sensory characteristics, such as surface friction, bending stiffness, compression, thickness and small-scale extension and shear, all of which play a role in determining garment making-up (tailorability) and appearance during wear. Such experts, who were frequently highly skilled, assessed the fabrics using their hands to perform certain physical actions on the fabric, such as rubbing, bending, shearing and extension (stretching). They expressed what they felt (i.e. their perceptions) in terms of subjective sensations, such as stiffness, limpness, hardness, softness, fullness, smoothness and roughness, which then formed the basis for the fabric selection.[2] Because of the way this was assessed, i.e. by tactile/touch/feel, and

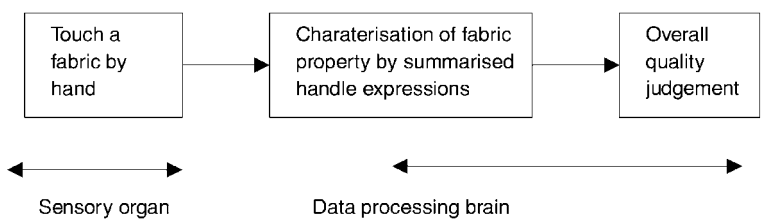


Figure 6.1 Process used by experts in the subjective evaluation of fabric handle. Source: Kawabata, 2000.[3]

Table 6.2 Fabric properties that are related to tailoring performance, appearance in wear, and handle

Property	Test	Tailoring performance	Wear appearance	Handle
Physical	Thickness	–	–	+
	Mass per unit area	+	+	+
Dimensional Shrinkage	Relaxation	+	+	–
	Hygral expansion	+	+	–
Mechanical	Extensibility	+	+	+
	Bending properties	+	+	+
	Shear properties	+	+	+
Surface	Compression properties	–	–	+
	Friction	–	–	+
	Surface irregularity	–	–	+
Optical	Lustre	–	+	–
Thermal	Conductivity	–	–	+
Performance	Pilling	–	+	–
	Wrinkling	–	+	–
	Surface abrasion	–	+	–

+ Important; – Less important
Source: De Boos, 1997.[4]

the terminology used, i.e. 'fabric handle or hand', it is sometimes incorrectly assumed that the assessment was purely aimed at arriving at a subjective measure of the fabric tactile-related properties (i.e. handle). In fact, in reality, the fabric handle, when so assessed by experts, provided a 'composite' measure of the overall garment-related quality of the fabric, including garment making-up, comfort, aesthetics, appearance and other functional characteristics (see Table 6.2). Nevertheless, although such experts were highly skilled and their judgement sensitive and reliable, the end result was still subjective and qualitative by nature and suffered from the inherent weakness of all subjective assessments, being amongst other things dependent upon the skills, training, background (cultural and other) of the evaluator. In the light of the above, the need to develop an objective (i.e. instrument) measurement system for assessing fabric quality became apparent, fabric objective measurement (FOM) being such an integrated system of measurement. The FOM instruments were designed so as to measure the low deformation forces encountered when the fabric is manipulated by hand and also during the garment making-up (tailoring) process and removes much of the guesswork from garment manufacturing.

Figure 6.2, taken from Kawabata and Niwa,[5] presents the development in textile science and engineering, including fabric objective measurement and the engineering of fabric quality and properties, during the past century.

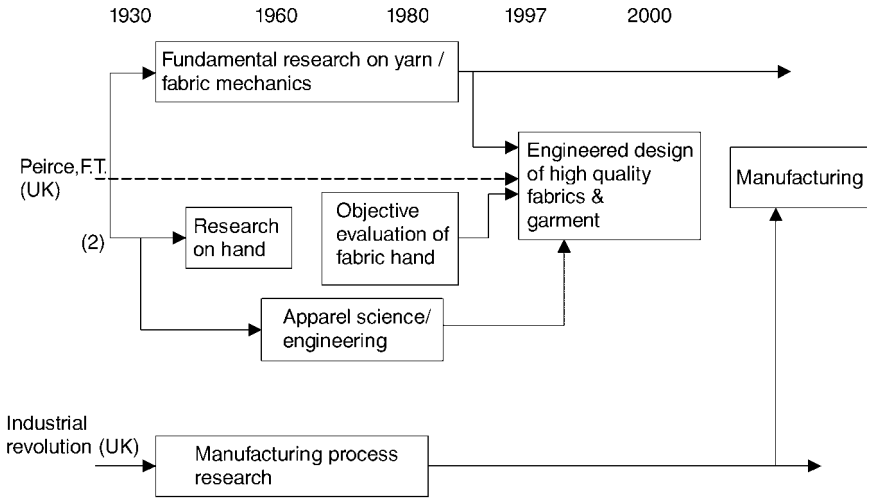


Figure 6.2 A history of the textile technology of the twentieth century. Source: Kawabata and Niwa, 1998.[5]

6.2 Reviews

There are various reviews on the topic covered by this chapter, as well as related topics. These include the following:

- The design logic of textile products[6]
- Clothing, textiles and human performance[7]
- Protective clothing[8]
- The thermal-insulation properties of fabrics[9]
- Science of clothing comfort[10]
- Apparel sizing and fit[11]
- Fabric objective measurement[12–25]
- Fabric handle[26]
- Modelling fabric mechanics[27]

6.3 Fabric objective measurement (FOM)

6.3.1 Background

Fabric objective measurement (FOM) provides a scientific means of quantifying the quality and performance characteristics of fabrics. Two issues need to be addressed in fabric objective measurement, namely what to measure and how to interpret the results. Niwa[28] stated that three criteria are used for the objective evaluation of fabric performance: good handle, good garment appearance and garment comfort, and that an ideal fabric should satisfy all three criteria.

Comfort generally comprises thermal comfort and mechanical comfort, the former being assessed from the permeability of the fabric to air, water and heat, and mechanical comfort being evaluated by the subjective assessment of handle, assessed visually and by tactile means.

According to Kawabata and Niwa,[5] clothing fabric performance needs to be assessed according to the following three requirements:

- Category A: utility performance (strength, etc.)
- Category B: comfort performance (fitting to the human body)
  - mechanical comfort
  - thermal comfort
- Category C: Fabric performance for the engineering of clothing manufacture.

Tests for the objective measurement of fabrics may be broadly classified as follows:[2]

- High-stress mechanical tests to measure properties, such as tensile strength, tear strength and abrasion, such tests normally being conducted until the fabric fails.
- Low-stress mechanical tests which reflect the range of stresses a fabric undergoes during normal use and which determine fabric handle (as well as making-up or tailoring performance and garment appearance).

At the present time, and as used here, FOM refers to the instrument measurement of those fabric properties (i.e. quality) which affect the tactile, making-up/tailorability and appearance-related properties of fabrics in garment applications, and generally involves the following characteristics: mostly small-scale deformation characteristics (bending, shear, compression and extension) as well as dimensional stability-related characteristics, such as hygral expansion and relaxation shrinkage.

In its broadest sense, fabric objective measurement of finished fabric has three main uses for quality control:[4]

- to ensure fabrics are easy to tailor
- to ensure garments keep their shape during wear
- to provide information on fabric handle.

The above factors are interrelated and, in many cases, are dependent upon the same, or similar, fabric properties (see Table 6.2). Tables 6.2 and 6.3 contain a list of fabric properties which are believed to be related to these quality control objectives. Test methods related to the fabric properties are also listed. The tests have been rated according to their importance for assessing the relevant property.

Based upon extensive research, it has been well established that the garment quality and appearance and its making-up processing and performance are determined by the fabric mechanical and surface properties.[2,23] The quality of

Table 6.3 Basic fabric mechanical properties and related quality and performance attributes of fabrics and garments

Fabric mechanical properties	Quality and mechanical performance
Uniaxial and biaxial tension	Fabric handle and drape Fabric formability and tailoring properties
Shear under tension	Garment appearance and seam pucker
Pure bending	Mechanical stability and shape retention
Lateral compression	Relaxation shrinkage, dimensional stability and hygral expansion
Longitudinal compression and buckling	Wrinkle recovery and crease retention Abrasion and pilling resistance
Surface roughness and friction	Mechanical and physiological comfort

Source: Postle, 1983.[24,29]

fabrics, their (tailorability and the subsequent appearance and performance of garments) can, in fact, be related to six basic fabric mechanical properties as shown in Table 6.3, with the quality and mechanical performance characteristics to which they relate[24,29] together with the fabric dimensional properties.

Fabric objective measurement is widely recognised as a key component for the success of the textile and clothing industries in the highly competitive environment and quality conscious and demanding consumers of the twenty-first century. Table 6.4 lists the various areas of application of FOM. Fabric objective measurement technology provides the key whereby the extensive experimental and theoretical research of the previous century may be implemented by the textile and clothing industries,[23] the underlying concept

Table 6.4 Application of fabric objective measurement technology

1. Objective measurement of fabric quality and handle and their primary components for various textile products.
2. Design and production of a diverse range of high quality yarns and fabrics using objective mechanical and surface-property data.
3. Objective evaluation and control of textile processing and finishing sequences for the production of high quality yarns and fabrics.
4. Objective evaluation of fabric tailorability and finished garment quality and appearance.
5. Objective specifications by tailoring companies for fabric selection, production planning, process control and quality assurance, using fabric mechanical and dimensional property data.
6. Measurement and control of the comfort, performance and stability of fabrics and clothing during use.
7.* Evaluation of the effect of changes in fabric finishing routines, including decatising, on fabric tailorability.

* Author's addition
Source: Postle, 1983, 1989.[23,29]

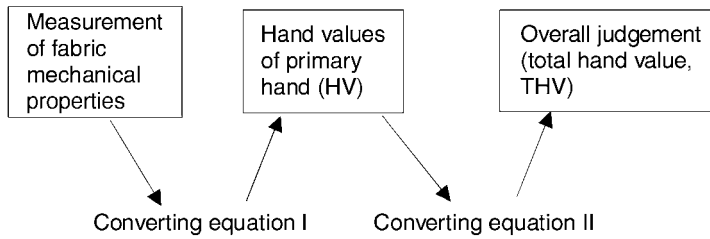


Figure 6.3 System for the objective evaluation of fabric handle. Source: Kawabata, 2000.[3]

being that a necessary and sufficient set of instrumental measurements be made on fabrics in order to specify and control the quality, tailorability and ultimate performance of an apparel fabric (see Table 6.4, Ref. 23). It also establishes an objective basis and language for communication between researchers, industry sectors (notably between fabric and garment manufacturers) and traders in fabrics and garments.

Although an important step towards the objective or quantitative assessment of fabric 'handle' and quality was the work of Peirce,[30] the most significant advance occurred early in the 1970s when Kawabata and Niwa organised the Hand Evaluation and Standardisation Committee in 1972[31] as a research committee of the Textile Machinery Society in Japan, inviting a number of experts in handle evaluation to join the committee. Through extensive research, involving experts from the clothing industry, the committee selected and defined the 'primary fabric handle' expressions and related these to the mechanical properties of the fabric[32] (Figs 6.1 and 6.3). This will be discussed in more detail later. An integrated system of FOM, the Kawabata Evaluation System for Fabrics (KES-F, later to become the KES-FB system), was the most important outcome of this work. This pioneering work laid a solid foundation for the accurate and routine measurement of those fabric properties which determine fabric handle and garment making-up and appearance and will be discussed in more detail later. Along similar, but greatly simplified lines, the CSIRO in Australia, developed the FAST (Fabric Assurance by Simple Testing) system many years later, for measuring the main fabric properties affecting garment making. The FAST system will also be discussed in more detail later.

The Kawabata and FAST systems measure similar low-stress fabric mechanical properties (compression, bending, extension and shear) and their results are generally in good agreement, although they differ somewhat in the measurement principles which they use, there being good correlation between similar parameters measured on the two systems and also on other systems. The results obtained on the two systems are plotted on control charts, sometimes called 'fingerprints', and comparisons between fabrics as well as diagnosis of tailoring problems can be made more easily when information is presented in

this way. Originally the Kawabata system was essentially aimed at predicting the feel, handle and appearance of fabrics, whereas the FAST was essentially aimed at predicting fabric tailorability.[15] The KES-F system measures fabric surface characteristics and recovery properties which the FAST system does not, whereas the FAST also measures relaxation shrinkage and hygral expansion and calculates formability which the KES-F system does not. Sule and Bardhan[15] have summarised the differences between the two systems with respect to predicting tailorability as follows: the KES-F system does not consider relaxation shrinkage or hygral expansion in adjudging tailorability, while the FAST system ignores linearity of tensile as well as tensile bending and shear hysteresis, to which the Kawabata system attaches considerable importance.

Discriminant and neural network analyses,[33] utilising KES-F and FAST fabric measurements, have been used to develop models to classify cotton, linen, wool and silk fabrics. The models based upon neural network analysis classified the fabrics better than did those based upon discriminant analysis.

Although the Kawabata and FAST systems dominate the fabric objective measurement market, various alternative or complementary systems have been developed,[15,34] such as a portable system,[34] the Instron,[35] a polymeric human finger sensor (artificial finger), to measure fabric handle and frictional properties,[36,37] as well as a system of on-line measurement of fabric compressional behaviour.[38] Work is also under way to develop a haptic simulation model of fabric forces on the fingers and hand associated with feeling a fabric via highly sensitive touch response transducers,[39] enabling users to evaluate fabric handle without actually touching the fabric.

6.3.2 Typical fabric properties measured in FOM

Compression

Fabric compression normally refers to the difference in fabric thickness under different loads, also termed the thickness of the surface layer and provides a measure of fabric softness or fullness.[40] The surface released thickness, i.e. difference between the surface layer thickness before and after steaming, provides a measure of how stable the fabric finish is.

Dimensional stability

Generally there are the following three main types of dimensional change resulting from changes in the environment:[4]

- relaxation
- hygral
- thermal.

In practice, only the first two are generally considered important and measured.

The stability tests provide a measure of the potential change in fabric dimensions when exposed to changes in moisture, and normally consist of relaxation shrinkage and hygral expansion.[40] During finishing, most fabrics are dried under tension, which is not released until the fabric is exposed to moisture, typically during final pressing, at which stage the fabric undergoes relaxation and returns to its original dimensions, this being termed relaxation shrinkage. Some relaxation shrinkage is beneficial to avoid bubbling in the pleat formation process and to shrink out any residual fullness in the garment during final pressing,[40] while excessive shrinkage creates problems which will be discussed later.

Hygral expansion refers to reversible changes in fabric dimensions when the fabric is exposed to changing moisture, and excessive hygral expansion results in a change in appearance, seam pucker, bubbling and even delamination of fused panels. Excessive hygral expansion can also cause problems in pleating.[40] Problems relating to hygral expansion typically occur when the garments are made under low humidity conditions and then exposed to conditions of high humidity.[40]

Together with relaxation shrinkage, hygral expansion can cause problems with sizing, seam appearance, waviness, pucker, pattern matching at seams and the balance or appearance of the finished garment after making-up and during wear.[41]

Tensile and shear

Fabric tensile, and sometimes also recovery and hysteresis (energy loss) properties, are measured under low deformation forces, these also being used to calculate properties such as deformability.

Low fabric extensibility can lead to difficulties in producing overfeed seams, leading to problems in moulding and seam pucker.[40] High extensibility can lead to the fabric being stretched during laying-up, causing the cut panels to shrink when they are removed from the cutting table, this often being mistaken for relaxation shrinkage. Fusible tape can be used to stabilise fabrics with excessive extensibility. Shear rigidity can be calculated from the bias extensibility, while formability is calculated from the extension at 5 gf/cm and 20 gf/cm, together with fabric bending rigidity, being the product of fabric bending rigidity and initial fabric extensibility.[40] Inadequate warp formability necessitates refinishing of the fabric to increase warp extensibility. For wool fabrics, hygral expansion, relaxation shrinkage and extensibility are often related.

Friction and roughness

A measure of fabric friction and roughness can be obtained by measuring either fabric-against-fabric or fabric-against-metal static and dynamic friction.[40] This property is related to fabric handle.

Bending rigidity

Fabric bending length is generally measured and used to calculate the fabric rigidity. Fabrics with relatively high values of bending rigidity will feel stiffer

but will not generally cause problems in making-up. Fabrics with low values can lead to problems during making-up (tailoring), for example distortion during cutting as well as seam pucker during sewing.[40]

6.3.3 Kawabata system

A detailed description of the Kawabata system and instruments is given in Ref. 42. The Kawabata System for Fabrics (KES-F, later renamed as the KES-FB) consists of the following four instruments[2] (see Figs 6.4 and 6.5 and Table 6.5).

1. *Tensile and shear tester (KES-FB1)*. A tensile test is conducted by clamping the sample between chucks. A shear test is conducted under a constant tension, provided by a dead weight attached to the fabric sample.
2. *Bending tester (KES-FB2)*. A fabric sample is mounted in a vertical plane and a pure curvature is applied to record moment-curvature relationships.

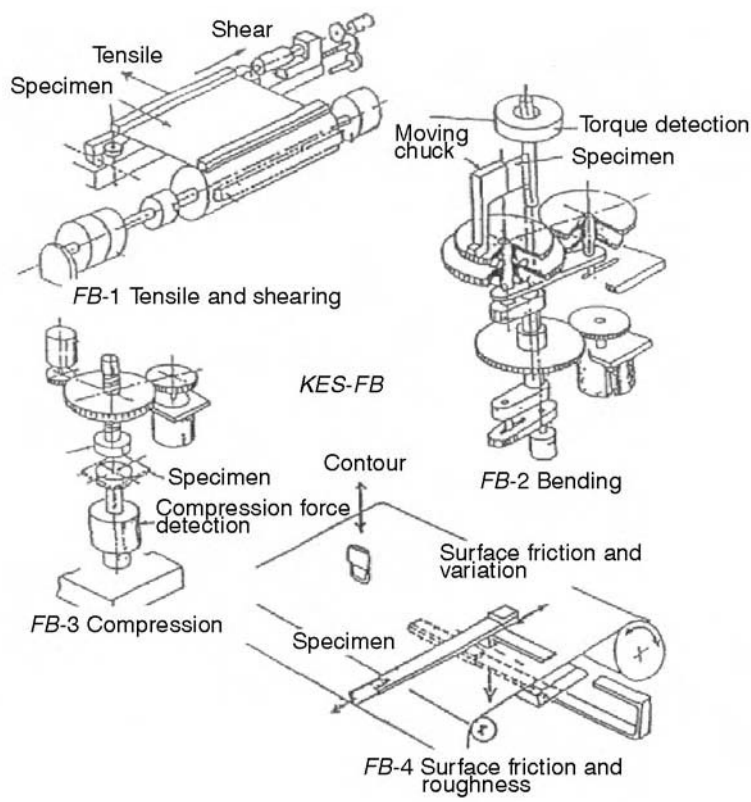


Figure 6.4 The KES-F system for measuring fabric mechanical properties. Source: Kawabata and Niwa, 1991.[43]

3. *Compression tester (KES-FB3).* A fabric sample is compressed in the thickness (lateral) direction, using a compression head, and the load-deformation curve is recorded.
4. *Surface tester (KES-FB4).* Surface roughness and the coefficient of friction are measured using two contact sensors, one for measuring thickness variation and the other for measuring frictional force. The fabric sample is moved, relative to the sensors, under a constant tension.

These instruments can test fabrics automatically and provide continuous stress-strain curves. Load and deformation are measured using sensors and recorded using an *X-Y* plotter.

Figure 6.5 shows the principles used in the measurement of fabric properties by the four KES-F instruments.[24,29] Figure 6.6[29] shows typical graphical outputs (deformation-recovery curves) of the KES-F instruments, which illustrate the non-linearity and hysteresis of the curves, and the need to select the maximum values for the recovery part of the cycle in accordance with the values experienced in the performance of the garment. The hysteresis (losses) of the curves are due to interfibre friction and the visco-elastic properties of the fibres.[24] Typical bending/shear deformations are reversible, i.e. they can be deformed in either direction to give positive or negative curvatures. Tensile deformations are not reversible since the fabric tends to buckle under logitudinal compressive loads. For small deformations, the shear and bending rigidities, as defined by the gradients of the graphs, are linear,[24] these together with hysteresis, being important in determining the ease with which fabrics drape and can be forced into complex three-dimensional shapes without puckering. Hysteresis behaviour is important in terms of fabric resilience or springiness.

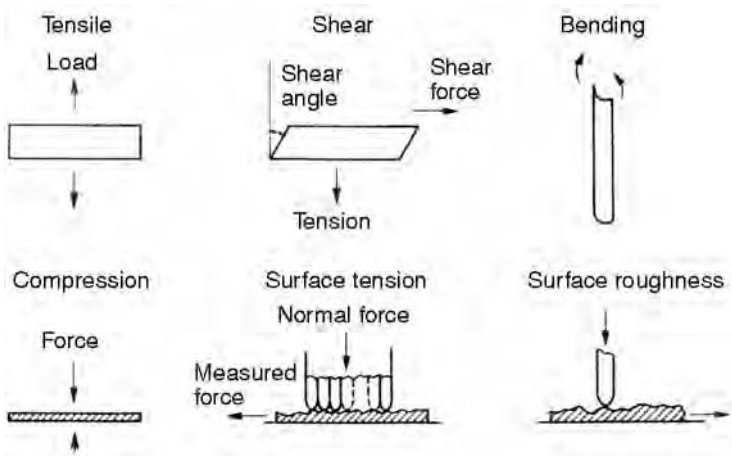


Figure 6.5 Principles used in the KES-F instruments for the objective measurement of fabric mechanical and surface properties. Source: Postle, 1983, 1989.[24,29]

Table 6.5 The sixteen parameters describing fabric mechanical and surface properties

Tensile	(KES-FB1)	LT	Linearity of load/extension curve
		WT	Tensile energy (gf. cm/cm^2)
		RT	Tensile resilience (%)
		EM	Extensibility, strain at 500gf/cm tensile load
Shear	(KES-FB1)	G	Shear rigidity (gf. cm/deg)
		2HG	Hysteresis of shear force at 0.5° shear angle
		2HG5	Hysteresis of shear force at 5° shear angle
Bending	(KES-FB2)	B	Bending rigidity
		2HB	Hysteresis of bending moment
Lateral compression	(KES-FB3)	LC	Linearity of compression/thickness Curve
		WC	Compressional energy (gf. cm/cm^2)
		RC	Compressional resilience (%)
Surface characteristics	(KES-FB4)	MIU	Coefficient of friction
		MMD	Mean deviation of MIU
		SMD	Geometrical roughness (μm)
Fabric construction		W	Fabric weight per unit area (mg/cm^2)
		T_o	Fabric thickness (mm)

Source: Postle, 1983.[24,29]

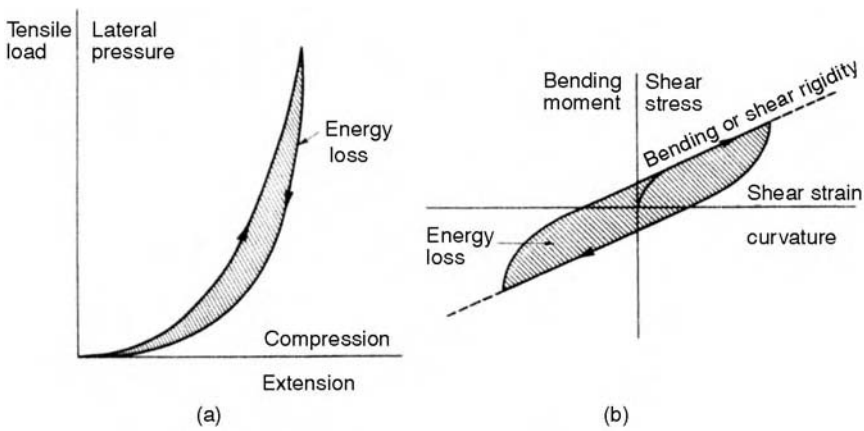


Figure 6.6 Typical deformation-recovery curves for (a) fabric extension or lateral compression, and (b) fabric bending or shear, showing the energy loss during a complete cycle as the shaded area. Source: Postle, 1983.[29]

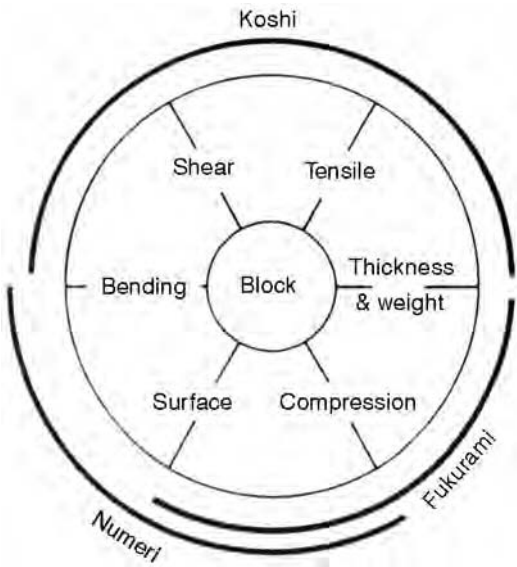


Figure 6.7 Relation between the three primary hands and the mechanical properties. The related properties are covered by a line of the corresponding hand. Source: Hand Evaluation and Standardization Committee, 1972–1975.[31]

The three primary handle values (PHV) arrived at were Koshi (stiffness), Numeri (smoothness) and Fukurami (fullness) and were related to the KES-F measured fabric properties as illustrated in Fig. 6.7, using elaborate statistical analysis. Further handle values, Shari (crispness) and Hari ('anti-drape stiffness') were added for men's summer suitings and women's fabrics (see Table 6.6).

An outcome of the above development is that fabric handle can be objectively graded in terms of the 'Total Handle Value' (THV), and garment (suit) appearance in terms of the Total Appearance Value (TAV).[3] See Fig. 6.8 and Table 6.7[14] for the interpretation of the values, TAV providing a measure of tailorability and drape/suit appearance.

Table 6.6 Primary hands

KOSHI	'Stiffness'	A measure of crispness in bending; springy flexural rigidity
NUMERI	'Smoothness'	A measure of smooth, supple and soft feel
FUKURAMI	'Fullness and softness	A measure of bulk, with springiness in comparison; rich and warm
SHARI	'Crispness'	A measure of a crisp rigid fabric surface, with a cool feel
HARI	'Anti-drape stiffness'	A measure of flare, the opposite of limp conformability

Source: Hearle, 1993.[44]

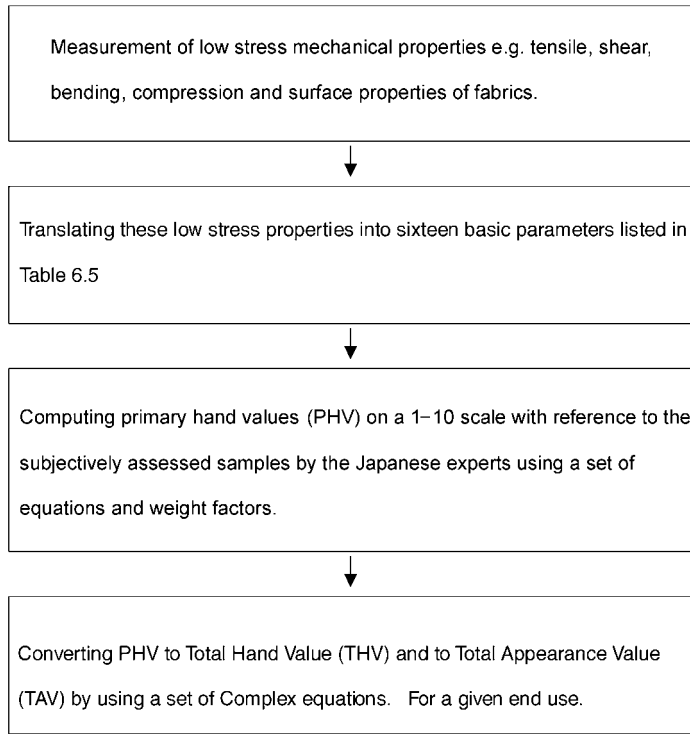


Figure 6.8 Basis of objective evaluation of KES-FB system. Source: Kawabata and Niwa, 1989.[46]

Experience over many years has suggested that the KES-F measurements may be standardised in terms of the 16 parameters listed in Table 6.5:[29] In the Kawabata (KES) system, the quality, tailoring and appearance performance of fabrics can be related to six basic fabric mechanical properties[45] (see Table 6.3). The relationship between KES-F measured properties and tailorability and appearance is illustrated in Tables 6.8, 6.9 and 6.10[46] and Figs 6.9 and 6.10.[47]

Table 6.7 Influence of measured parameters on PHV

PHV	Measurable parameter
Smoothness (Numeri)	Surface, compression and shear
Stiffness (Koshi)	Bending rigidity, weight, thickness, shear and surface
Fullness and softness (Fukurami)	Compression surface, thickness, shear
Crispness (Shari)	Surface, bending and tensile
Antidrape/Spread (Hari)	Shear, surface and bending

Source: Sule and Bardhan, 1999.[13]

Table 6.8 The desirable range of mechanical properties for high-quality suit production

Mechanical parameter	Range for good appearance and good tailorability	Range for especially good appearance
EM_1 (%)	4–6	4–6
EM_2/EM_1 (%)	>1	>2
RT (%)	65–76	72–78
G (gf. cm/deg)	0.5–0.7	0.5–0.7
2HG5 (gf/cm)	0.8–1.7	0.6–1.5

Source: Kawabata and Niwa, 1989.[46]

Table 6.9 The range of mechanical properties for fabric to be rejected

Mechanical parameter	Range for rejection
EM_1 (%)	>9 or <3
EM_2 (%)	<4
2HG5 (gf/cm)	<4

Source: Kawabata and Niwa, 1989.[46]

Mori[48] lists the following requirements for apparel fabrics:

- Relaxation shrinkage of fabric must be less than 2% and hygral expansion less than 7% for both warp and weft directions. Specifications for steam-press shrinkage are also being formulated.

Table 6.10 Interrelation between difficulties in sewing process and ranges of mechanical parameters

Range of parameters	Difficulty predicted in:
LT<0.55 or >0.7	Overfeed operations
RT>70	Cutting process
RT<55	Steam-press operations
LT<0.55 and RT>73 or LT<0.55 and RT <55	Especially difficult in overfeed operations
EM_1<3 or >8	Overfeed operations
EM,>5	Cutting operations
EM_2<4	Overfeed operations
EM_2/EM_1>3	Sewing operations and steam-press operations
G<0.6 or >0.95	Overfeed operations
2HG5>3	Overfeed operations

Source: Kawabara and Niwa, 1989.[46]

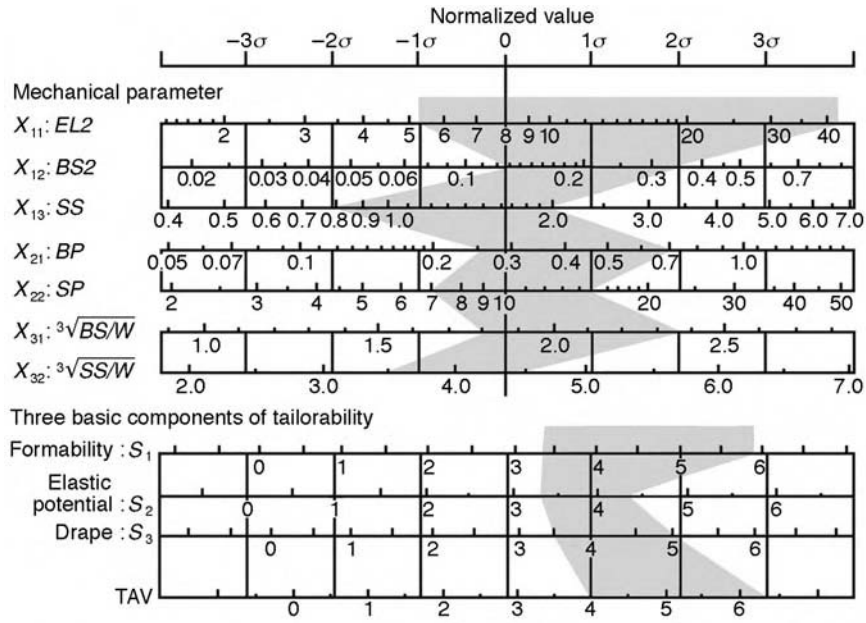


Figure 6.9 High TAV zone for suit expressed by the three components. Source: Kawabata and Niwa, 1994.[47]

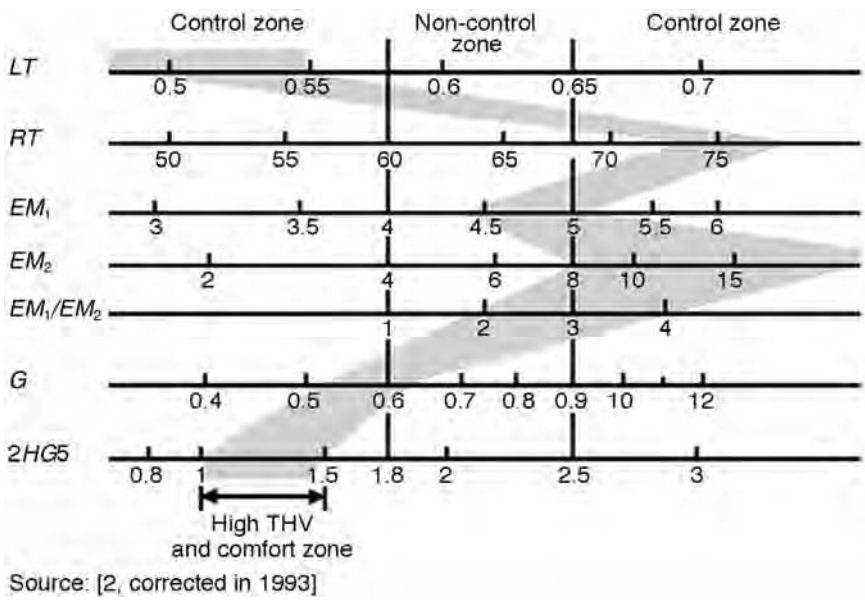


Figure 6.10 'Tailoring Control Chart' and high quality zone from wear comfort. Source: Kawabata and Niwa, 1994.[47]

- Extensibility of polyester/wool/mohair blended fabrics for summer suits should be greater than 4% (KES-F, standard testing condition) in the weft direction (EM2 $\geq$ 4%).
- The extensibility of wool gaberdine, polyester/wool tussah and polyester/wool tropical must be between 4% and 8% in the warp direction (4% $\leq$ EM1 $\leq$ 8%).
- Shear hysteresis (at shear angle 5º) must be less than 2.5 gf/cm (KES-F, standard testing condition) for suit and jacket fabrics (2HG5 $\leq$ 2.5 gf/cm).

Furthermore, the criteria for high-quality fabrics, termed ideal fabrics, were created. It is now required to inter-link fibre science to enable a more accurate engineering design of fabrics (see Fig. 6.2). The test results from the Kawabata system, although primarily aimed at defining handle, will show which fabrics will go through a clothing factory easily and efficiently, which will need special care, with indicated adjustments of machine settings and which will cause serious problems.[44]

Kawabata and Niwa[5] stated that an ideal suiting fabric should satisfy the following three conditions:

1. Good handle (high THV)
2. Good suit appearance (high TAV)
3. Mechanical comfort conditions (shaded zone on control chart)

For example, warp and weft extension at a load of 500 g/cm should preferably be 4% or higher for wool fabrics.

Table 6.11 gives the proposed criteria which a fabric needs to satisfy if it is to be considered a 'perfect' or 'ideal' fabric.[5]

Table 6.11 The criteria for ideal fabric

	Type of suiting		Remarks
	Winter-autumn	Mid-summer	
1 Total Hand Value (THV)	*THV* $\geq$ *4.0*	*THV* $\geq$ *3.5*	*THV:* 1 (poor)–5 (excellent)
2 Total Appearance Value (TAV)	*TAV* $\geq$ 4.0	TAV $\geq$ *4.0*	*TAV:* 1 (poor)–5 (excellent)
3 Mechanical comfort (must be inside the snake zone)	0.58$\geq$ LT$\geq$0.50 78$\geq$RT$\geq$73 5.1$\geq$$EM_1$$\geq$4.3 18$\geq$$EM_2$$\geq$7.5 3.0$\geq$EM2/EM1$\geq$1.3 0.65$\geq$G$\geq$0.50 1.5$\geq$2HG5$\geq$0.8	0.60$\geq$ LT$\geq$0.50 78$\geq$RT$\geq$73 5.1$\geq$$EM_1$$\geq$4.3 18$\geq$$EM_2$$\geq$7.5 3.0$\geq$EM2/EM1$\geq$1.3 0.65$\geq$G$\geq$0.50 1.5$\geq$2HG5$\geq$0.8	LT: Average of LT_1 and LT_2 RT: Average of RT_1 and RT_2

Suffix 1; warp direction, 2; weft direction
Source: Kawabata and Niwa, 1998[5]

Shishoo[49] also presents a table indicating the relationship between KES measured mechanical properties and tailoring properties. The KES system is also able to distinguish differences in finish, for example differences between classes of silicone finishes[50] on polyester/cotton fabrics, and has been applied to evaluating the quality of ladies' garments.[51]

Chen *et al.*[52] used a method of fuzzy comprehensive evaluation to solve the problem of grading fabric softness as a measure on the Kawabata KES-FB instruments. Based upon the KES-FB measurements, Chen *et al.*[53] proposed a neural network computing technique to predict fabric end use.

6.3.4 FAST system

The Fabric Assurance by Simple Testing (FAST) system was developed in the 1980s by the CSIRO Division of Wool Technology, Australia, as a simpler alternative to the more sophisticated Kawabata system, and consists of three individual instruments (FAST-1, FAST-2 and FAST-3)[2] as well as a test method (FAST-4). The FAST instruments are similar in operation to conventional measuring instruments, except that measurement is carried out using sensors, and the test results are displayed digitally.

FAST-1
Compression meter (FAST-1), measures:

- fabric thickness (T)
- fabric surface thickness ($ST = T_2 - T_{100}$)
- released (relaxed) surface thickness.

The compression meter[54] measures the thickness of fabrics at two loads 2 gf/cm^2 (0.196 kPa) and 100 gf/cm^2 (9.81 kPa). This allows the calculation of the fabric surface thickness, the difference in thickness between the two loads which is a measure of the amount of compressible fibre or pile on the surface of the fabric and can be used to ascertain the extent and consistency of fabric surface processes, such as singeing, cropping, raising, pressing, etc. A further measurement of the fabric surface thickness, after release in steam (or even water), provides a measure of the stability of the finish of the fabric; the larger the difference, the less stable the finish. This measurement is important in determining the extent of subsequent changes in appearance and handle of the fabric after garment pressing and can indicate the potential re-emergence of such things as running marks.[54]

FAST-2
Bending meter (FAST-2), measures:

- bending length (BL in mm – measured at an angle of 41.5º)

- bending rigidity (BR in μN/m) = $9.8 \times 10^{-6}\ W\ (BL)^3$
  (where W = fabric weight (g/m^2)).

The bending meter measures[54] the bending length of fabric from which the bending rigidity can be calculated. This is an important property for the handle of the fabric and also influences the cutting performance and the ease with which the fabric can be processed by automated handling equipment.[54] Too stiff a fabric can lead to problems in moulding the fabric, whereas too limp a fabric can be difficult to cut as it will easily distort and can also lead to seam pucker.

FAST-3

Extension meter (FAST-3), measures:

- warp extensibility
- weft extensibility
- bias (45º) extensibility
- shear rigidity (N/m) = 123/EB5 (% bias extension).

The extension meter[54] measures the extensibility of the fabric at three loads, 5 gf/cm (4.9 N/m), 20 gf/cm (19.6 N/m) and 100 gf/cm (98.1 N/m), in the warp and weft direction to indicate potential problems in the laying up of the fabric and in seams that require overfeed. This information is also combined with the bending rigidity to determine the fabric 'formability' which is a measure of the fabric's propensity to pucker when it is compressed along seams, a possibility along with seam blowing, when formability is low. The extensibility is also measured on samples that are cut on the bias (45º to the warp) to determine fabric shear rigidity. This measurement indicates potential problems in laying up and in the fabric's ability to form smooth three-dimensional shapes, such as are needed around the sleeve head and shoulder region in a structured jacket.[54] Low shear rigidity indicates that the fabric will be easily distorted in laying up, marking and cutting, whereas a high value indicates that the fabric will be difficult to form into smooth three-dimensional shapes, causing problems in moulding and sleeve insertion. Too low a shear rigidity could indicate that the fabric will be difficult to lay up and may require pinning, whereas too high a value could indicate problems with moulding the fabric and inserting sleeves. Low extensibility can lead to difficulties in producing overfeed seams, problems in moulding and seam pucker. High extensibility can lead to the fabric being stretched during laying up, causing the fabric panels to shrink when removed from the cutting table.

FAST-4

Dimensional stability test method (FAST-4), measures:

- relaxation shrinkage (RS) = $(L_o - L_D)/L_o$
- hygral expansion (HE) = $(L_w - L_D)/L_D$

where L_o = the original length, L_D = the dried length, and L_W = the relaxed length in water.

The dimensional stability test enables both the relaxation shrinkage and the hygral expansion of the fabric to be determined.[54] Relaxation shrinkage is the once only change in fabric dimensions associated with the release of strains set up in the fabric during spinning, weaving and finishing (e.g. if a fabric is dried under a high tension during finishing). This change can be brought on by exposure of the fabric to steam, water or high humidity. Depending upon which stage during garment manufacture this change manifests itself, the problem can range from one of incorrect sizing to poor appearance on and around fusibles and seams. This is also a critical fabric property for processes, such as pleating, where there are certain minimum requirements for sharp, smooth pleats.

Hygral expansion is the reversible change in fabric dimensions associated with the absorption and desorption of moisture by hygroscopic fibres such as wool. The appearance of garments can deteriorate when exposed to high humidity if the hygral expansion is high, especially those that were made up under conditions of low relative humidity.[54]

From the above measured properties, other properties, such as 'formability' ($F(mm^2)$ = BR (E2O − E5)/14.7) and 'finish stability', can be calculated. For example, if the ratio of surface thickness after and before relaxation is over 2.0, it indicates improper finishing or 'definishing'.[13] Formability (compressibility × bending rigidity or extensibility at low loads × bending rigidity, the latter being used on the FAST) is a measure of the ability of fabric to accommodate 'in-plane' compression without buckling, such as that encountered during tailoring, and is a direct measure of seam puckering, low formability indicating a tendency to pucker.

Table 6.12 Summary of CSIRO's FAST system

Instrument and test	Measures	Predicts problems in:
FAST-1	Thickness	Pressing
	Compression	Finish stability
FAST-2	Bending	Cutting, automated handling
FAST-3	Extensibility	Laying up, pattern matching, overfed seams, moulding
	Shear	Laying up, moulding, sleeve insertion
FAST-2 & 3	Formability	Seam pucker
FAST-4	Relaxation shrinkage	Size, seam pucker and pleating
	Hygral expansion	Looks, pleating

Source: Sule and Bardhan, 1999.[13]

Table 6.13 Fabric properties associated with problems in garment making

Property	Potential problem
Low relaxation shrinkage	Bubbling of fused panels
	Delamination of fused panels
	Bubbling in pleating
	Difficulty shrinking out fullness
High relaxation shrinkage	Excessive fusing press shrinkage
	Excessive steam press shrinkage
	Variation in size of cut panels
Excessive hygral expansion	Excessive shrinkage during manufacture
	Bubbling of fused panels
	Bubbling of pleated panels
Low formability	Difficulty in sleeve setting
Low extensibility	Difficulty with sewing overfed seam
	Difficulty in pressing
	Difficulty shrinking out fullness
High extensibility	Difficulty matching checks
	Difficulty sewing unsupported seams
	(Warp) Easy to stretch in laying up leading to shrinkage problems
Low bending rigidity	Difficult to cut and sew
	Automated handling problems
High bending rigidity	Difficult to mould and press
Low shear rigidity	Easy to distort in laying up, marking and cutting
High shear rigidity	Difficulty in garment moulding
	Difficult to form smooth 3D shapes

Source: Anon.[56]

Table 6.14 Fabric properties associated with potential poor garment appearance in wear

Property	Potential problem
Low relaxation shrinkage	Bubbling/waviness in fused panels
	Delamination of fused panels
	Seam pucker
High relaxation shrinkage	Size variation
	Seam pucker
Excessive hygral expansion	Bubbling/waviness in fused panels
	Poor shape retention
	Seam pucker
Low formability	Puckering of seams
	Difficulty in pressing
Low bending rigidity	Poor shape retention
	Soft drape of sleeves
Low shear rigidity	Poor garment shape retention
	Soft drape of sleeves
Excessive increase in surface thickness	Poor appearance retention (fabric)
	Re-emergence of running marks or cracking and distortion of fabric

Source: Anon.[56]

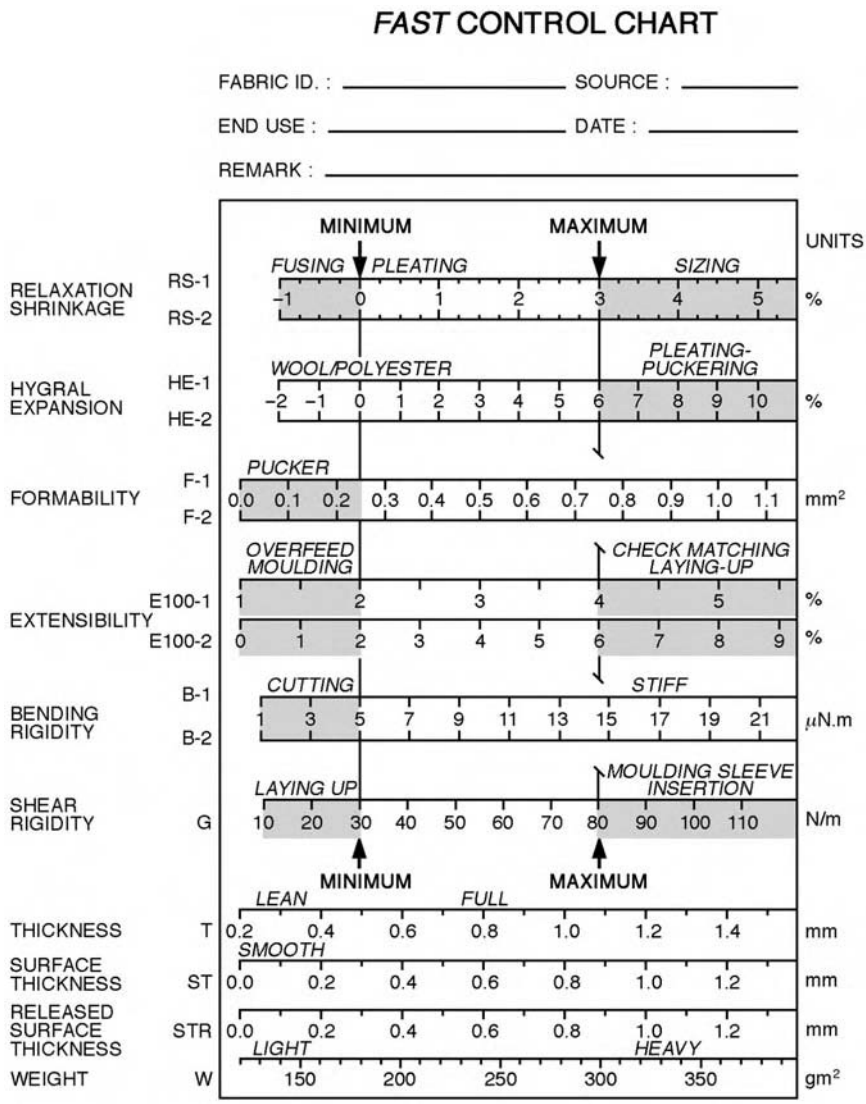


Figure 6.11 The FAST control chart for light-weight suiting fabrics. Source: Anon.[57]

In addition to the above properties, 'seam pressing performance' (PP) can also be predicted, using the crease pressing performance test which involves inserting a crease in a sample and then measuring the recovery of the crease under standard atmospheric conditions. It enables the propensity of a fabric to produce blown seams (i.e. seams which do not remain flat) after pressing, to be predicted.[55]

Table 6.12[13] provides a summary of the FAST system. Table 6.13 summarises the FAST fabric properties associated with problems in garment

making[56] while Table 6.14 lists those FAST fabric properties associated with potentially poor garment appearance.[56] Figure 6.11 shows the FAST control chart on which measured fabric properties are plotted as a 'fingerprint', for easy diagnosis and corrective action.

6.4 References

1 Hearle J W S, 'Can fabric hand enter the dataspace', *Tex. Horizons Int*, April, 1993 **13**(2) 14–16.
2 Potluri P, Porat I and Atkinson J, 'Towards automated testing of fabrics', *Int J Cloth Sci Technol*, 1995 **7**(2/3) 11.
3 Kawabata S, 'Fabric quality desubjectivised', *Text Asia*, July, 2000 **31**(7) 30–32.
4 De Boos A G, 'The objective measurement of finished fabric', in Brady, P R (ed.), *Finishing and wool fabric properties, A guide to the theory and practice of finishing woven wool fabrics*, CSIRO, IWS, 1997, 44.
5 Kawabata S and Niwa M, 'Influence of fibre process parameters on product performance', *Proc Fibres to Finished Fabrics, Fibre Science/Dyeing & Finishing Groups Joint Conf*., The Textile Institute, Dec., 1998, 1.
6 Matsuo T and Suresh M N, 'The design logic of textile products', *Text Progr*, 1997 **27**(3).
7 Laing R M and Sleivert G G, 'Clothing, textiles and human performance', *Text Progr*, 2002 **32**(2).
8 Bajaj P and Sengupta A K, 'Protective clothing', *Text Progr*, 1990 **22**(2/3/4).
9 Ukponmwan J O, 'The thermal-insulation properties of fabrics', *Text Progr*, 1992 **24**(4).
10 Li Y, 'Science of clothing comfort', *Text Progr*, 1999 **31**(1/2).
11 Le Pechoux B and Ghosh T K, 'Apparel sizing and fit', *Text Progr*, 2002 **32**(1).
12 Bishop D P, 'Fabrics: Sensory mechanical properties', *Text Progr*, 1996 **26**(3).
13 Sule A D and Bardhan M K, 'Objective evaluation of feel and handle, appearance and tailorability of fabrics, Part I: The FAST system of CSIRO', *Colourage*, **46**(9) 19–26.
14 Sule A D and Bardhan M K, 'Objective evaluation of feel and handle, appearance and tailorability of fabrics, Part II: The KES-FB system of Kawabata', *Colourage*, 1999 **46**(12) 23.
15 Sule A D and Bardhan M K, 'Objective evaluation of feel and handle, appearance and tailorability of fabrics, Part III: Critical review of work done during the past two decades', *Colourage*, 2000 **47**(9) 29.
16 Smuts S, Lee J and Hunter L, 'A review of fabric objective measurement', *TexReport, No. 3*, Division of Textile Technology, CSIR, Port Elizabeth, 1991.
17 Kularni S G, 'Fabrics and tailorability', *Indian Text J*, Sept., 1998 **108**(12) 22.
18 Postle R, 'Fabric objective measurement: 3, Assessment of fabric quality attributes', *Text Asia*, July, 1989 **20**(7) 72.
19 Harlock S C, 'Fabric objective measurement: 4, Production control in apparel manufacture', *Text Asia*, 1989 **20**(7) 89.
20 Curiskis J I, 'Fabric objective measurement: 5, Production control in textile manufacture', *Text Asia*, 1989 **20**(10) 42–59.
21 Postle R, 'Fabric objective measurement: 6, Product development and implementation', *Text Asia*, 1989 **20**(10) 59.

22 Curiskis J I, 'Fabric objective measurement: 7, Summary and conclusions', *Text Asia*, 1989 **20**(11) 55–61.
23 Postle R, 'Fabric objective measurement: 1, Historical background and development', *Text Asia*, 1989 **20**(7) 64.
24 Harlock S C, 'Fabric objective measurement: 2, Principles of measurement', *Text Asia*, 1989 **20**(7) 66.
25 Geršak J, 'A system for prediction of fabric appearance', *Text Asia*, 2002 **33**(4) 31.
26 Cardello A V and Winterhalter C, 'Predicting the handle and comfort of military clothing fabrics from sensory and instrumental data: Development. application of new psychophysical methods', *Text Res J*, 2003 **73**(3) 221–237.
27 Hearle J W S, Potluri P and Thammandra V S, 'Modelling fabric mechanics', *J Text Inst*, 2001 **92** Part 3 53.
28 Niwa M, 'Clothing science, the way ahead', *Text Asia*, 2002 **31**(2) 27.
29 Postle R, 'Objective evaluation of the mechanical properties and performance of fabrics and clothing', in *Objective evaluation of apparel fabrics*, p1 R. Postle, S. Kawabata and M. Niwa, eds, *Proc 2nd Australia-Japan Symp,* Melbourne, 1983, *Text. Mac. Soc. Japan*, Osaka, 1983.
30 Peirce F T, 'The handle of cloth as a measurable quantity', *J Text Inst*, 1930 **21** T377.
31 'Hand evaluation and standardization comm.', *H.E.S.C. Techn Rep*, No. 1 – No. 30, *Text Mach Soc Japan*, 1972–1975.
32 Kawabata S and Niwa M, 'Analysis of hand evaluation of wool fabrics for men's suit using data of thousand samples and computation of hand from the physical properties', *Proc 5th Int Wool Text Res Conf*, **V**, 413, Aachen 1975.
33 Lai S-S, Shyr T-W and Lin J-Y, 'Comparison between KES-FB and FAST in discrimination of fabric characteristics', *J Text Eng*, 2002 **48**(2) 43.
34 Fan J, Gardiner I V and Hunter L, 'A portable tester for nondestructively measuring fabric properties', *Text Res J*, 2002 **72** 21–26.
35 Pan N, Zeronian S H, and Ryu H-S, 'An alternative approach to the objective measurement of fabrics', *Text Res J*, 1993 **63** 33–43.
36 Ramkumar S S, 'Artificial finger can measure fabric's hand', *Int Fiber J*, 2000 **15**(6) 88.
37 Ramkumar S S, Wood D J, Fox K and Harlock S C, 'Developing a polymeric human finger sensor to study the frictional properties of textiles, Part I: Artificial finger development', *Text Res J*, 2003 **73** 469 and 'Part II: Experimental Results', *Text Res J*, 2003 **73** 606.
38 Huang W and Ghosh T K, 'Online characterization of fabric compressional behavior', *Text Res J*, 2002 **72** 103–112.
39 Govindaraj M, Pastore C, Raheja A and Metaxas D, 'Haptic simulation of fabric hand', *National Tex Center Res Briefs*: S00-PHO8, June 2002.
40 Basu A, 'Fabric objective measurement for garment industries', *Indian Text J*, April, 2002 **112** 29.
41 Wemyss A M and White M A, 'Observations on relationships between hygral expansion, set and fabric structure, objective measurement: Applications to product design and process control', in S. Kawabata, R. Postle and M. Niwa (eds), *Proc 3rd Japan-Australia Joint Symp*, Kyoto Sept., 1985, p.165.
42 Kawabata S, *The Standardisation and Analysis of Hand Evaluation*, 2nd edition, Hand evaluation and standardisation committee, *Text Mach Soc Japan*, Osaka 1980.

43 Kawabata S and Niwa M, 'Objective measurement of fabric mechanical property and quality', *Int J Cloth Sci Technol*, 1991 **3**(1) 7.
44 Hearle J W S, 'Can fabric hand enter the dataspace? Part II: Measuring the unmeasurable?' *Text Horizons, Int.*, June, 1993 **13** 16.
45 Behera B K and Hari P K, 'Fabric quality evaluation by objective measurement, *Indian J Fibre Text Res*, 1994 **19** 168–171.
46 Kawabata S and Niwa M, 'Fabric performance in clothing and clothing manufacture', *J Text Inst*, 1989 **80** 19.
47 Kawabata S and Niwa M, 'High quality fabrics for garments', *Int J Cloth Sci Technol*, 1994 **6**(5) 20.
48 Mori M, 'Fabric design and production on the basis of objective measurement of fabric mechanical properties in co-operation with apparel company engineers', in R. Postle, S. Kawabata and M. Niwa (eds), *Proc 2nd Australia-Japan Symp*, Melbourne 1983, p. 55.
49 Shishoo R L, 'Evaluation of fabrics', *Text Asia*, 1991 **22**(8) 102.
50 Sabia A J and Pagliughi A M, 'The use of Kawabata instrumentation to evaluate silicone fabric softeners', *Text Chem Col*, 1987 **19**(3) 25.
51 Kawabata S and Niwa M, 'Objective evaluation of the quality of ladies' garments', *Int J Cloth Sci Technol*, 1992 **4**(5) 34.
52 Chen Y, Collier B, Hu P and Quebedeaux D, 'Objective evaluation of fabric softness', *Text Res J*, 2000 **70** 443.
53 Chen Y, Zhao T and Collier B J, 'Prediction of fabric end-use using a neural network technique', *J Text Inst*, 2001 **92** Part I 157.
54 Tester D H and De Boos A G, *FAST fabrics, a report on how a new method of Fabric Objective Measurement (FAST) can provide the garment maker with a surer method of predicting the tailoring performance of fabrics*, CSIRO Division of Wool Technology.
55 Minazio P G, 'FAST – Fabric assurance by simple testing', *Int J Cloth Sci,Technol*, 1995 **7**(2/3) 43.
56 Anon, '5. Garment manufacturing and appearance problems associated with fabric properties', *FAST User's Manual*, p. 17.
57 Anon, *FAST Instruction Manual*, CSIRO Division of Wool Technology, Australia.

7

Garment drape

L HUNTER AND J FAN

7.1 Introduction

The outstanding property of a textile fabric, which distinguishes it from other materials, such as paper or steel, is its ability to undergo large, recoverable draping deformation by buckling gracefully into rounded folds of single and double curvature.[1] According to the *Textile Terms and Definitions* of the Textile Institute,[2] drape is defined as 'The ability of a fabric to hang limply in graceful folds, e.g. the sinusoidal-type folds of a curtain or skirt'. It refers to the fabric shape as it hangs under its own weight. Cusick[3] defined the drape of a fabric as 'a deformation of the fabric produced by gravity when only part of the fabric is directly supported'.

Drape is an important component of the aesthetic appearance and appeal of garments, and also plays a crucial role in garment comfort and fit. Drape appearance depends not only on the way the fabric hangs in folds, etc., but also upon the visual effects of light, shade and fabric lustre at the rounded folds of the fabric as well as on the visual effects of folding on colour, design and surface decoration.[4] A fabric is said to have good draping qualities when it adjusts into folds or pleats under the action of gravity in a manner which is graceful and pleasing to the eye.[5] In practice, drape is usually assessed visually, or subjectively, and the actual assessment greatly depends upon such factors as fashion, personal preference, human perception, etc.

Drape is therefore a complex combination of fabric mechanical and optical properties and of subjectively and objectively assessed properties. Furthermore, there is frequently an element of movement, for example, the swirling movement of a skirt or dress, and therefore dynamic, as opposed to static, properties are also involved. In recent years, therefore, a distinction has been made between static and dynamic drape.

7.2 Reviews on drape

Jacob and Subramaniam[6] and Hu and Chan[7] have briefly reviewed published work on drape. Subramaniam[8,9] undertook thorough reviews of the published

work on fabric bending and drape, and in 1983 Subramanian *et al.*[10] also reviewed published work on fabric shearing properties which play an important role in fabric drape.

7.3 The measurement of fabric drape

Although drape is usually assessed subjectively, considerable research has been carried out with a view to its objective measurement, and to relate the drape, so measured, to objectively measure fabric mechanical properties, notably bending and shear stiffness.

Initially, because of the large effect of bending stiffness on drape, instruments were designed to measure fabric bending length (the length of fabric which bends to a definite extent under its own weight), which provided a fairly good measure of the fabric draping properties, more particularly of the two-dimensional (2D) drape, as opposed to the three-dimensional (3D) drape which occurs in practice. Considerable work has been carried out in this field and a number of instruments have been developed and marketed for this purpose. 2D drape tests (cantilever method) cannot, however, accurately reflect fabric drape, since the latter involves three-dimensional double curvature deformations. Therefore, to better quantify the latter, various objective measurement techniques have been designed to simulate the subjective methods (e.g. laying the fabric over a pedestal or mannequin, allowing the fabric to fall naturally into folds and assessing the size and frequency of the folds). The most widely adopted method is to allow a circular disc of fabric to drape into folds around the edges of a smaller circular platform or template. Such instruments are commonly referred to as 'drapemeters'.

The more realistic and practical determination of drape took a great step forward with the development of an instrument, termed a drapemeter, for measuring three-dimensional drape. This was largely the consequence of the pioneering work of Chu *et al.*[11] who developed a method of measuring drape by means of the F.R.L. Drapemeter, quantifying drape as a dimensionless drape coefficient (DC%). Cusick[3,12] subsequently developed what has become known as Cusick's drapemeter (Fig. 7.1)[13] and which has become the standard method of measuring drape coefficient. It uses a parallel light source which causes the shape of the draped fabric to be projected onto a circular paper disc. The drape of a fabric is popularly defined as the area of the annular ring covered by the vertical projection of the draped fabric expressed as a percentage of the area of the flat annular ring of fabric, this being termed the drape coefficient.[3] In practice, the contour of the shadow is often traced onto the paper and cut out for weighing.[14] Cusick[14] defined the drape coefficient (DC%) as the weight of the paper of the drape shadow (W_2) expressed as a percentage of the paper weight (W_1) of the area of the full annular ring (Fig. 7.2).

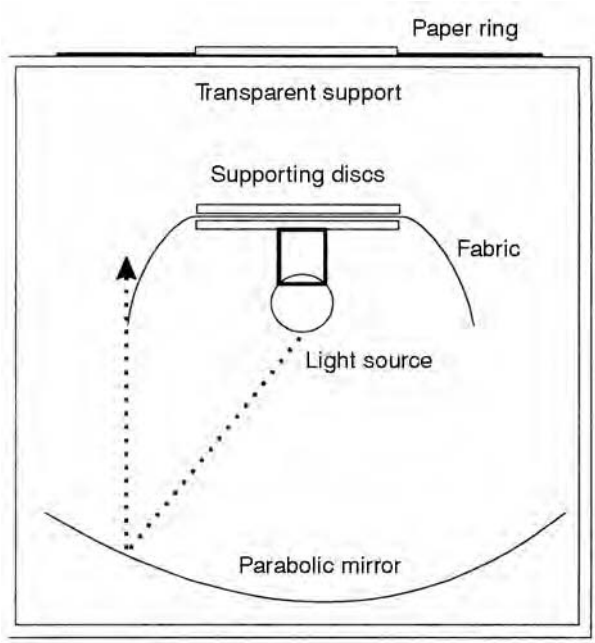


Figure 7.1 Cusick's Drapemeter. Source: Chung 1999.[13]

$$DC\% = \frac{W_2}{W_1} \times 100 \tag{7.1}$$

A measure of 100% on this instrument, which is widely used even today, indicates a completely rigid (stiff) fabric while a value of 0% represents a completely limp fabric, the values in practice ranging from about 30% for a loose, open weave rayon fabric to about 90% for a starched cotton gingham, and about 95% for stiff nonwovens.[7]

Since different template sizes can be used, which influence the drape coefficient, the diameter of the template must be given together with the drape result. Ideally, the template size should be such that the measured drape coefficient

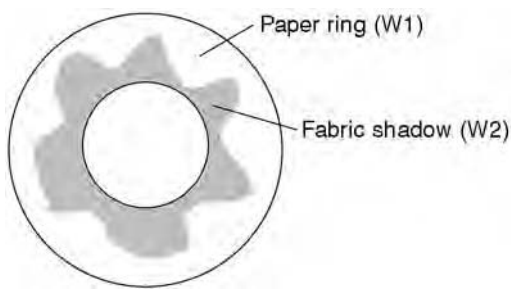


Figure 7.2 Drape image. Source: Chung 1999.[13]

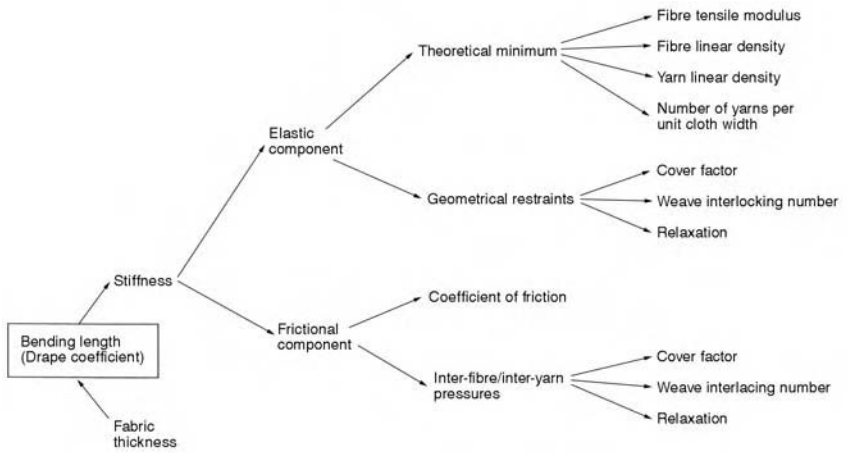


Figure 7.3 Some factors contributing to fabric drape behaviour. Direction of arrows indicates whether an increase or decrease in a given parameter will produce an increase in the drape coefficient of the fabric. Source: Anon, 1981.[15]

falls between 40 and 70%. Some of the factors contributing to fabric drape are shown in Fig. 7.3.[15]

Typical examples of 'drapemeters' include that of Cusick, F.R.L., I.T.F. and the M.I.T. Drape-O-Meter. Other principles of measuring drape include the force to pull a circular fabric sample at a constant speed through a ring, the force being termed the 'drape resistance' of the fabric. Collier[16] developed a digital drapemeter. Matsudaira *et al.*[17] used an image analysis system (Fig. 7.4) to measure static and dynamic drape. Vangheluwe and Kiekens[18] also used image analysis (video digital camera and computer-based image processing system) to measure the drape coefficient, while Stylios *et al.*[19] developed the next generation of drapemeters, enabling 3D static and dynamic drape to be measured by means of a CCD camera as a vision sensor. Image analysis enables many measurements to be made in a relatively short time.

7.4 Empirical prediction of static drape

Various empirical studies have attempted to identify those fabric properties which affect drape coefficient and to quantify the effects by means of regression equations and other analytical techniques.

One of the earliest studies on fabric drape is that of Peirce.[20] Initial studies demonstrated the dominant role of fabric stiffness on drape, with fabric weight also playing a role, though a lesser one. For example, Chu *et al.*[11] showed that drape depended upon three basic fabric properties, namely Young's Modulus (Y), cross-sectional moment of inertia (I) and fabric weight (W) (drape coeff. $= f(B/W)$, where $B = YI$). Later studies demonstrated the effect of fabric shear

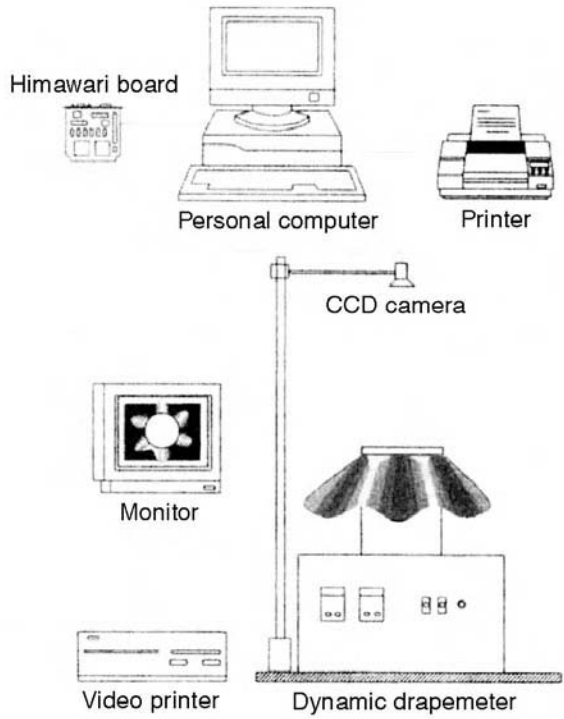


Figure 7.4 An image analysis system for measuring static and dynamic drape behaviour of fabrics. Source: Matsudaira *et al.*, 2002.[17]

on drape. For example, Cusick[3,14] demonstrated, both theoretically and experimentally, the effect of shear stiffness on drape, deriving the following empirical equation relating drape coefficient to bending length and shear angle, 'shearing' being the deformation which results in a flat fabric when opposing forces act parallel to each other (shear stiffness being the shear angle at which a fabric begins to buckle):

$$DC = 35.6C - 3.61C^2 - 2.59A + 0.0461A^2 + 17.0 \qquad (7.2)$$

where DC = the drape coefficient, C = the bending length measured with the Shirley Stiffness Tester and obtained from $C = \frac{1}{4}(C_1 + C_2 + 2C_b)$, where C_1 = is bending length in the weft direction; C_2 = bending length in the warp direction; C_b = bending length in the bias (45%) direction; and A = the shearing angle at a shearing stiffness value of 2g wt. cm/cm^2.

Table 7.1 gives drape coefficients given by Sudnik,[21] using an improved version of Cusick's drapemeter. Sudnik also concluded that the optimum drape coefficient depends upon fashion and end-use.

Table 7.1 Drape coefficients (%)

End use	Template A (24)	Template B (30)	Template C (36)
Lingerie	<80	<40	<20
Underwear	65–90	30–60	15–30
Dresswear	80–95	40–75	20–50
Suitings	90–95	65–80	35–60
Workwear, rainwear	>95	75–95	50–85
Industrial	>95	>95	>85

Source: Sudnik[21]

Kim and Vaughn[22] showed that drape was not so much affected by the fabric weight, but had a closer relationship with the fabric bending, shearing and tensile parameters.

Tanabe *et al.*[23] used multiple-variance regression analysis to show that drape coefficient is affected by fabric bending modulus (B), bending hysteresis (HB) and weight (W), the correlation being increased by introducing the anisotropy of the bending properties into the regression equation. Using photographs of draped fabrics varying greatly in drape coefficient, Suda and Ohira[24] concluded that the drapeability of fabrics of equal drape coefficient can be determined visually and that it was easiest to do so with fabrics having a drape coefficient of around 30%.

Using the F.R.L. Drapemeter, Morooka and Niwa[25] derived the following empirical equation relating fabric drape to KES parameters, finding that fabric weight and bending modulus were the most important parameters.

$$DC = 5.1 + 115.0\sqrt[3]{\frac{B_{90}}{W}} + 131.1\sqrt[3]{\frac{B_o}{W}} + 1.2\sqrt[3]{\frac{B_{45}}{W}} \tag{7.3}$$

where: W = fabric weight per unit area (mg/cm^2)
B_{90} = bending rigidity (gf. cm^2/cm) in the warp direction
B_o = bending rigidity (gf. cm^2/cm) in the weft direction
B_{45} = bending rigidity (gf. cm^2/cm) in the bias direction
DC = drape coefficient.

According to Sudnik,[26] drape is affected by the fabric flexural rigidity (or stiffness), i.e. the elastic component, as well as by the frictional couple (i.e. nonelastic component), the latter being partly dependent upon the amount of shear.

Gaucher[27] found that, for the weft and warp knitted fabrics they investigated, bending length, thickness and secondary shear modulus played the main role in determining drape. Using a theoretical approach, Hearle and Amirbayat[28] showed that a more complicated relationship existed between fabric drape coefficient and mechanical properties, possibly involving anisotropic in-plane

and out-of-plane bending, cross-term elastic constants and nonlinearity of response. They related the fabric geometric form to two dimensionless energy groups J_1 and J_2, where, in terms of material properties:

$$J_2 = Y\ell^2/B \text{ and } J_2 = W\ell^3/B \tag{7.4}$$

where: B = bending stiffness
W = fabric weight
Y = fabric membrane modulus and
ℓ = the characteristic length defining the size of the material.

The more generalised expression is:

$$DC = f(J_1, J_2, \pi_3\pi_4\pi_5) \tag{7.5}$$

where: DC = drape coefficient
$\pi_3 = G/Y$
$\pi_4 = T/B$
$\pi_5 = \mu$, where G, T and μ, respectively, are the overall shear modulus, overall torsional rigidity and overall Poisson's ratio from all directions.

Niwa and Seto[29] introduced bending and shear hysteresis into the relationship, relating drape coefficent to mechanical properties as follows:

$$DC = b_o + b_1\sqrt[3]{\frac{B}{W}} + b_2\sqrt[3]{\frac{2HB}{W}} + b_3\sqrt[3]{\frac{G}{W}} + b_4\sqrt[3]{\frac{2HG}{W}} \tag{7.6}$$

where: DC = drape coefficient
b_1 to b_3 are constants
B = bending rigidity
$2HB$ = bending hysteresis
W = fabric weight per unit area
G = shear stiffness
$2HG$ = shear hysteresis.

Collier and Collier[16,30] also demonstrated the importance of shear hysteresis in determining the drape coefficient.

Hu and Chan[7] related the Cusick drapemeter drape coeffient to the KES-F mechanical properties, finding logarithmic regression equations, of the form:

$$DC = b_o + \sum_{i=1}^{n} b_i \ln x_i \tag{7.7}$$

or

$$\ln DC = b_o + \sum_{i=1}^{n} b_i \ln x_i \tag{7.8}$$

better than simple linear regression equations, their results for bending and shearing were similar to other results, but two additional parameters, LT (tensile) and MMD (surface roughness) were also significant. They compared the various models, and found that all bending and shear properties can be related to drape, but that three or four parameters were probably enough for an accurate prediction.

Matsudaira and Yang[31] found that there existed an inherent node number for any fabric, and the conventional static drape coefficient (DC_s) could be measured accurately by an imaging system. Yang and Matsudaira[32] also derived regression equations from the static drape shape of isotropic and anisotropic fabrics, using cosine functions, and showed that static drape coefficient (DC_s) and the number of nodes (n), can be calculated from the following equations:

$$DC_s = \frac{4a^2 + 2b^2 + 2a_m^2 + b_m^2 - 4R_0^2}{12R_0^2} \tag{7.9}$$

$$n = 12.797 - 269.9\sqrt[3]{\frac{B}{W}} + 38060\frac{B}{W} - 2.67\frac{G}{W} + 13.03\sqrt{\frac{2HG}{W}} \tag{7.10}$$

where Ro = the radius of the circular supporting stand of the drapemeter (e.g. 63.5 mm)

a = a constant showing the total size of a two-dimensionally projected area (mm),

b = a constant showing the height of a sine wave of the two-dimensionally projected shape (mm), and

a_m and b_m = constants showing fabric anisotropy, derived as follows:

$$a = 35.981 + 1519\sqrt[3]{\frac{B}{W}} - 204300\frac{B}{W} + 23.27\sqrt[3]{\frac{G}{W}} + 0.0178G$$

$$b = 29.834 - 1.945n - 0.0188G - 91.84\frac{2HG}{W}$$

$$a_m = 9063\left(\frac{B_1 - B_2}{W}\right)^{2/3} \qquad b_m = 6224\left(\frac{B_1 - B_2}{W}\right)^{2/3}$$

where: B = bending rigidity (mN. m^2/m)

G = shear rigidity (N/m/rad)

$2HG$ = shear hysteresis at 0.0087 radian (N/m)

W = fabric weight (g/m^2)

B_1 = bending rigidity in warp direction

B_2 = bending rigidity in weft direction

Yang and Matsudaira[33] also quantitatively related the basic fabric mechanical parameters to static drape shape, using computer simulation.

Okur and Cihan[34] related drape to FAST properties, finding shear coefficient to have the greatest effect on drape, followed by the bending properties and the

extension at 45° bias angle (used to calculate shear stiffness), 86% of the variation in drape coefficient could be explained by C2, C1, EB5 and E20-2, only the first three being useful for the prediction of the drape coefficient.

7.5 Dynamic fabric drape

Because an element of movement is frequently involved in garment drape, various workers have investigated dynamic, as opposed to static, drape. Yang and Matsudaira[35] derived the following dynamic drape coefficient (D_d), with swinging motion, which is more closely related to human motion in walking:

$$Dd = 90.217 + 0.1183W - 720.7\sqrt[3]{\frac{B}{W}} - 41.1\sqrt[3]{\frac{G}{W}} \tag{7.11}$$

Yang and Matsudaira[35–37] defined drape coefficients in the revolving state and also with a swinging motion and proposed a relationship between these coefficients and the basic Kawabata KES-F mechanical parameters. Subjective evaluation of dynamic drape is highly correlated with dynamic bending and shear properties as well as the KES-F hand values. Lai[38] applied the regression method and artificial neural network to predict the dynamic visual appearance of a swirling skirt from the fabric mechanical properties, with a view to replacing the subjective assessment with a more objective assessment. It was found that the neural network method provided a more accurate prediction than the regression method.[36] Two fabric mechanical properties were key in the prediction of skirt swirl, namely:

$B =$ bending rigidity: gf. cm^2/cm

$2HG =$ hysteresis at 0.5°; gf. cm

Matsudaira *et al.*[17,39] showed that both the static and revolving dynamic degree of spreading of the (revolving fabric) drape coefficients decreased through the various finishing stages, especially with relaxation, defining the revolving drape increase coefficient.

Lai[38] applied the regression method and artificial neural network to predict the dynamic visual appearance of a swirling skirt from the fabric mechanical properties, with a view to replacing the subjective assessment with a more objective assessment. It was found that the neural network method provided a more accurate prediction than the regression method.

7.6 Seamed fabric drape

The drapeability of a seamed fabric or garment is affected by both the flexibility of the materials and by the construction of the seam. Although much research has been done on fabric drape, in practice the fabric almost always has a seam

which influences its drape behaviour. Comparatively little work has been done on the drape of seamed fabrics.

Chung[13] presented a detailed review of studies on drape, both static and dynamic, on both unseamed and seamed fabrics and investigated the effect of seam allowance, type and position on woven fabric drape. She found that bending length increased with the insertion of a vertical seam, while drape coefficient increased with the addition of radial seams, increasing the seam allowance having little effect. The highest drape coefficient occurred with the circular seam located just out of the pedestal.

7.7 Modelling fabric and garment drape

Hardaker and Fozzard[40] stated that one of the main obstacles in developing 3D garment CAD systems is the difficulty in modelling garment drape. Various researchers have attempted to model the draping behaviour of fabrics and garments, testing their models against experimental results. Generally two approaches are followed in modelling garment drape, namely geometric and physical.[41]

The geometrical approach treats the fabric as a deformable object, represented by a grid or two-dimensional array in three-dimensional coordinates, and drape is simulated by approximating the shape of the fabric surface to constraint points.[42–44] Since fabric properties are not incorporated in the existing geometrical models, these have limited use in 3D CAD.

The physical approach employs a conventional theory of mechanics, elasticity, and/or deformation energy to model complex fabric deformation during draping. Conventional continuum mechanics and the finite element method[45–47] were used to simulate complex fabric draping with only limited success compared to the simple geometric approach because the fabric undergoes complex and large deformation.

For example, Collier *et al*.[48] used a geometric non-linear finite element method to predict drape. They assumed the fabric to be a shell membrane with orthotropic rather than isotropic properties, finding that three independent parameters, tensile moduli in the two principal planar directions and Poisson's ratio, were required to predict drape. Gan *et al*.[49] applied geometric nonlinear finite elements, associated with a shell element, to model large fabric deformation, such as drape, the fabrics being considered as orthotropic and linearly elastic.

Chen and Govindaraj[50] used a shear flexible shell theory to predict fabric drape, taking the fabric to be a continuous, orthotropic medium, and using finite element formulations to numerically solve the governing equations under specific boundary conditions. The fabric characteristics used in the model were Young's modulus in the warp and weft directions, shear modulus and Poisson's ratio. Their physically-based modelling tied in closely with the processes of mathematical modelling and moved towards using drape modelling in apparel

CAD and made-to-measure garment-making applications, also being applicable to the study of fabric deformation during the apparel assembly process.

Postle and Postle[51] developed a commercially applicable mathematical model for fabric buckling, folding and drape, fabric bending and interfibre friction within the fabric being considered in their mathematical model, which involved solving nonlinear differential equations which had analytical (as opposed to numerical) solutions (called solitary wave or soliton solutions).

Kang and Yu,[52] developed a nonlinear finite element code to simulate the three-dimensional drape shapes of woven fabrics, assuming the fabric was an elastic material with orthotropic anisotropy, also considering fabric drape to be a geometric nonlinear phenomenon.

Stump and Fraser[1] applied a simplified model of fabric drape, based upon a two-dimensional elastic ring theory, to the circular geometry of the drapemeter, using a parameter incorporating fabric properties and drape geometry, to characterise the drape response of the energy contained in a series of deformed rings. They could also explain the fact that a particular fabric does not always drape with the same number of nodes. They focused attention on the large deflection and nonlinear kinematics associated with deep drape.

Bao *et al*.[53] conducted experimental and simulation studies on the MIT drape behaviour of fabrics, finding that the nonlinear finite element method, combined with the incremental method in which an elastic shell models the fabrics, simulated the large deformation of a fabric, such as in drape. They found that the fabric drape depended upon bending and torsional rigidity, but not on extensional or shearing rigidity.

Lo *et al*.[54] found that their model, using polar co-ordinates, for predicting fabric drape profile (i.e. characterised in terms of drape coefficient and node locations and numbers) could accurately predict the drape coefficient, node locations, node numbers and node shape in the fabric drape profile. Constants in the drape profile model could be obtained by regression analysis involving bending and shear hysteresis. They concluded that drape profile may be better predicted directly from bending and shear hysteresis.

Termonia[55] used a discrete model of fibres on a lattice to determine the importance of bonding pattern, laydown non-uniformities, fibre length and orientation distribution on the bending stiffness and drape of nonwovens.

Another physical approach involves the use of deformation energies with certain dynamic constants[17,56–58] which is particularly suitable for modelling dynamic garment drape in a virtual fashion, provided effective collision direction and response algorithms are developed.

Particle-based physical models[59–61] have been proposed and show some potential. Based on the microstructure of woven fabric, Breen *et al*.[59] assumed that the fabric consists of a set of particles interacting according to certain physical laws (Fig. 7.5). Stylios *et al*.[19] assumed the fabric is formed of rigid bar-deformable nodes and the governing differential equations of motion and

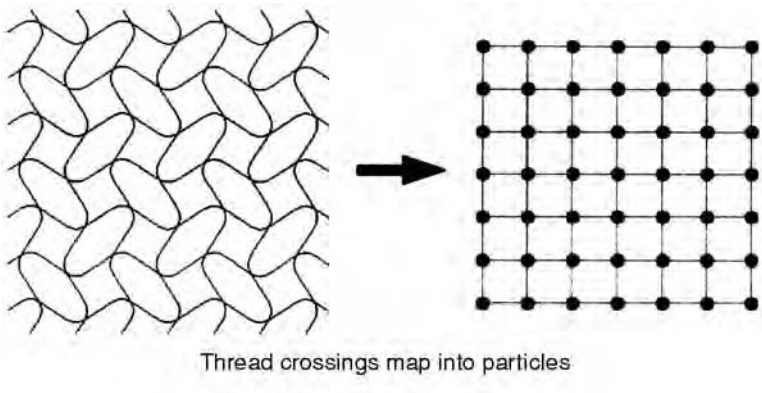


Figure 7.5 Particle-based model. Source: Breen *et al.*, 1994.[59]

deformation incorporating fabric mechanical properties were used to produce draping simulation.

Fan *et al.*[41] stated that such conventional methods, based upon fabric mechanics, have the advantage of understanding the fundamentals but have difficulty in accounting for the effects of accessories, seams and styles, their application to more complex garments being questionable. Using a database of stored drape images of garments made of typical fabrics, Fan *et al.*[41] demonstrated the feasibility of using a fuzzy-neural network system to predict and display drape images of garments comprising different fabrics and styles. A prototype drape prediction system was developed to predict the drape of a ladies' dress style made from different fabrics. The advantage of the fuzzy-neural network approach is that they allow very fast computation, provided the database contains an adequate number of drape images, and used to train the fuzzy-neural model, the predicted drape image will be very close to the actual one. The disadvantage is that only a limited number of styles and changeable feature dimensions can be accommodated.

Fan *et al.*[41] concluded that drape simulation was a complex and challenging task, and that their approach tested satisfactorily against lady's dresses and of a wide range of fabrics.

7.8 Drape models in commercial CAD and Internet systems

Drape modelling, in particular 3D visualisation of designed garments in draped form, is one of the key technologies in computer-aided garment design (CAD) and Internet apparel systems. It is essential for designers to assess the design, fabric suitability and the accuracy of garment patterns in a computer environment. It is also essential for the popular Internet systems to work effectively for trading and retailing as, without it, buyers and consumers will not be able to

assess garment style, appearance, fit and suitability through the Internet. In this section, various draping models in commercial apparel CAD and Internet systems are reviewed.

7.8.1 Gerber system

Gerber Technology's apparel CAD system,[62,63] AccuMark APDS-3D, is a product acquired from Asahi Chemical Industry Co. Ltd. The system allows pattern makers to select patterns from AccuMark™ Pattern Design and instantly view them assembled on a 3D dress form. The garment can be modified to change the fit or even the design on the 3D form. Garments can be viewed with fabric designs/textures and drape characteristics for a realistic representation, essentially creating a virtual sample.[62]

The APDS-3D program enables pattern makers to select patterns from a file library, it modifies them in two or three dimensions using exact body measurements, and instantly re-drapes the revised patterns in three dimensions. The pattern is designed, manipulated or simply recalled from a pattern library on screen and can then be virtually 'sewn together' and placed onto a virtual stand. The virtual stand can be rotated to allow the garment to be viewed from any angle. It can also be adjusted to any specific body measurements, whether standard sizes or individual customer measurements, to allow the operator to visualise a garment in any size.

Modifications can be made in two or three dimensions. Any changes made to the pattern on the stand are automatically translated into a two-dimensional pattern and vice versa. The scanned or digitally photographed images of the fabric can be rendered on the garment surface to give a realistic look in terms of colour, texture and surface design. Since fabric mechanical properties are important to drape, for example, a garment in the same pattern made of soft-flowing silk will give a completely different look from that made of a stiffer cotton material, a number of fabric coefficients in the KES-F measurements or fuzzy values can be entered, to simulate the drape properties of different fabric types, giving a relatively accurate visualisation of the finished sample. Full-colour 3D styles can be printed on any Windows-compatible colour printer.

AccuMark APDS-3D is claimed to be one of the most technologically advanced 3D systems available for the pattern design process. It can significantly reduce the time needed to create the most accurate, realistic draping effects and communicates these results seamlessly to the AccuMark Pattern Design for actual pattern design.

7.8.2 PAD System

The PAD System offers the following two 3D CAD software systems:[64–66]

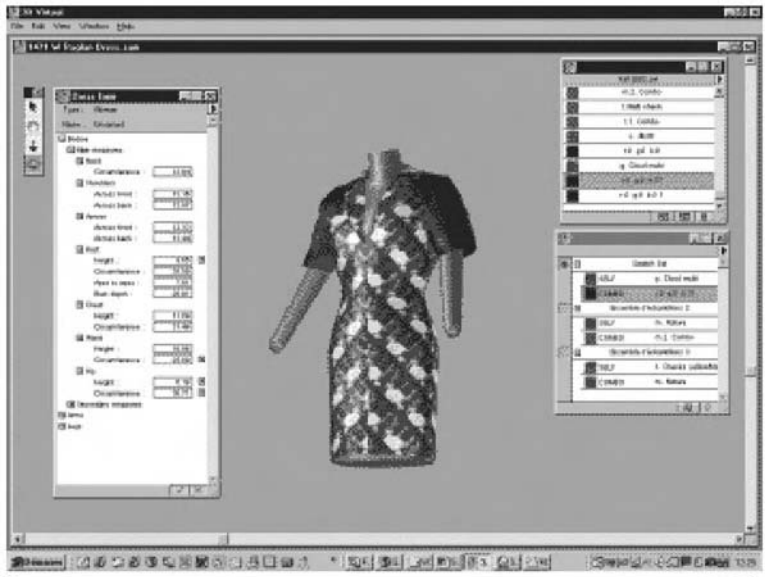


Figure 7.6 Visualisation of garment in 3D. Source: URL.[64]

3D virtual design sofware

3D virtual design software gives users the possibility to visualise all modifications to pattern pieces in real time. Figure 7.6 shows a virtual garment generated by the system. The software has the following features:

- texture and colour library
- simple garment and sewing line settings
- automatic link to master pattern module
- fast transformation between 3D image and 2D patterns
- 2D technical sketch window generated from 3D simulation to be used with the pattern file as a visual reference
- tool box for 3D setting, fold parts and texture positioning
- instant display of style with fabric swatch and colour
- new swatch library to show all colour combinations available for the style
- modifiable dress form measurements.

Hauté Couture 3D software

The Hauté Couture 3D software is an application which addresses the growing needs of the 3D animation industry with regard to the production of high quality, photo-realistic, 3D garments. This software includes a graded, framed and sewn pattern library. It has the following features:

- interface between the PAD System and Maya
- 2D environment and specialised tools for fast and easy sewing of pattern pieces

- darts automatically receive sewing information which can be exported to Maya
- possibility to import any 3D model or character
- intelligent placement of pattern panels around the character in a user friendly interface
- ease of use with practical working methods
- link between Hauté Couture 3D files and master pattern files
- sewing and placement information is retained even when patterns are modified
- pattern pieces are an excellent reference for placing seams or other garment details in the texture viewer
- export option to Maya ASCII format for patterns and sewing information
- possibility of exporting up to 200 graded patterns at once
- PAD tools for Maya allow application of the sewing information with a single click
- PAD tools for Maya enable the pattern pieces in the 3D scene to be replaced automatically to avoid repetitive placing of pieces
- graded, framed and sewn patterns for men and women.

7.8.3 Maya Cloth™

Maya Cloth™ (Fig. 7.7) is a software designed for the animation industry. Garments are created with Maya Cloth in much the same way as they are in real life. Patterns are designed and then sewn together virtually. The 3D drape of garments can be easily modified by altering the pattern and the types of material used. Fabric properties, such as thickness, weight, extensibility and stiffness, can

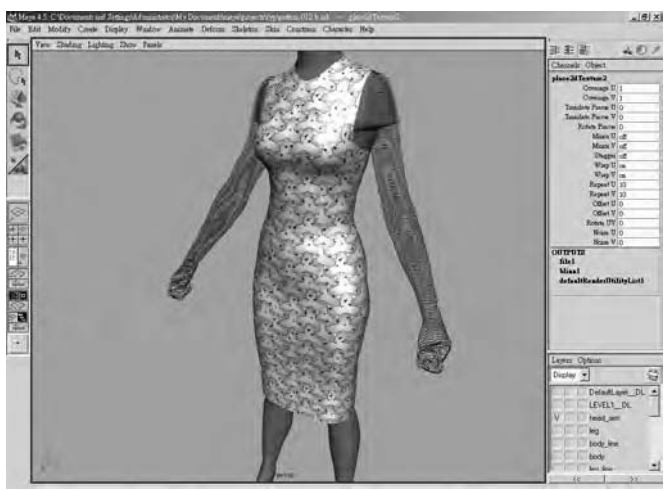


Figure 7.7 Computer screen of Maya Cloth™.

be changed in a relative scale (not in terms of strict mechanical properties) to change the drape effect.[67] When the virtual person is animated, the dynamic draping effect is simulated. Figure 7.7 shows a clothed person created using the Maya Cloth™ software.

7.8.4 Syflex system

The Syflex LLC system[68] was developed by Syflex LLC and PAD System Inc for the 3D animation market. It is claimed to be superior in terms of speed, stability, simulation and ease of use. Any vertex of the cloth can be nailed. These nails may be animated as any other object. Any vertex can be pinned to another static or moving object. The properties of a cloth, such as its mass or stiffness,

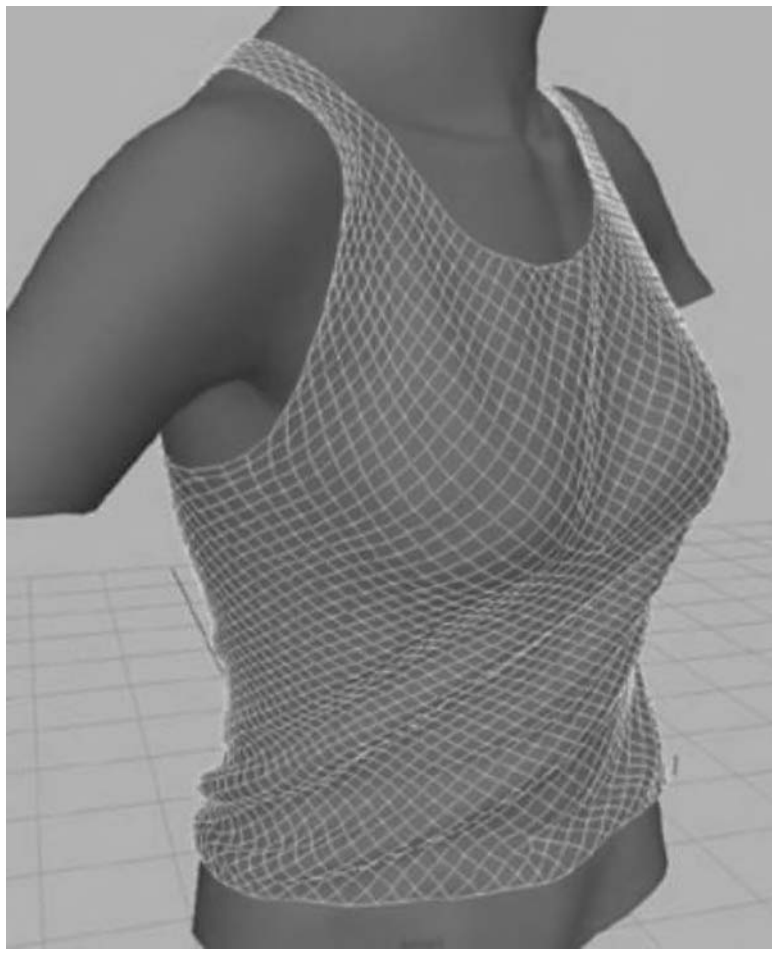


Figure 7.8 Cloth simulation in Syflex. Source: URL.[68]



Figure 7.9 Virtual draping of clothing in My Virtual Model™. Source: URL.[69]

can be modified on a per vertex basis, using artisan maps. This allows a precise control over the surface. Collisions of the cloth with any static or moving object are computed accurately. To optimise collisions, the user can specify which faces may collide. Self-collisions are also available. The simulator adapts to any movement which the characters perform, for example, running or dancing. It allows artists to animate any kind of clothing, such as t-shirts, trousers, aprons, skirts and jackets. It also provides all the flexibility necessary to model any kind of material, such as cotton, silk and leather. Figure 7.8 shows an animation from the Syflex system.

7.8.5 Draping models used on the Internet

Drape models have been incorporated in Internet websites for virtual shopping. For example, in landsend.com,[69] customers can log onto the Web[70] using My Virtual Model™ (Fig. 7.9) to create their own model (3D mannequin) by submitting their body measurements and appearance details, such as height, weight, shoulder width and hair colour. After creating their own model, customers can select the outfit from the web store to drape onto the model. Users can also rotate the model to view the outfit from different sides.

7.9 Concluding remarks

Initially, work on drape concentrated on its accurate measurement and on the empirical prediction of drape from the fabric mechanical properties, notably,

bending and shear rigidity and hysteresis. More recently, however, attention has increasingly focussed on modelling garment drape, this being important for developing 3D garment CAD systems. Ideal drape models should not only be able to display the static drape of the garment realistically with 3D renderings of design features, colours and surface textures, but simulate the animated dynamic drape. It should have the capability to convert 3D shapes into 2D patterns or vice versa. Although most apparel CAD systems or drape models on the Internet are claimed to present realistic draping effects, the real performance needs to be evaluated by the end user.

Although significant improvements in the drape models have occurred over the past two decades, further development in this area is still needed. As Wentzel[70] pointed out, 'the imagery of the virtual 3D sample is still flat; the stand and garment look somewhat sterile. Although fabric coefficients can be entered, the representation of the fabric drape still leaves some room for improvement'. When 3D animation is to be achieved, the challenge is greater. The resolution of the 3D virtual garment is still low in real-time presentation. Owing to the complexity and high polygon calculation, it takes a long time to achieve accurate performance of 3D animation. When the virtual garment is presented in a dynamic way or 360° rotation, the figure tends to show a lot of shading and poor texture effects.

7.10 References

1. Stump D M and Fraser W B, 'A simplified model of fabric drape based on ring theory', *Text Res J,* 1996 **66**(8) 506–514.
2. *Textile Terms and Definitions* (Ninth Edition), Manchester, Textile Institute, 1991, 95.
3. Cusick G E, 'The dependence of fabric drape on bending and shear stiffness', *J Text Inst,* 1965 **56** T596.
4. Bishop D P, 'Fabrics: Sensory and mechanical properties', *Textile Topics*, 1996 **26**(3) 1–62.
5. Chu C C, Hamburger W J and Platt M.M, 'Determination of factors which influence the draping properties of cotton fabrics', USDA ARS 72–17 (Feb., 1963).
6. Jacob M and Subramaniam V, 'A review of the literature on drape and pilling properties of textile fabrics', *Colourage*, 8 Jan., 1987 **34**(1) 21–22.
7. Hu J and Chan Y F, 'Effect of fabric mechanical properties on drape', *Text Res J,* 1998 **68**(1) 57–67.
8. Subramaniam V, 'Bending properties of textile structures I, II and III', *Indian Text J*, Dec., 1980 **91**(3) 93–107; Jan., 1981 **91**(4) 95–107; Feb., 1981 **91**(5) 87–102.
9. Subramaniam V, 'Non-linear bending of textile materials', *Man-made Text India*, 1981 **24**(8) 409, 411–413.
10. Subramaniam V, Chanchal B, Vatsala R and Rajendran B, 'Shearing properties of fabrics – A review. Part I: Test methods', *Man-made Text India*, 1983 **26**(6) 259–270.
11. Chu C C, Cummings C L and Teixeira N A, 'Mechanics of elastic performance of textile materials, Part V: A study of the factors affecting the drape of fabrics – The

development of a drape meter', *Text Res J*, 1950 **20** 539.
12. Cusick G E, 'The resistance of fabrics to shearing forces', *J Text Inst*, 1961 **52** T395.
13. Chung J, *The effect of assembly methods of a garment on fabric drape*, PhD Thesis, Institute of Textiles and Clothing, The Hong Kong Polytechnic University (Jan., 1999).
14. Cusick G E, 'The measurement of fabric drape', *J Text Inst*, 1968 **59** 253.
15. Anon, 'Fabric drape', (A review), *IWS F.A.C.T. Technical Information Letter, (*March, 1981) **9**.
16. Collier B J, 'Measurement of fabric drape and its relation to fabric mechanical properties and subjective evaluation', *Cloth Text Res J,* 1991 **10**(1) 46–52.
17. Matsudaira M, Yang M, Kinari T and Shintaku S, 'Polyester ''Shingosen'' fabrics characterised by dynamic drape coefficient with swinging motion', *Text Res J,* 2002, **72**(5) 410–416.
18. Vangheluwe L and Kiekens P, 'Time dependence of the drape coefficient of fabrics', *Int J Cloth Sci Technol,* 1993 **5**(5) 5–8.
19. Stylios G, Wan T R and Powell N J, 'Modelling the dynamic drape of garments on synthetic humans in a virtual fashion show', *Int J Cloth Sci Technol,* 1996 **8**(3) 95.
20. Peirce F T. 'The ''handle'' of cloth as a measurable quantity', *J Text Inst,* 1930 **21** T377.
21. Sudnik Z M, 'Objective measurement of fabric drape: Practical experience in the laboratory', *Text Inst Ind*, (Jan., 1972) **10** 14.
22. Kim C J and Vaughn E A, 'Physical properties associated with fabric hand', *AATCC Book of Papers, 1975, National Technical Conf, 78* (Oct., 1975).
23. Tanabe H, Akamatsu A, Niwa M and Furusato K, 'Determination of a drape coefficient from the basic mechanical properties of fabrics', *J Japan Res Assoc Text End-uses*, 1975 **16**(4) 116–120.
24. Suda N and Ohira M, 'Study on drapeability of fabrics, II: Visual assessment of drapeability', *J Japan Res Assoc Text End-uses*, 1975 **16**(4) 128–132.
25. Marooka H and Niwa M, 'Relation between drape coefficients and mechanical properties of fabrics', *J Text Mach Soc Japan* [English Edition], 1976 **22**(3) 67–73.
26. Sudnik M P, 'Rapid assessment of fabric stiffness and associated fabric aesthetics', *Text Inst Ind*, (June, 1978) **16**(6) 155–159.
27. Gaucher M I, 'The physical properties that influence the drape of knitted fabrics', *Canadian Text J*, (Nov., 1981) **98**(11) 52–58.
28. Hearle J W S and Amirbayat J, 'Analysis of drape by means of dimensionless groups', *Text Res J*, 1986 **56**(12) 727–733.
29. Niwa M and Seto F, 'Relationship between drapeability and mechanical properties of fabrics', *J Text Mach Soc Japan*, 1986 **39**(11) T161–168.
30. Collier B J and Collier J R, 'CAD/CAM in the textile and apparel industry', *Cloth Text J,* 1990 **8**(3) 7.
31. Matsudaira M and Yang M, 'Measurement of drape coefficients of fabrics and description of those hanging shapes', *J Text Mach Soc Japan*, 1997 **50**(9) T242.
32. Yang M and Matsudaira M, 'Measurement of drape coefficients of fabrics and description of those hanging shapes, Part 2: Description of hanging shape of anisotropic fabric', *J Text Mach Soc Japan*, 1998 **51**(4) T65.
33. Yang M and Matsudaira M, 'Measurement of drape coefficients of fabrics and description of those hanging shapes, Part 3: The effect of fabric parameters on drape shapes', *J Text Mach Soc Japan*, 1998 **51**(9) T182.

34. Okur A and Cihan T, 'Prediction of fabric drape coefficients from FAST data', *Text Asia*, 2002 **33**(7) 28–31.
35. Yang M and Matsudaira M, 'Measuring drape coefficients of fabrics and description of those hanging shapes, Part 6: Evaluation of dynamic drape behavior of fabrics in swinging motion', *J Text Mach Soc Japan*, 2001 **54**(3) T57.
36. Yang M and Matsudaira M, 'Measurement of drape coefficients of fabrics and description of those hanging shapes, Part 5: Relationship between dynamic drape behavior of fabrics and mechanical properties', *J Text Mach Soc Japan*, 2000 **53**(5) T115.
37. Yang M and Matsudaira M, 'Measurement of drape coefficients of fabrics and description of those hanging shapes, Part 4: Evaluation of dynamic drape behavior of fabrics using a testing device', *J Text Mach Soc Japan*, 1999 **52**(9) T167.
38. Lai S S, 'Objective evaluation model of visual elegance of swirl skirts, Part (I): Regression method, Part (II): Neural network method', *J Text Eng,* 2002 **48**(4) 111 and 117.
39. Matsudaira M, Yang M, Kinari T and Shintaku S, 'Changes in the static and dynamic drape coefficients of polyester fabrics through the finishing stages', *Text Res J,* 2003 **73**(1) 59–63.
40. Hardaker C H M and Fozzard G J W, 'Towards the virtual garment: Three-dimensional computer environments for garment design', *Int J Cloth Sci Technol*, 1998 **10**(2) 114–127.
41. Fan J, Newton E and Au R, 'Predicting garment drape with a fuzzy-neural network', *Text Res J*, 2001 **71**(7) 605–608.
42. Aono M, 'A Wrinkle propagation model for cloth', *Proc. Computer Graph Int. '90*, Springer-Verlag, 96 Tokoyo, 1990.
43. Matsuura S, 'Shape visualisation method and apparatus', German patent no. 4301698, 1993.
44. Weil J, 'The synthesis of cloth objects', *Proc. SIG-GRAPH'86, Computer Graph*, 1986 **20**(4), 44.
45. Amirbayat J and Hearle J W S, 'The complex buckling of flexible sheet materials, Part I: Theoretical approach, and Part II: Experimental study of three-fold buckling', *Int J Mech Sci,* 1986 **28**(6) 339.
46. Lloyd D W, 'The analysis of complex fabric deformation' in Hearle, J.W.S., Thwaite, J.J. and Amirbayat, J., (eds), *Mechanics of flexible fibre assemblies*, NATO ASI Series, 311, 1980.
47. Werner S, *Vibrations of shells and plates*, 2nd edn. Marcel Dekker, New York, 1993.
48. Collier J R, Collier B J, O'Toole G and Sargand S M, 'Drape prediction by means of finite-element analysis', *J Text Inst*, 1991 **82**(1) 96–107.
49. Gan L, Ly N G and Steven G P, 'A study of fabric deformation using nonlinear finite elements', *Text Res J*, 1995 **65**(11) 660–668.
50. Chen B and Govindaraj M, 'A physically based model of fabric drape using flexible shell theory', *Text Res J*, 1995 **65**(6) 324–330.
51. Postle J R and Postle R, 'Depicting the drape', *Text Asia,* Oct., 1995 **26**(10) 29–31.
52. Kang T J and Yu W R, 'Drape simulation of woven fabric by using the finite-element method', *J Text Inst*, 1995 **86**(4) 635–648.
53. Bao L, Takatera M, Sawada K, Sakurai M, Nakazawa M and Shinohara A., 'Effect of mechanical properties on MIT drape behaviours of fabrics', *Sen-i Gakkaishi*, 2002 **58**(3) 77–83.

54. Lo W M, Hu J L and Li L K, 'Modelling a fabric drape profile', *Text Res J*, 2002 **72**(5) 454–463.
55. Termonia V, 'Lattice model for the drape and bending properties of nonwoven fabrics', *Text Res J,* 2003 **73**(1) 74–78.
56. Boulic R, Thalmann N M and Thalmann D, 'A global human walking model with real-time kinematic personification', *The Vis Computer*, 1990 **6**(6) 344.
57. Carignan M, Yang Y, Magnenat-Thalmann N. and Magnenat-Thalmann D, 'Dressing animated synthetic actors with complex deformable clothes', *Computer Graph, Proc. SIGGRAPH*, 1992 **26**(2) 99.
58. Terzopoulos D, Platt J, Barr A.and Fleischer K, 'Elastically deformable models', *Computer Graph*, 1987 **21**(7) 205.
59. Breen D E, House D H and Wozney M J, 'A particle-based model for simulating the draping behaviour of woven cloth', *Text Res J*, 1994 **64**(11) 663–685.
60. Eberhardt B, Weber A and Strasser W, 'A fast, flexible, particle-system model for cloth draping', Computer Graphics in Textiles and Apparel, *IEEE Computer Graph Appli Mag*, 1996 **16**(5) 52–59.
61. Leung K Y C, Taylor G, Yuen M M F and Kung A, 'Three-dimensional simulation and presentation system for the garment industry', *Proc. 5th Asian Text. Conf.,* 336 Japan, 1999.
62. URL:http://www.gerbertechnology.com/gtwww/03Prods/cad/pattern/APDS3-D.htm
63. URL:http://www.gerbertechnology.com/gtwww/01library/Literature/Apparel/eng/APDS3-DE.pdf
64. URL: http://www.padsystem.com/en/index.html
65. Shepard A B and Schultz S D, 'PAD systems offers advanced functions in new software', Canadian-Apparel, (Nov./Dec., 2001) 6.
66. Shepard A B and Schultz, S.D., 'CAD/CAM companies reinvent themselves', Canadian-Apparel, (July/Aug., 2000) 21.
67. URL:http://www.alias.com/eng/products-services/maya/file/maya5_specsheet.pdf
68. URL: http://www.syflex.biz/
69. URL: http://www.landsend.com/
70. Wentzel B, 'The shape of things to come', *Fashion Business Int*, (June/July, 2002) **5** 28.

8

3D body scanning

W YU

8.1 Introduction

For the spatial analysis of clothing appearance and fit, a 3D digitisation of body form and clothing surface is essential. Since the late 1980s, 3D body scanning has received great attention and wide application in the clothing field. Variation in body size and shape can be assessed quantitatively and expressed by contour maps or polygons. The following are four main clothing applications of body scanning: non-contact body measurements for size survey, pattern generation for customisation, a tailor-made mannequin for a target market, and clothing fit evaluation of appearance, such as drape, wrinkling and bagging. Other than clothing, it can be applied also in the medical field for the screening of spinal deformities, the bust and abdomen volume during pregnancy, facial palsy and fat distribution. Animation and sculpture are also a possibility, but will not be discussed in this chapter.

Amongst so many possible applications, the main applicable result of 3D body scanning is the point data cloud to be used for the generation of virtual or physical dress model, critical landmarks and anthropometric data to guide the design and sizing of garments. One significant advantage of most 3D body scanners is the rapid scanning time and more accurate reproducible measurements. This machine generates an unlimited number of linear and nonlinear measurements of the human body in just a few seconds. It also delivers the output in a digital format which can be integrated automatically into apparel CAD systems such as Gerber and Lectra. This makes it possible to create garments which can mould to the three-dimensional shapes of unique human bodies.

This chapter reviews the development, technologies and application of non-contact body measurement and garment analysis systems in four categories: moiré topography, laser scanning, infrared scanning and photogrammetry. The methods using ultrasound and MM wave technologies are not included in this publication.

8.2 Global development of body scanners

Early in the fifteenth century, Leonardo da Vinci[1] was fascinated by the survey of the human body. The idea was adapted, and the methods were assimilated into the possibilities of today. Since the late 1800s, anthropologists used tape measures and callipers which are still being utilised for measuring the human body.[2] These methods are time consuming and often not accurate. Therefore, many researchers all over the world have directed their efforts towards obtaining more reliable measurements and 3D profiles of the human body using various techniques. These developments are described here in three geographic categories: Asia, America and Europe.

8.2.1 Asian development

In Asia, Japan was the first country to develop non-conventional measuring devices to capture the 2D and 3D body profiles of human subjects. The methods include sliding gauge, gypsum moulding, silhouetter, moiré camera, infrared scanner and laser scanner.

Japan

Sliding gauge

Research and development of 3D body scanners in Japan show a typical step-by-step technological transformation process from linear to 2D before reaching 3D, from contact to non-contact from photographic to moiré contour and infrared to laser.

In a big leap from linear tape measurements, a manual sliding gauge has been cleverly developed to trace the 2D sectional curves of the human body (Fig. 8.1). It used a series of aluminium sticks, equal in length and 5 mm in diameter, which were pushed smoothly towards the body surface, thus the curve connecting the

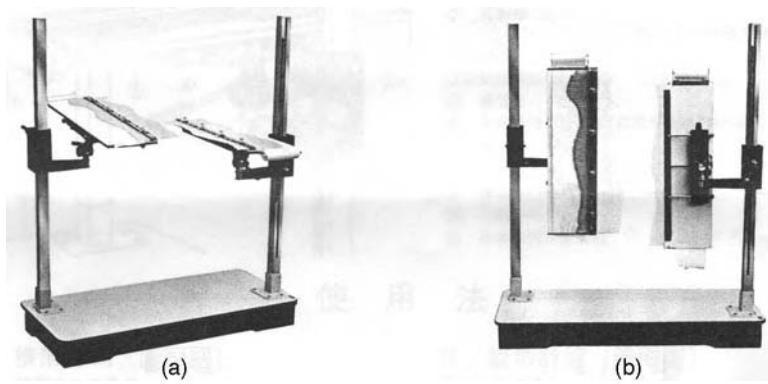


Figure 8.1 (a) Horizontal sliding gauge and (b) vertical sliding gauge. Source: Yamakoshi Seisakusho Co., Ltd.

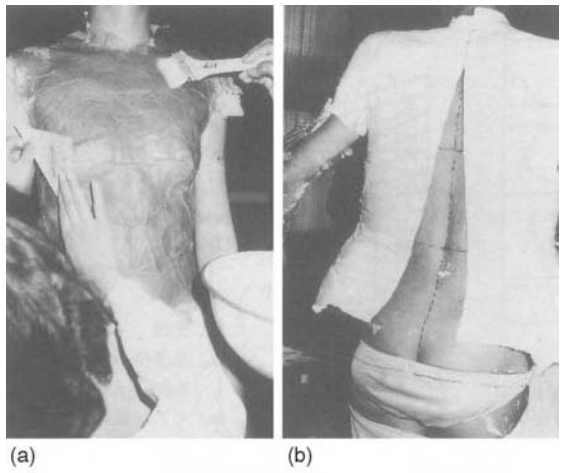


Figure 8.2 (a) Algin Method and (b) Gypsum Method. Source: By courtesy of Asakura Publishing Co., Ltd., Fig. 2.19 in Yoshiko Nakaho *et al*: *Clothing Construction*, 1995. Asakura Publishing Co., Ltd, Tokyo, Japan.

points of the other ends of the sticks was traced on paper for further computation of body measurements and sectional areas. Based on this concept, a mechanical sliding gauge instrument was later developed for measuring a complete set of body measurements in three dimensions. However, it has not been widely accepted by academic institutions because of its bulkiness and clumsy procedure.

Algin/gypsum moulding

To obtain a continuous 3D profile of a human body, direct skin-contact moulding methods, algin or gypsum have been used (Fig. 8.2). The researcher uses a brush to paint the liquid material to cover the skin under investigation, allowing it to dry, and then removing the dried 'shell' from the body surface, where the information of the 3D body shape was copied as the inner part of the shell. This is a direct method of taking body measurements, but too expensive for use.

Silhouetter

For non-contact measurement, a 'silhouetter' has been developed to capture a 2D photograph of a body contour with a background of a calibrated standard grid. This system consists of a booth with a large grid wall, a series of fluorescent light tubes and an instant camera (Fig. 8.3). A computerised silhouette analyser,[4] which electronically processes data on the contours, was also developed by Wacoal in 1984.

Moiré camera

Developed from photography, shadow moiré topography has been applied in the academic field for research on the 3D observation of the human body and its

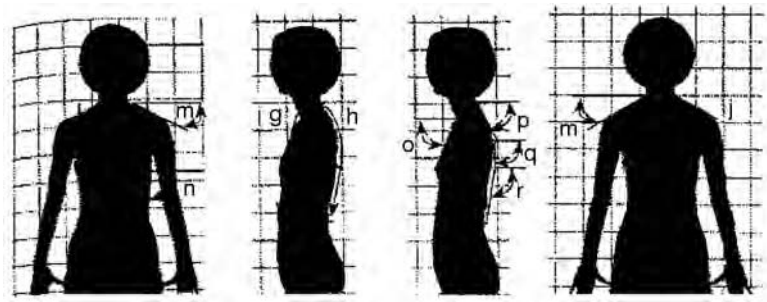


Figure 8.3 Silhouette analyser. Source: Reprinted from Applied Ergonomics, 23(3), Gazzuolo *et al*, 'Predicting garment pattern dimensions from photographic and anthropometric data' Copyright (1992), with permission from Elsevier.[16]

relationship to clothing patterns. In the 1980s, Fujinon used projection moiré topography to produce a moiré camera which has also been widely used in clothing research (Fig. 8.4). With a great reduction in size and weight and increased portability, the moiré scanner became commercially available from Fujinon in the 1990s. It is mainly used for the screening of spinal deformity of schoolchildren.

Infrared scanner

With the limited digital technology available in the 1980s, moiré images always contained noise which caused difficulties in terms of automatic processing. Therefore, Japanese researchers shifted their attention to infrared and laser technologies in the 1990s. Hamamatsu and Conusette are two major companies selling commercial infrared body scanners.

Conusette's products are particularly designed for mass customisation of ladies' foundation garments. Therefore, only the upper torso of a scanned body is analysed (Fig. 8.5). This system provides a whole body balance check, judging the most suitable underwear for the body's current shape, and uses computer graphics to simulate the future development of the body. Ageing simulation shows what the body will look like after five or ten years, based on the shape of the present figure. By superimposing the present figure over the future figure, ladies can formulate fashion, diet and healthcare plans.[5]

Laser scanner

At present, laser-based technology has become the key trend for 3D body scanning. Voxelan, originally developed by NKK in Japan, was taken over by the Hamano Engineering Company in 1990. It offers several series of laser scanners for measuring the head, half body and the whole body (Fig. 8.6). About 80 companies and institutions in Japan have used Voxelan's laser system since it was introduced.

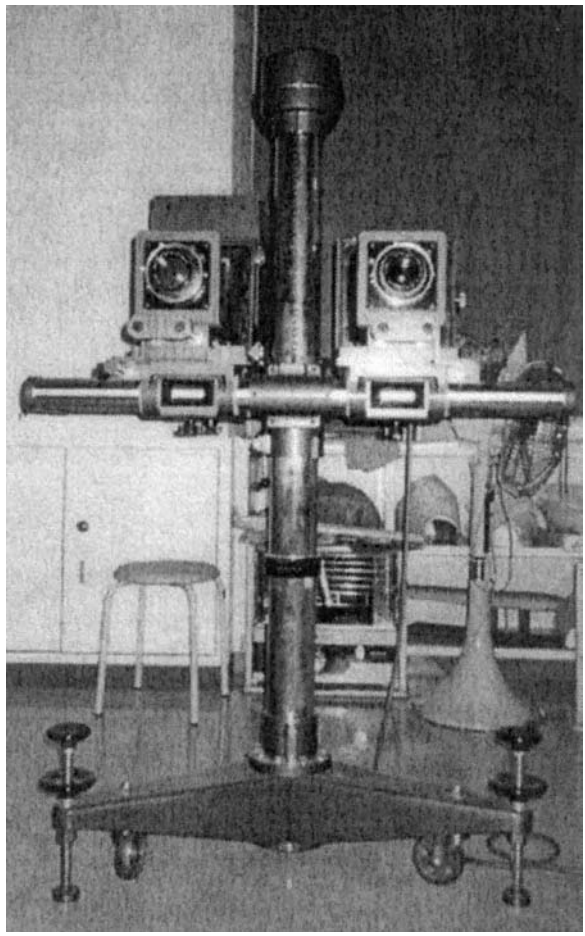


Figure 8.4 Fujinon Moiré Camera in 1980s. Source: Fujinon: *www.fujinon.co.jp*

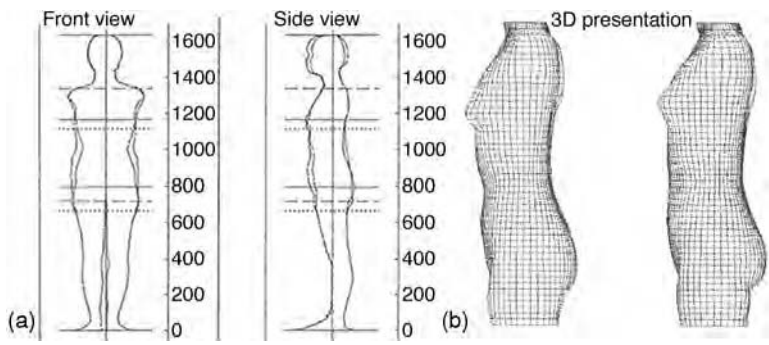


Figure 8.5 Output of Conusette's scan. Source: Hokuriku Co. Ltd., sample print screen from Conusette Infrared body scanner, 2003.

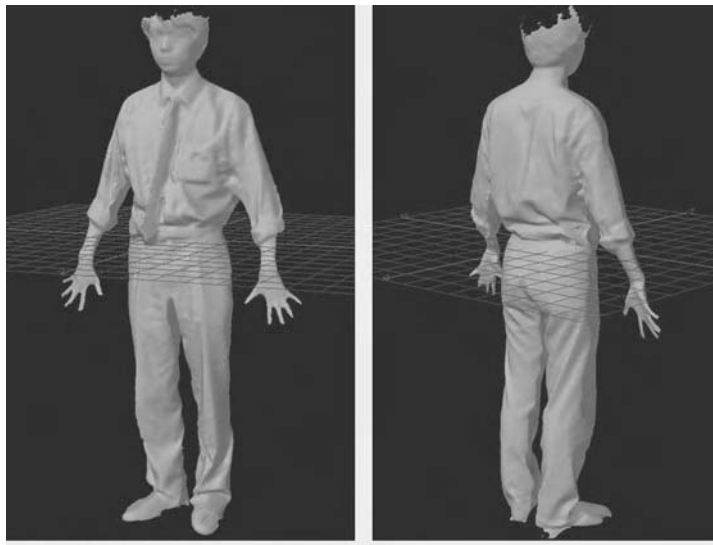


Figure 8.6 Digital output from Voxelan laser scanner. Source: Measured by VOXELAN.

In 2001, a non-contact 3D form measurement device, called 'Cubic', was developed in a joint industry-university research project with Bunka Women's University, Japan. It uses halogen light and takes about one second to obtain the body measurements, with an accuracy of 1 to 3 mm, depending on the image coverage (Fig. 8.7). The machine structure is light in weight and fit for easy transportation. Customerised software is provided in accordance with its needs. Texture and colour indications are also possible.

China

Hong Kong

In Hong Kong, the University of Science and Technology (HKUST) developed a computer-aided system in 1998 for three-dimensional mannequin generation and

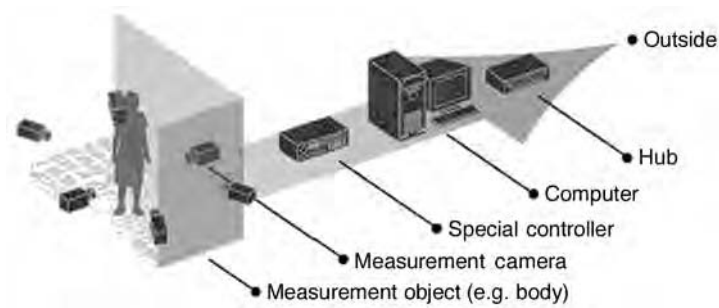


Figure 8.7 Cubic's hardware structure. Source: *http://www.cubic-inc.co.jp*



Figure 8.8 Close look at CubiCam.

garment design. Twelve images of 2D outlines, at six angles and two levels, were captured using digital cameras. Using a parametric feature-based design, simulated mannequins of men, women and children of varying ages and different sizes were demonstrated. The garment patterns were graphically sewn together and overlaid on the CAD-based mannequin. The garment models can also simulate the effects of different fabric materials based on fabric objective measurement.[6]

The present author, attached to the Hong Kong Polytechnic University, has patented a low-cost and compact body scanner called 'CubiCam' based on modified moiré topography (Fig. 8.8).[7] 'Cubi' means 3D, 'Cam' sounds like a little camera, quick, easy, cheap and cheerful. It is best used for body measurement, shape capturing, e-fitting and e-commerce on fashion and/or medical products. The hardware operates without a dark room, high power or professional calibration. There are six 'S' advantages: small, slim, saving, simple to use, swift and safe. It measures 160 mm W $\times$ 405 mm D $\times$ 390 mm H, which makes it the smallest 3D body scanner on the market. It is slim, as the lens

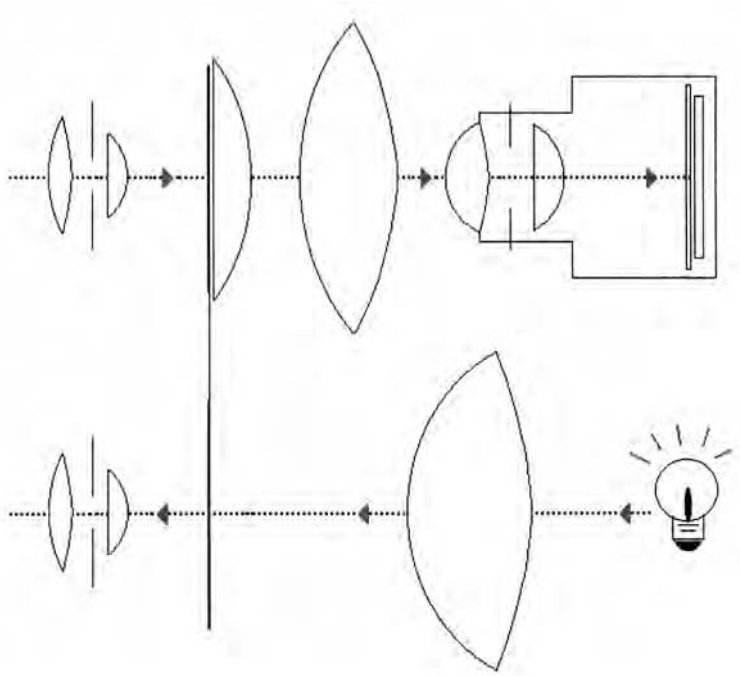


Figure 8.9 CubiCam's optical design. Source: Yu *et al.,* 1999.[20]

has a wide coverage of 925 mm (horizontal) × 1110 mm (vertical) at a short distance of 1200 mm (Fig. 8.9). A low-cost design is achievable because only one digital camera is required. It is simple to use due to its simple installation without high power voltage. Calibration is easy with this portable design. It is also swift, since less than 1/1500th of a second is required for image capture. It could enhance better accuracy with minimal body movement. The scanner works under normal lighting conditions with no laser, infrared or harmful radiation, therefore it is intrinsically safe.[8]

Taiwan

In Taiwan, the Industrial Technology Research Institute (ITRI) developed a portable 3D scanner 'Gemini' using opto-electronic application technology. A laser beam was projected to measure the body's surface profile dimensions. To avoid blind spots, ITRI used six optical detectors that performed simultaneous 360º inspections. It also utilised in-house developed 3D data integration and editing software to achieve high speed human body scanning. This technology has been transferred to domestic manufacturers. In February 2000, ITRI installed a scanner in the Chang Gung Memorial Hospital to collect 3D data of the human body. A total of 4500 people were scanned by the year 2002. Gemini was primarily designed for medical use, but now ITRI has also built up a

database linked to the Taiwan Body Bank and provides information to garment manufacturers.

8.2.2 American development

Early in 1964, the first full-scale male dummy was designed using anthropometric measurements employing a simple three-dimensional technique.[9] Vietorisz used a light source and an arrangement of photo detectors to measure a person's silhouette. In the late 1970s, systems utilising lasers were developed. In 1977 Clerget, Germain and Kryze were the first to illuminate their measured objects with a scanning laser beam.[10] David and Lloyd Addleman developed a scanning laser beam system in 1985, which is now marketed as Cyberware.

Using laser scanning, Cyberware has revolutionised computer graphics so as to work with true human faces and forms. The first body scanner was announced in 1987 for surface digitising and the measurement of a living human body. This trend began in the mid-1980s for the head, face and other body parts (hands, feet and the torso) and has recently evolved into whole-body imaging. In May 1995, Cyberware announced the introduction of the first 3D scanners to capture the shape and colour of the entire human body in one pass.[9] It was mainly applied to measuring individuals in the US Air Force for perfect fit uniforms and the Computerisation Anthropometric Research and Design Laboratories, with over 30 industrial partners in 2002.

In 1998, TC^2 made their first commercial 3D body scanner available to the clothing industry. Soon after its announcement, four systems were delivered to Levi Strauss, US Navy, North Carolina State University and Clarity Fit Technologies. Using this system, Lands' End has successfully carried out 14 city mobile scanning tours. In 2001, the first made-to-measure apparel store was launched at Brooks Brothers in New York. Due to its good support, TC^2 was selected by the Donghua University in China and several national size surveys, such as the 'SizeUK' project in 2000, 'SizeUSA' in 2002 and 'Size MX' in Mexico in 2004.[11]

8.2.3 European development

United Kingdom

The earliest 3D body scanning system in Britain, the Loughborough Anthropometric Shadow Scanner (LASS) was patented in 1987. Loughborough University has interrogated the 3D body data in collaboration with manufacturing companies including Marks & Spencer, Courtaulds Lingerie, Kennett & Lindsell, Bairdwear, Bentwood, Celestion and Fermark. The body data was obtained by scanning 155 women of various shapes and sizes using LASS, which enables accurate 3D measurements of the entire human body to be obtained in approximately three minutes.[12]

The UK Defence Clothing and Textile Agency (DCTA) in Colchester collaborated with researchers at the National Engineering Laboratory in Glasgow, Scotland. In 1996 they developed a 3D measurement system known as Auto-Mate.

DCTA operates a body measurement booth and offers either access to direct body measurement data, taken by a computer, or the facility and operators to take the measurements customers require for a given population. The design team provides corporate tailoring and offers designs in the form of demonstration garment/pilot models or fashion drawings. Their Ballistics Protection unit offers the design and the construction of body armour to provide the levels of protection required by their customers.

In 1996, Wicks and Wilson went into partnership with a London teaching hospital, needing a commercial partner, as part of a 3D facial scanning project. This project led to the development of TriForm systems using the moiré fringe technique, for head and body scanning.[13] It established a partnership with Body Shape Scanners Inc. in the USA and developed the new Body shape software aimed specifically at health clubs. The TriForm 3D body scanners have been used by David Lloyd Leisure Centres throughout the UK to track changes and improvements to the body shapes of their club members since October 2002.

France

Telmat Industrie developed the SYMCAD automated body measuring system. It was used by the French Navy to improve the fit of their uniforms in 1995. Recently the new 3D version was used within the clothing industry. It can capture the 3D shape of the customer instantaneously, and therefore is not affected by movement such as breathing, which could be detrimental during a scanning process. Each measurement is automatically calculated within ± 2 mm accuracy (Fig. 8.10). Nottingham Trent University has used SYMCAD in the analysis of human size and shape for the purpose of manufacturing clothing since the late 1990s.

For the first time, in 1998, the SYMCAD system was linked to the GGT Accumark MTM made-to-measure system, and then automatically to the GGT Cutting Edge knife, providing instantaneous and automatic customer fit garments. The Hollings Faculty of the Manchester Metropolitan University also used this booth to capture human body images and developed their MICROFIT made-to-measure systems.[14] Similar systems include the AssyCAD system, which also allows customer-specific data management, automatic alterations and direct marker making, where standard patterns are augmented with measurements for the desired adjustments. Data can be entered via GOweb which provides a medium through which standard collections and tailored garments can be offered. The customer can individually select the desired details, such as pockets, collars, colours and fabrics. According to Assyst, the



Figure 8.10 SYMCAD OptiFit. Source: SYMCAD OptiFit: 3D body measurement booth by TELMAT Industrie (France) ©2003.

system allows presentations of various collections or brand names at 'virtual tailor' at the Internet shopping centre.

Germany
Tecmath is strong at the ergonomic simulation of human beings in the automotive industry. The company has been actively involved in the field of clothing since 1995, providing 2D and 3D scanners, called Vitus. More than 150 body scanners have been sold to retailers, e.g. C&A, armies and research institutes in the field of mass customisation and clothing.[15] Tecmath has become the leading supplier of 3D body scanners in recent years. Since October 2002 the Human Solutions division of Tecmath has formed an independent company.

8.3 Principles and operations of body scanning technologies

All body scanning technologies use optical devices for non-contact measurements. Before the development of 3D methods, various types of 2D photographic methods, such as silhouetter, were commonly used to present a complicated body profile. Since the 1980s, 3D body scanning technologies have grown rapidly and they can be grouped into four categories: structure light, laser, infrared and photogrammetry.

3D scanning is a procedure used to build a digital 3D copy of a physical surface. The main difficulty resides in obtaining the actual shape of the surface, that is, the volume which the surface occupies in space. In the 3D scanning process, the digitiser, camera or scanner acquires range images, very much like contour maps. They are then processed by modelling software and converted to point positions in space. The shape acquisition can be sequential, one point or line at a time. Others are computer-controlled sensors. The technology may also

obtain colour information of the body texture, which is automatically fitted to the digital surface. This is all done without contact and in a short period of time.

8.3.1 2D photographic methods

Basic principle

The basic photographic set up of a silhoutter is shown schematically in Fig. 8.11. Each subject was photographed from three perspectives: anterior, lateral and posterior. Three black and white 127 × 178 mm photographs were developed and a vernier calliper was used to measure the length, width and depth on the photographs. Angles were transferred to tracing paper and measured with a protractor. Locations of photographic dimensions are defined. Technical limitations forced the researchers to measure photographs of the 50 female subjects manually, the intention being to provide the theoretical justification and methodology for a low-cost automated process of data collection, using video capture and computerised processing of visual data.[16]

Loughborough University – LASS

Using LASS, a person is required to stand as still as possible when the strips of light are projected onto the body and measured by TV cameras. This procedure is repeated 150 times whilst the subject is rotated through 360º. Four strips of light are used to allow adjustment for any movement. The strips are projected at

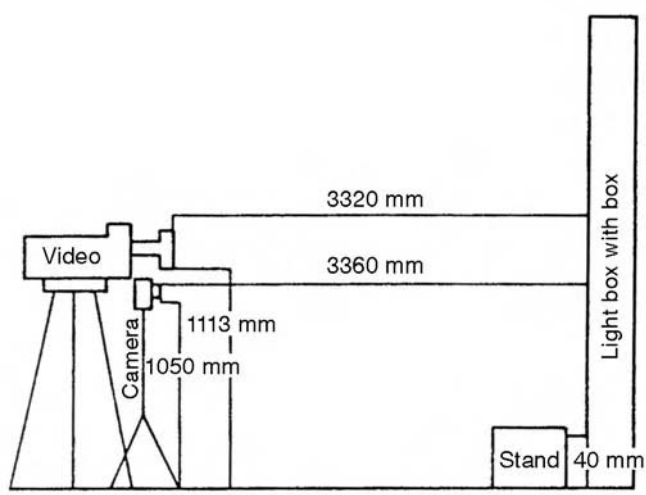


Figure 8.11 Schematic set up of 2D photographic methods. Source: Reprinted from Applied Ergonomics, 23(3), Gazzuolo *et al* 'Predicting garment pattern dimensions from photographic and anthropometric data' Copyright (1992), with permission from Elsevier.[16]

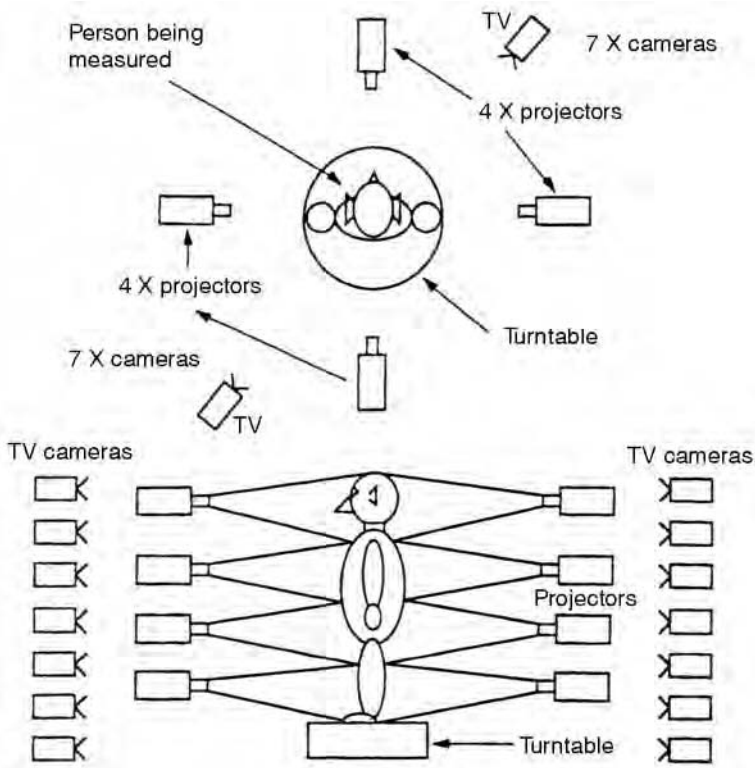


Figure 8.12 Schematic set up of LASS system. Source: Reprinted from *Endeavour*, 13(4), 'The Loughborough Anthropometric Shadow Scanner (LASS)', Jones PRM, *et al*, 162–168., Copyright 1989, with permission from Elsevier.[12]

an angle, so the observed deviation at any point depends on the radius of the body at that point. The exact radius can then be calculated. The set up of the LASS system is shown schematically in Fig. 8.12.

Loughborough's curve-fitting process treats the body as a series of horizontal 'slices', each of which can be edited in 2D. Sixteen data points are fitted around each slice and the process is repeated for 32 slices, each chosen to correspond to a particular anatomical landmark. The 3D body surface can then be re-created. Finally, the arms are edited out and the surface smoothed.[12]

Telmat-SYMCAD

In the SYMCAD booth, a person stands in the middle of the booth dressed only in underwear. A digital camera captures the front and profile images of the silhouette. By tracing the outlines of the silhouette, the software calculates their dimensions, even allowing for posture.

HKUST's computer vision
Fourteen cameras and two projectors are used without involving a sophisticated lens. The data are basically generated from 2D profiles and the 3D human model is generated by digital ellipses. It requires a large space, lengthy capturing time and a completely dark environment.

8.3.2 Structure light

Structure light-based scanning is widely used in the clothing field because it is much less expensive than the laser. Within this category, there are mainly two types of different technologies used: moiré topography and phase shift. Examples of products include CubiCam, TC^2 and Wicks and Wilson.

Moiré topography
As an optical phenomenon, moiré fringes were referred to in scientific literature more than 100 years ago, but the early authors referred to them as 'watery or wavy patterns'. Moiré topography is a contour mapping technique, which involves positioning a grating close to an object and observing its shadow on the object through the grating. For the measurement and display of an object's three-dimensional form, two techniques, namely shadow and projection moiré topography, are commonly applied.

Shadow moiré topography
In the shadow moiré technique, a linear grating is placed close to the surface to be evaluated. A shadow of the grating is cast onto the object when illuminated by a light source. The shadow pattern thus formed is distorted as a result of the three-dimensional shape of the object. Moiré fringes are generated when a camera records the superimposed shadow pattern through the grating. Initially in 1969, Pirodda[17] introduced this concept, and considerable interest[18, 19] in its application followed.

The basic advantage of moiré photography is to overcome the fundamental limitation of conventional photographs in that each image is not solely a two-dimensional projection of a three-dimensional object, but is actually a three-dimensional 'map' of the surface since measurements on these photographs can be correctly scaled. The depth data in the form of the fringes with the linear measurements of image, can allow measurements in space. This gives permanent records of body morphology, and also reliable cross-sectional measurements.

Takasaki[19] initially introduced an application of moiré fringes for the measurement of the human body in 1970 (Fig. 8.13). At that time, difficulties still existed in getting a good fringe contrast due to the following factors: large size and depth required; limitations of exposure time for a living body; and poor contrast due to the blurring of the shadow of the grating cast on a living body.

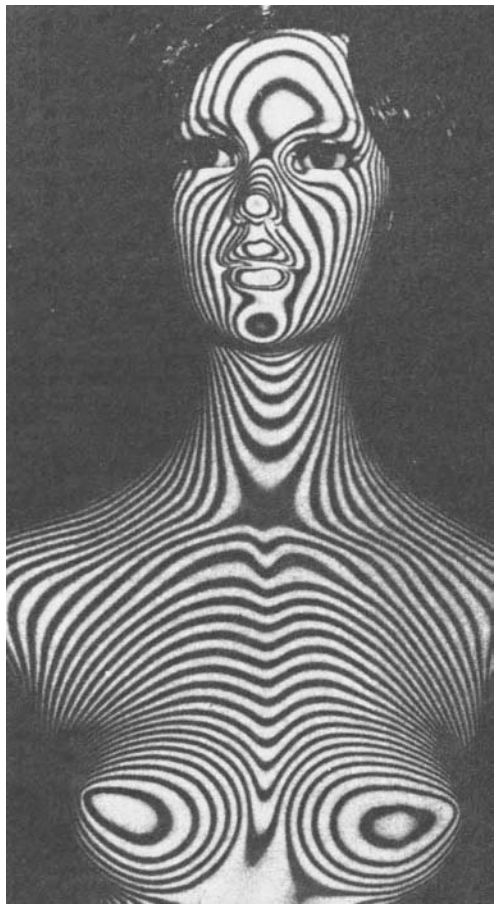


Figure 8.13 Figure of moiré image of human body. Source: Takasaki 1973.[19]

Detailed techniques for improvements were given three years later by Takasaki.[19]

Projection moiré topography

In the projection moiré technique, the specimen is obtained by projecting the image of a grid onto the object. The specimen grid is photographed together with a separate reference grid, and the moiré pattern is formed in the image plane of the recording camera as a result of the interference of the two grid images.

Hong Kong Polytechnic University – CubiCam

Initially, 3D body scanners faced common obstacles, such as high cost, complicated installation, large space and darkroom requirements. In 1999, The Hong Kong Polytechnic University invented a 3D body scanner, CubiCam[20] to provide a satisfactory technological solution. Based on a modification from

projection moiré topography, CubiCam uses normal flashlight for quick illumination. It can form high-contrast, high-resolution moiré topographic contours of the human body surface at a short distance under ambient light within a second. Inaccuracies caused by body movement or breathing have been eliminated. The whole system can be easily transported because a darkroom and heavy installation are not required. The system utilises the optical interference caused by two identical high-density gratings. Once the reference grating is projected onto the surface of the human body by an objective lens, its varying dimension will deform the grid line shadow. This deformed style of grating will then be captured simultaneously by another identical objective lens.

Consideration has to be given to the fact that a moiré photograph is a central-perspective representation of the photographed object. Different scale factors therefore apply to the fringes, depending on the distance from the camera they represent. Also, the depth interval of successive fringes is not constant but increases with the distance from the camera.

Nuoro Ailun – complex phase tracing (CPT) technique

Nuoro Ailun has built an instrument, using moiré technique, to capture two images of the object with projected sinusoidal fringe pattern for the human back topography measurement and shape analysis. They called this technology the complex phase tracing (CPT) technique. This construction has several advantages, such as short time image acquisition, insensitivity to the external illumination, fast image processing and portability of the instrument. It also does not require a phase unwrapping procedure. It can also access the natural image of the patient without a superimposed fringe pattern. During construction of the instrument, three particular solutions, namely regarding illumination, projection system and new fringe generator were patented. The proposed modification of the PLL and CPT technique was presented. Hence, a new method of image registration and processing was applied. The prototype of the system was tested in collaboration with the Rome Catholic University in the preparation of the medical software for the human back shape analysis.

RSI – DigiScan

RSI's DigiScan 2000 system is the first 3D scanner following the principles of modularity and standard components integration. Customers can purchase a scanning solution tailored to their needs. The user selects the projector having the resolution, image size and brightness they require, and at the price they can afford. The system can be configured to allow for body digitising. A $2.5 \times 2.5 \times 2.5$ m cabin house, two projectors and 12 cameras are used (Fig. 8.14). Mirrors guide the projected light onto the person's body surface, which is observed by the cameras. Shape measurement and texture acquisition are completed within two seconds.



Figure 8.14 RSI DigiScan 2000. Source: RSI.

Phase shift

TC^2 (Textile and Clothing Technology Corporation) has built up a custom apparel design and manufacturing system using a moiré-based light projection system, known as PMP (phase measuring profilometry) (Fig. 8.15).[21] This method involves shifting the grating preset distances in the direction of the varying phase, and capturing images at each position. It uses a white light source to project a contour pattern (sinusoidal fringes) on the surface of the object. As irregularities in the shape of the target object distort the projected grating, the resulting fringe patterns describe the surface contour. By using the four captured images, the phase pixel can be determined.

The system is currently configured using three platforms with two cameras mounted vertically on each. Two platforms are positioned in front of a subject at about 30 degrees from the centre; and the third platform is located directly behind the subject. The six separate camera images are integrated to form the

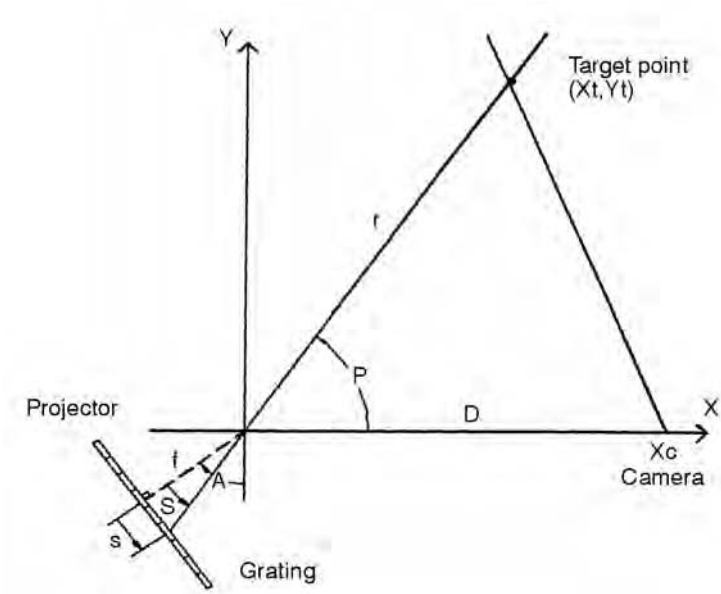


Figure 8.15 TC^2 PMP theory. Source: Textile/ Clothing Technology Corporation by Demers M. H., Hurley J. D. and Wulpern R. C., 'Three-dimensional Surface Capture for Body Measurement Using Projected Sinusoidal Patterns', *SPIE vol. 3023,* March 1997, p. 21.

complete image. The total body coverage is estimated at about 95%. The estimated scanned volume is approximately 2 m high × 1 m wide × 1 m long. Image resolution is 1–2 mm, with an accuracy of about 3 mm. Images obtained from the system are black and white.

In the UK, in 1998 Wicks and Wilson[13] developed TriForm, using a white halogen light. The whole body is captured in less than ten seconds and a full colour 3D point cloud is processed and displayed in less than one minute. The curtained booth provides privacy for the person being scanned who will ideally be wearing light form fitting clothing or underwear (Fig. 8.16). Various configurations of TriForm 3D scanners are available, including specialised units for capturing the human head, legs or whole body.

Each unit includes a projector and a camera. The projector shines horizontal patterns of striped light onto the surface to be scanned. The camera captures each of the patterns as they are projected. The TriForm body scanner has a total of four capture units, each using mirrors to capture the surface of the body from two directions, giving a total of eight views. As soon as the images have been captured, they are automatically passed to a PC controller where the distortions in the patterns are analysed and the coordinates of the 3D surface are calculated. Approximately 1.5 million points are calculated to describe the entire body.



Figure 8.16 TriForm 3D body scanner. Source: TriForm 3D body scanner manufactured by Wicks and Wilson.[13]

Telmat – OptiFit

According to Telmat, OptiFit is their latest development. It comprises body measurement extraction software, including body shape analysis and data transfer modules to link to the CAD/CAM systems. It is insensitive to body movement and not affected by the colour of the underclothes. Only 50 ft^2 of floor space is required. Associated with it is the Body Card, a card which contains the customer's body measurements in the required format. It is extremely suitable for the retail industry. Moreover, it could also operate as a mobile version, to undertake measurement surveys at geographically dispersed locations. OptiFit is also used for generating a consistent body measurement database of any target population and is a statistical tool for the definition of optimised size charts.

Telmat acquires pieces of information in 1/25th of a second. It takes 30 seconds for the cameras to move along the beams and acquire data of the whole body. This system is able to generate 70 precise body measurements. It takes less than 15 seconds for the system to extract this data. All the resulting measurement data can be integrated into apparel CAD systems, such as Gerber

Technology's AccuMark system or Lectra System's Modaris software.[22] Telmat also developed the framework of a partnership with the French Navy.[23]

8.3.3 Laser scanning

Basic principle

The scanner projects a line of laser light right around the body. The laser line is reflected into cameras located in each of the scan heads. Data is obtained using a triangulation method in which a strip of light is emitted from laser diodes onto the surface of the scanned object, and then viewed simultaneously from two locations, using an arrangement of mirrors. Viewed from an angle, the laser stripe appears deformed by the object's shape. CCD sensors record the deformations and create a digitised image of the subject. The cameras positioned within each of the scanning heads move vertically along the length of the scanning volume.[21] The laser scanner generates RGB colour values, and uses a process of identifying colour-coded landmarks for data extraction. Figure 8.17 shows a schematic presentation of 3D Scanner's ModelMaker.

Cyberware

Cyberware first introduced the whole-body laser scanners, WB2 and WB4, for clothing applications. The anthropometry group at Wright-Patterson Air Force Base acquired the first WB4 which cost $410,000 in April 1998. It scans the entire human body of a cylindrical volume 2 m high with a diameter of 1.2 m, in colour, in 12 seconds. WB2 and WB4 use two or four scanning units, mounted on vertical towers, respectively (Fig. 8.18). The WB4's use of four instruments improves accuracy on the sides of the body and in difficult-to-reach areas, such as under a person's arms, soles of the feet and the groin.[9] With a person standing on either scanner's platform, the instruments start at the person's head and move

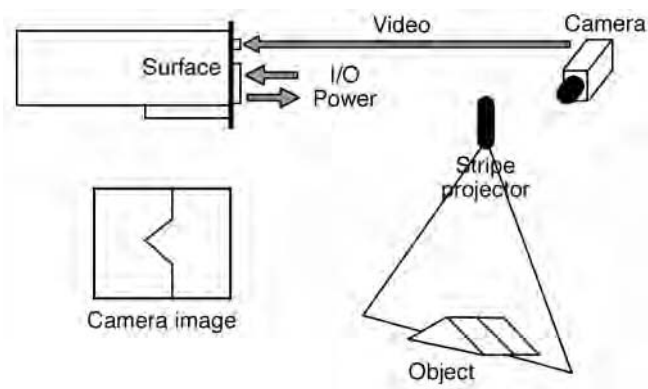


Figure 8.17 3D Scanner's ModelMaker. Source: 3-D Scanner's ModelMaker. *www.3-Dscanners.com*

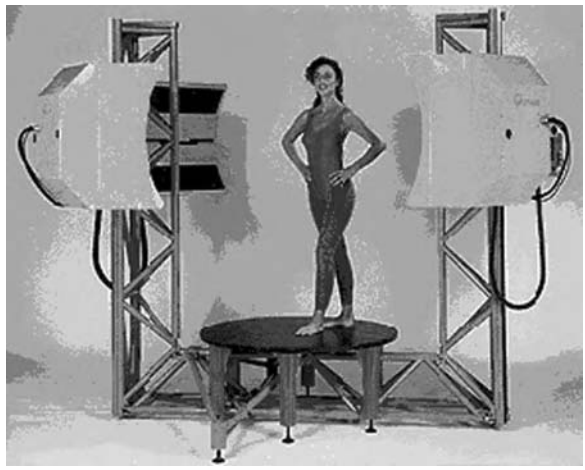


Figure 8.18 Cyberware WB4 Scanner. Source: Cyberware.

down to scan the entire body. Within seconds after completing a scan, graphic tools at the workstation let users view the results. The CyZip software then combines the models from the multiple scanning units into one smooth and complete 3D model of the human body.

The WB scanners are also of special interest to animators, anthropologists and designers, who can obtain alternatives to inaccurate models of the body, based on over-simplified or stylised forms. The WBX version is for clothing measurement, which can be generated with a substantial reduction in complexity, size and cost. The cycle time was reduced to 20 seconds and the price reduced to $150,000.[24] The WBX was tested at the Marine Corps Recruit Depot in San Diego.

A scan results in two data sets, each the size of about half a megabyte and containing geometric and texture information. Each format is based on a regular grid of 512 angles and 450 points in a vertical direction. Image resolution ranges between 2 to 4 mm in the X- and Y-axes and less than 1 mm along the Z-axis. The digitising speed for the maximum scanned volume is about 17 seconds, which yields about 400,000 3D co-ordinates on the surface of an adult human body.

TecMath

TecMath's system takes several pictures of the person in different postures, using a special video camera in front of a light source of four diode lasers with diffraction optics. Measurement time is only two seconds, ensuring minimal scanning error due to postural sway or body movements, with simultaneous scanning of the front and back of the person. Interpretation is done with a 3D human model, known as RAMSIS, an ergonomic tool. Accuracy is reported to be within 1 cm of the body height, and the scanned range of the body height is

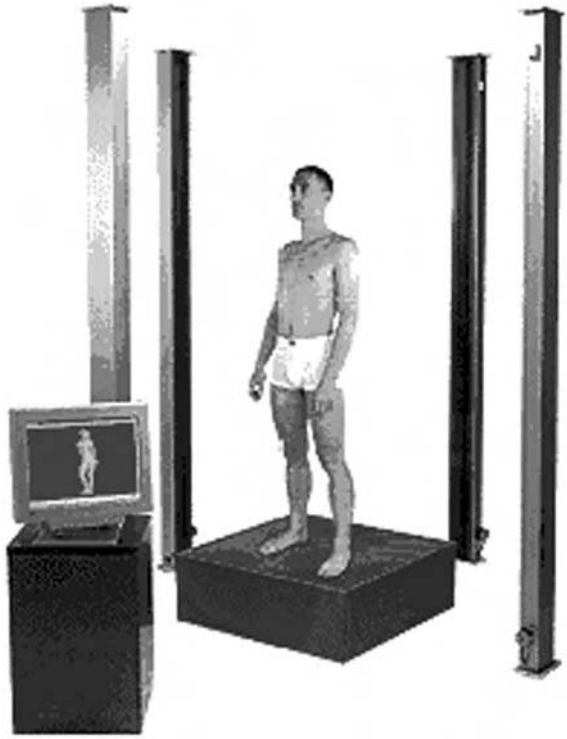


Figure 8.19 Vitus body scanner. Source: Human-Solutions.

from 1 m to approximately 2.2 m. The measured data enable input to CAD systems for automated made-to-measure pattern construction or adaptation. The system interfaces with third party pattern design systems, such as Gerber Technology and GRAFIS.[25]

Contour and Vitus are TecMath's products in human solutions. Contour has been used to develop the fit of army clothing and to select sizes from tables, which contain basic body dimensions for companies, such as KAKA, DoB and Bundeswehr.[15] Vitus is a 3D scanning system with an automatic calibration facility and an option for colour texture. It allows visualisation of up to 16 million triangles (Fig. 8.19).

Hamano-Voxelan

The Voxelan scanner is the only scanner which uses vertical laser stripes. The model HEV-1800HSW (Fig. 8.20) is used for the whole body measurement; HEC-300DS is for face scanning and HEV-50S is for wrinkle measurement. The resolution ranges from 0.8 mm for the body to 0.02 mm for wrinkles. The virtual body is generated from the measured shape data as cyberspace representations. A bird's-eye view of a wired form can be obtained, so the perimeter and area of cross-section as well as diameter across its sides can be measured.



Figure 8.20 Voxelan's HEV-1800HSW scanner. Source: Measured by VOXELAN.

Cubic
Traditional measurement devices weigh over 100 kg and involve a measurement time of over 10 seconds. In contrast to this, 'Cubic' has the highest measuring speed, less than 1 second, and weighs a lot less. The flexible structure of Cubic can cope with various business interests due to its hardware structure. It is active in various fields. The specifications of the device and the application software can be customised in accordance with the customer's needs.

Polhemus – FastScan
FastScan is the industry's most portable and lightweight handheld scanner (Fig. 8.21). The measurements are made by smoothly sweeping the wand over the object, an image of the object simultaneously appearing on the computer screen and the finished scan is processed so as to combine overlapping sweeps. The three-dimensional data can then be saved for loading into other programs.

FastScan is designed to scan non-metallic, opaque objects. It works by projecting a fan of laser light onto the object, while cameras on the wand view the laser from either side to record the 3D surfaces of the object. It incorporates Polhemus' patented Fastrak motion tracking technology in the wand itself. The magnetic tracker is used to determine the position and orientation of the wand, enabling the computer to reconstruct the full three-dimensional surface of the object. By attaching a second tracker receiver one could scan moveable objects as well.

8.3.4 Infrared technology

Basic principle
An infrared (IR) imaging sensor operates in the IR region of the electromagnetic spectrum. A lens coupled to a detector, which converts the IR energy to an

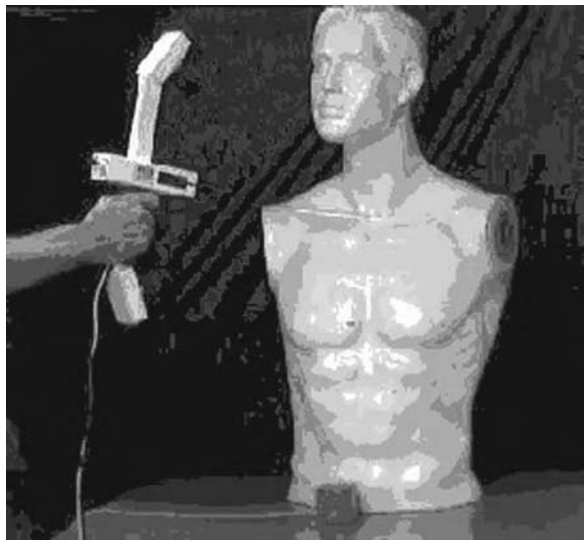


Figure 8.21 FastScan scanner. Source: Polhemus.

electrical signal, focusses on the scene.[26] Figure 8.22 shows a schematic representation of an IR sensor.

With an infrared LED and a semiconductor position-sensing detector (PSD), triangulation is used for the rapid, non-contact measurement of three-dimensional shapes of target objects. It measures the 3D shapes of the human body by positioning multiple distance sensors around the person being measured.

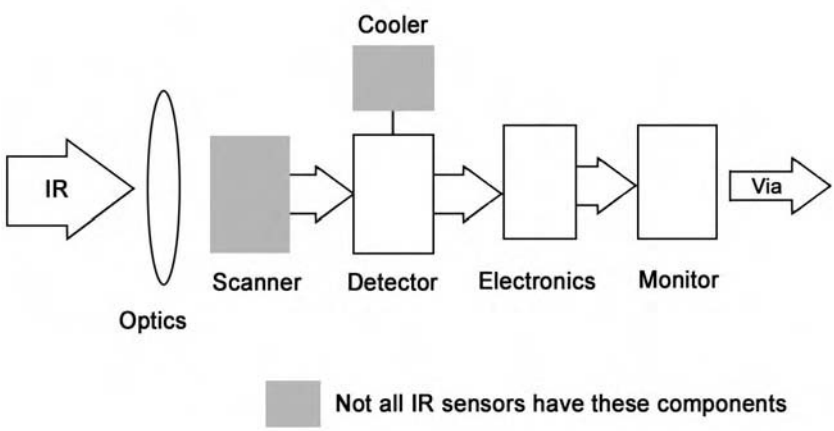


Figure 8.22 IR sensor. Source: Crawford, 1998.[26]

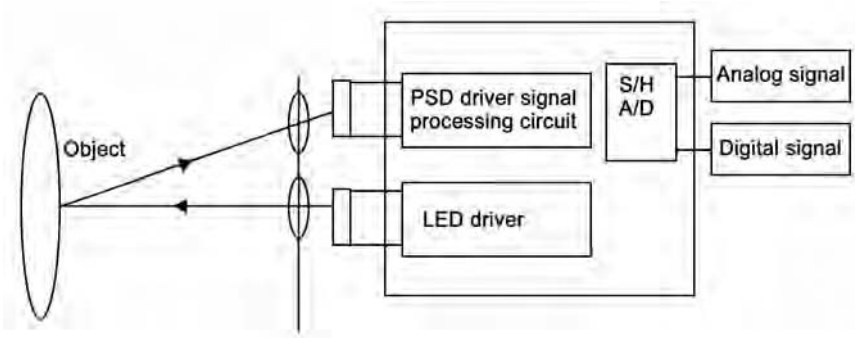


Figure 8.23 LED with PSD system. Source: Kaufmann, 1997.[27]

Hamamatsu

The Hamamatsu's Body Lines (BL) scanning system uses a near infrared LED (light emitting diode) to obtain data scans. The detector lens is a combination of spherical and cylindrical lenses which generate a slit beam on the position sensitive detectors (PSD) (Fig. 8.23). According to Kaufmann,[27] PSD's are used to compensate for the shadowing of one of the detectors. Hamamatsu worked with the University College of London in human modelling.

Hokuriku – Conusette

Conusette was developed to give women beautiful bodies. Therefore, only the bust, waist, and hip sizes are measured. Thereafter, the system provides a whole body balance check, judges the most suitable underwear for the body's present shape, and uses computer graphics to simulate future body changes. Ageing simulation shows what the future holds for the female body at any given age, based on the shape of the present figure. By superimposing the present figure onto the future figure, ladies can formulate fashion, dieting and healthcare plans.

8.3.5 Photogrammetry

A normal picture on paper or film is photographed with only one lens and cannot convey a true spatial perception. The use of two lenses, imitating the eyes, can create such a spatial image. When we examine a stereo picture, we form a perception of space in our mind (Fig. 8.24).[28]

If two charge coupled device (CCD) cameras are placed at some parallax angle, two slightly different images of the same object are obtained. The distance between the points on the object and the base plane can be calculated by geometrical analysis of the difference between the two images (Fig. 8.25). Where the distance on the image planes of the two cameras differ and the distance between the camera and the centre of object is known, the normal distance between a target point and the base plane can be determined.[29]

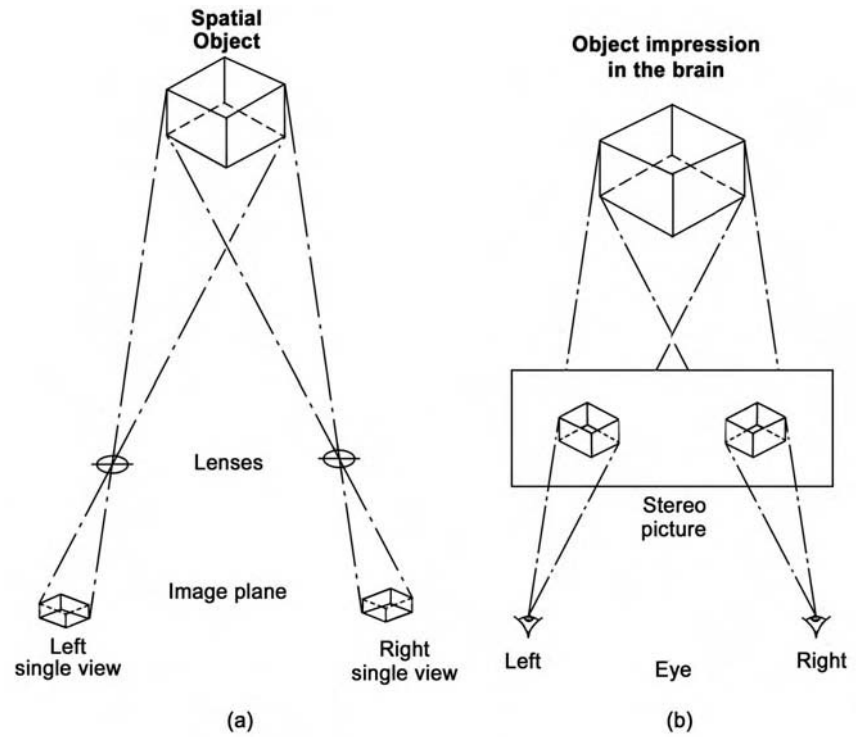


Figure 8.24 Stereo picture. Source: Stereoscopy.com/ Alexander Klein.

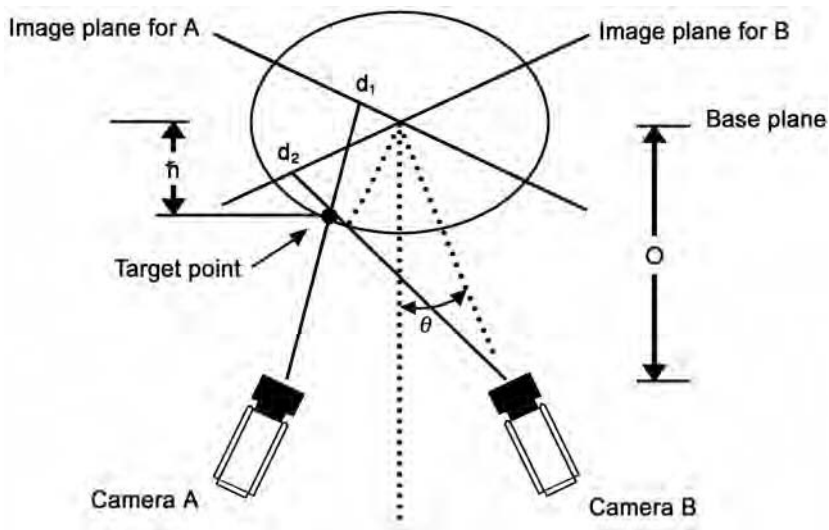


Figure 8.25 Schematic diagram of stereoscopy. Source: Tae and Sung 2000.[29]

The universal procedure to obtain a complete digital 3D model by means of optical digitising involves first acquiring a variety of partial views of the surface, as seen from a selection of angles, in order to cover all the surfaces of the object. For instance, when digitising a head, the usual procedure would be to acquire seven partial views, two of the front, at an angle, one on each side, for each of the ears, two of the back, again at an angle, and finally one of the top. These partial models are brought into a common system of co-ordinates and then combined to reproduce the overall shape of the object. They are then merged to produce a single polygonal model which includes all the surfaces captured during the digitising process.

Inspeck – Capturor II

A 3D Capturor II, being introduced by Inspeck, uses halogen light technology to digitise a view in less than a second. Involuntary movement during image acquisition is of little consequence compared to laser acquisitions. It can also scan hair and provide textures more realistically. The texture of each partial model is merged to form a single texture for the merged model which results in a complete 3D model.[30]

A complete 3D model, in 360º, can be obtained by taking multiple image acquisitions using a single digitiser. The multiple views can be combined in Inspeck's EM software. It also allows the simplification of polygons, editing texture (2D/3D) and exporting to various 3D graphics software packages, such as Softimage©, 3D Studio Max and Maya. If the 3D model needs to be animated, more functionality, such as NURBS generation, sub-surface and morphing tools will increase and accelerate workflow. Another possibility is to configure more than one digitiser to work together as a system. Multiple digitisers can be combined for a single image acquisition of a human subject. This is what Inspeck calls the multi-head system. These systems come with a calibration target, which eliminates time-consuming view alignment steps.

Cubic

In Japan, Cubic uses halogen lights for illumination while the 3D image of the human body is captured by two CCD cameras placed at an angle. This system has two models (Fig. 8.26). One is a compact measurement device that uses only one lamp and therefore is light in weight and gives an accuracy of 1 mm. The other is an entire body measurement device, which uses four lamps and covers a body of 700 mm high, giving a precision of 3 mm.[31]

8.4 Benchmarking

3D body scanning technology has become more popular in the clothing industry. Many applications have been developed. This allows retailers to retain their old

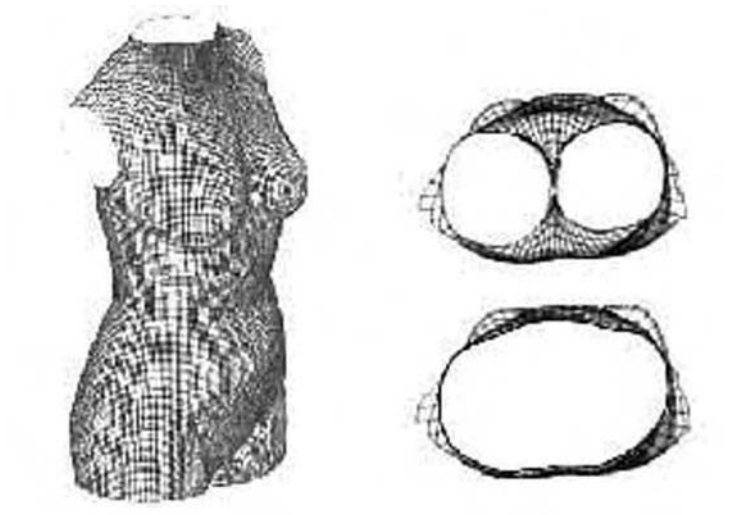


Figure 8.26 Cubic Compact Model and Entire Body Model. Source: http://www.cubic-inc.co.jp.[31]

customers with a value added professional service and to attract new customers who demand personal fit. Different 3D body scanners have distinct features and advantages. Table 8.1 lists the major 3D scanner manufacturers, and Table 8.2 provides a comparison between different body scanners.

The optical devices used by the 3D body scanners can be light projectors, CCDs and light sources (halogen, infrared or laser). For the human body, the

Table 8.1 Major 3D scanner manufacturers

Scanning system	Optical method	Website
Cubic	Laser technology	www.cubic-inc.co.jp
Cyberware – WB4	Laser technology	www.cyberware.com
DCTA – Automate	Phase shift	
Fujinon – FM40SC	Moiré topography	www.fujinon.co.jp
Hamamatsu – BodyLine	Infrared technology	www.hpk.co.jp
Hamano – Voxelan HEW1800	Laser technology	www.voxelan.co.jp
Hokuriku – Conusette	Infrared technology	
Inspeck – Capturor	Photogrammetry	www.inspeck.com
Loughborough – LASS	Photogrammetry	www.lboro.ac.uk
Polhemus – FastScan	Laser technology	www.polhemus.com
Poly U – CubiCam	Moiré topography	www.cubicam.com
RSI – DigiScan2000	Phase shift	www.rsi.gmbh.de
TC^2 – ImageTwin	Phase shift	www.tc2.com
TechMath – VitusSmart	Laser technology	www.human-solutions.com/
TELMAT – SYMCAD	Phase shift	www.symcad.com
Wicks and Wilson – TriForm	Phase shift	www.wwl.co.uk

Table 8.2 Comparison between different body scanners

Scanning system	Capture time	Process time	Total time	Dimension (W × H × D)	Booth size (W × H × D)	Weight (kg)	No. of sensors	Volume (W × H × D)	Data density	Accuracy	Room condition
Cubic	1 sec	N/A	N/A	3.5 × 1.5 × 1.7	3.5 × 1.5 × 1.7	30	2	0.185 × 0.7	N/A	3 mm	Dark
Cyberware WB4	17 sec	30 sec	47 sec	3.6 × 2.92 × 3	N/A	450	8	1.2 × 2	60000 per sec	5 mm × 2 mm	Dark
Hamamatsu BodyLine	10 sec	40 sec	50 sec	1.8 × 2.3 × 1.8	N/A	250	8	1 ×1.85 × 0.6	1894400	± 0.5%	Dark
Hamano-Voxelan HEW1800	10–60 sec	N/A	N/A	N/A	4 × 2.1 ×2	N/A	8	0.75 × 1.8 × 0.6	552960	± 2 mm	Dark
Hokuriku Conusette	16	10	26	N/A	1.6 × 2.3 × 1.59	350	6	0.4 × 1.7 × 0.48	65280	± 0.5%	Dark
Inspeck Capturor	0.3	N/A	N/A	0.15 × 0.45 × 0.31	3 × 2.3 × 1	N/A	2	0.85 × 2	N/A	4 mm	Dark
Polhemus FASTSCAN	N/A	N/A	N/A	N/A	N/A	N/A	2	0.075 × 0.68	N/A	1 mm	N/A
Poly U CubiCam	1/1500 × 3 sec	30	30	0.16 × 0.36 × 0.4	1.7 × 2.2 × 1	8.6	1	0.93 × 1.11	60000	4 mm	Normal
RSI DigiScan2000	< 1	N/A	N/A	N/A	2.5 × 2.5 × 2.5	N/A	12	N/A	N/A	0.2 mm	N/A
TC^2 ImageTwin	8 sec	45 sec	53 sec	N/A	3.3 × 5.9 × 2.4	N/A	6	1.1 ×1 ×2	400000	5–60 mm	Dark
TELMAT SYMCAD	7.2 sec	< 30 sec	< 37.2 sec	N/A	3 × 1.5 × 2.4	50	N/A	Whole Body	N/A	± 2 mm	Dark
Vitronics VitusPro	8–20 sec	30 sec	40 sec	2.5 × 3.1 ×1.85	N/A	N/A	16	2.1 ×1.2	2000000	1–2 mm	Dark
Wicks and Wilson TriForm	< 12 sec	240 sec	252 sec	0.2 × 0.64 × 0.44	2.3 × 1.5 × 2.4 m	1120 × 2	8	1.95 × 0.7	300000	± 2 mm	Dark

Source: Yu *et al.*, 2001.[8]

laser must be classified as Class 1 for eye safety. Most 3D body scanners project light rays horizontally. In the Cyberware, Vitronic and Hamamatsu systems, cameras or mirrors are mounted above and below the projection system. In the TecMath scanner, the cameras are mounted only above the laser projector. This means that the lower sides of some body parts may not be well represented. The CubiCam, TC^2 and Telmat Systems project structured light stripes onto the body, but the images are captured and analysed differently.

Speed is important in the reduction of human body movement artefacts.[32] Rapid data acquisition for the structured light system is certainly a major advantage over laser scanning. Structured light and laser triangulation systems measure similar degrees of coverage on the body surface. However, all systems attempt to reduce the scanner dimensions and booth size. This is of importance, especially for the retail sector where floor space is valuable. However, if multiple scan heads are placed at a significant distance from the body, a large space is required, unless mirrors are used, as in Wicks and Wilson. For a structured light system, image distortion easily occurs due to postural differences during different scans.[33] If mirrors are used, the complexity of the analysis increases.

Higher data density means more accuracy, but it also requires a longer scanning and processing time. The data size is an essential issue when data management, storage, usage and transmission are considered. Therefore, a compromise is needed in accordance with the users' requirements. With the new technologies, most scanners are designed to share and exchange information between computer applications and can also provide automatic measurement extraction from the scanned 3D data.

Most body scanners require a dark environment, which is not suitable for moving subjects, such as children. Therefore, a normal room environment is preferred. Only CubiCam has tackled this problem, using a flash-light system.

Since the introduction of body scanners, system costs have reduced a lot. The price may or may not include the computer interface, data storage devices, technical support and maintenance, or data extraction software.

8.5 Challenges of 3D body scanning

As 3D body scanning has developed since the late 1980s, some problems have affected its potential application. Researchers have carried out experiments and discussed these problems.[34] Various technical and application problems exist depending on the way in which information is extracted and manipulated from these images.

8.5.1 Missing areas

Most body scanners have difficulties in obtaining data from some hidden areas of the human body. For example, the armpits, the crotch and the areas under the bust and chin are often shaded.[33] This causes problems with missing data.[35]

Body parts, such as the shoulders and crotch, do not show up very well due to camera positioning. The TC^2-3T6 system uses six projectors and cameras; three for the upper part of the body and three for the lower part. The front of the body is captured by four cameras and the back by two cameras. As the viewing point of the scanning head is lower than the shoulders, the tops of the shoulders may not show up very well.

8.5.2 Body posture and movement

The human body is constantly changing, even when standing still. Movement due to swaying, breathing and posture changes during scanning can readily affect measurements, such as the chest circumference.[36, 37] For example, the Cyberware laser scanner measures the human body in 15 to 20 seconds as the cameras travel from head to toe. The effects of movement on the scanning quality and overall data accuracy is potentially quite significant and affects the integrity of the 3D image. With relatively rapid data capture time of less than one second, subject movement presents fewer problems.

8.5.3 Surface texture

Surface attributes of the skin and hair can markedly affect data quality. A laser scanner has trouble recording highly reflective body surfaces. Capturing hair has been a problem due to its fine texture, complex structure and many variants. For structure light systems, light absorption presents a problem. The translucence of the human skin allows penetration by the projected light into the body as the light reflects back to the surface; it can reduce the overall fringe contrast. With the present technologies, subjects are normally required to wear standardised close-fitting clothing during the scan. The ability to capture a good scan image of different skin colour and texture becomes a great challenge for on-going research of the structured light method.

8.5.4 Accuracy

Many military and commercial applications require the ability to measure and record precisely body size and shape. The ability of a given measurement system and accompanying data extraction software to obtain accurate and repeatable anthropometric data is important.

Standard industry clothing dimensions are recorded using a tape measure, which produces some compression of fat and muscle tissue. However, scanning systems yield surface measurements without compression, and therefore give results that vary from those using traditional methods. Anthropometric dimensions, such as body length, breadth and depth, are calculated straightforwardly from the interpretation of surface geometry. However, some measurements, such as chest depth, which include relatively more soft tissue, are more likely to differ from traditional results.

The Cyberware Natick scan system generally results in measurement values lower than those obtained with traditional anthropometry. The Hamamatsu BL scanning system, however, tends to produce either similar or larger circumference measurements than those observed for traditional anthropometry. It performs best on chest and hip circumferences. Hamamatsu is suitable for women's upper torso and tight undergarments. However, it still has difficulty with neck circumferences.

8.5.5 Body landmarking

Detecting the necessary landmark feature is an essential process in all types of body scanning, given the variations of human size, shape and posture. However, there is a lack of standardisation among the different systems. Simmons and Istook[10] have reported that different systems may identify landmarks and body measurements using different definitions, relative to traditional methods. Some scanners require manual methods to identify the subject's body landmarks and affix coloured labels to the bodies.[38, 39] If it takes a significant amount of time to prepare a subject for scanning and to do the landmarking manually, the benefits of using a scanning system decrease.

8.5.6 Software requirements

The development of data extraction software is important. The images cannot be exploited fully without automated software tools for visualisation, accurate anthropometrics and analysis.

8.6 Concluding remarks

It is clear that much work remains before 3D body scanning systems can be used successfully in automated clothing design and manufacture. Accurate human body size data and other related application software must be greatly enhanced. Although the potential of 3D body scanning seems tremendous, the cost and benefits will become more apparent with time. Technology improves the speed of image capture, reduces the errors arising from body movement,

improves accuracy and resolution and provides full colour as well as shape information. Probably any given method might suit some applications and not others. However, if a given system can consistently generate surface data to a known level of precision, the system should find broad acceptance.

8.7 References

1. Rosheim M E, 'In the footsteps of Leonardo', *IEEE Robotics & Automation Mag*, 1997, June, 12–14.
2. Delong M, Ashdown S, Butterfield L and Turnbladh K F, 'Data specification needed for apparel production using *computers', Cloth Text Res* J, 1993 **11**(3), 1–7.
3. URL: http://www.wacoal.co.jp/company/aboutcom_e/ningen/index_e.html.
4. Furukawa T, 'Computer speeds body shape data', *Daily New Record*, July, 1984 **14**(136), section 1, 20.
5. Conusette, *Body Shape Evaluation Report*, Internal document of Bonluxe (Asia) Ltd., Hong Kong, 1999.
6. Yuen M, '3D garment construction', *Text Asia*, 2000 **31**(4) 44–48.
7. Yu W M, Ng K P, Yan M C and Gu H B, 'Body scanner', Chinese patent no. ZL01269653.6, 2002.
8. Yu W M, Ng R and Yan S, 'A new approach to 3D body scanning', *Text Asia*, 2001 **32**(10) 23–26.
9. Simmons K P, 'Body measurement techniques: a comparison of three-dimensional body scanning and physical anthropometric methods', PhD Thesis, College of Textiles, Jan., 2001, North Carolina State University, North Carolina, USA.
10. Simmons K P and Istook C L, 'Body measurement techniques: a comparison of 3D body scanning and physical anthropometric methods', *Proc Seoul KSCT/ITAA Joint World Conf*, Seoul, South Korea, ITAA Publications, 2001.
11. TC^2, URL: www.tc2.com.
12. Jones P R M, West G M, Harris D H and Read J B, 'The Loughborough Anthropometric Shadow Scanner (LASS)', *Endeavour*, 1989 **13**(4) 162–168.
13. Wicks and Wilson, Triform System Description, URL: http://www.wwl.co.uk/wwl2/triform/PDF/design&manufacture.pdf.
14. Turner J P, 'Development of a commercial made-to-measure garment pattern system', *Int J Cloth Sci Technol*, 1994 **6**(4) 28–33.
15. Human-Solutions, URL: www.human-solutions.com.
16. Gazzuolo E, Delong M, Lohr S, La Bat K and Bye E, 'Predicting garment pattern dimensions from photographic and anthropometric data', *Appl Ergon*, 1992 **23**(3) 161–171.
17. Pirodda L, 'Principil e applicazioni di un metodo foto-grammetrico basato sull impiego del moiré', *Rivista di Ingegneria*, 1969 **12** 913–923.
18. Meadows D M, Johnson W O and Allen J, 'Generation of surface countours by moiré patterns', *Appl Optics*, 1970 **9** 942–947.
19. Takasaki H, 'Moiré topography', *Appl Optics – Opt Soc America*, 1973 **12**(4) 845–850.
20. Yu W M, Yan S and Gu H B, 'Design of 3D body scanner for apparel fit', *Proc 5th Asian Text Conf*, Kyoto Research Park, Japan, Federation of Asian Professional Textile Associations, Sept., 30–Oct., 2, 1999, 400–403.

21. Paquette S, '3D scanning in apparel design and human engineering', *IEEE Comput Graph Appl*, 1996 **16**(5) 11–15.
22. Hwang S J, 'Three-dimensional body scanning system with potential for use in the apparel industry', *Text Technol Management* 2001, North Carolina State University: Raleigh, p. 55.
23. Soir F, 'Made to measure for everybody', URL: http://www.symcad.com, 1999.
24. Apparel Research Network, Apparel Research Network (ARN) Redesigned 3D Whole Body Scanner – WBX for Recruit Clothing Issues, URL: http://arn2.com/docs/scan/systems/wbxwar.html, 2000.
25. Tait N, 'Is mass customization possible?', *Apparel Int*, 1998 **29**(7) 22–37.
26. Crawford F J, 'Electro-Optical Sensor Overview', *IEEE AES System Magazine*, 1998 Oct., 17–24.
27. Kaufmann K, 'Invasion of the Body Scanners', *IEEE Circuits and Devices Magazine*, 1997 **13**(3) 12–17.
28. Waack G F, *Stereo Photography, An Introduction to Stereo Photo Technology and Practical Suggestion for Stereo Photography*, Stereoscopy.com/ A. Klein, 1985.
29. Tae J K and Sung M K, 'Optimized Garment Pattern Generation Based on Three-Dimensional Anthropometric Measurement', *Int J Cloth Sci Technol*, 2000 **12**(4) 240–254.
30. Inspeck-Inc., URL: www.inspeck.com.
31. Cubic, URL: www.cubic-inc.co.jp.
32. Mckinnon L and Istook C L, 'The effects of subject respiration and foot positioning on the data integrity of scanned measurements', *J Fashion Marketing and Management*, 2002 **6**(2) 103–121.
33. Daanen H A M and Jeroen-van-de-Water G, 'Whole body scanners'', *Displays*, 1998 **19** 111–120.
34. Bougourd J P, Dekker L. Ross P G and Ward J P, 'A Comparison of Women's Sizing by 3D Electronic Scanning and Traditional Anthropometry', *J Text Inst*, 2000 **91**(2) 163–173.
35. Brunsman M A, Daanen H M and Robinette K M, 'Optimal postures and positioning for human body scanning', *Proc. Int Conf Recent Advances in 3-D Digital Imaging and Modeling (Cat. No.97TB100134)*, Los Alamitos, CA, USA and Ottawa, Ontario, Canada, IEEE Comput Soc Press, 1997.
36. Daanen H A M, Brunsman M A and Robinette K M, 'Reducing movement artifacts in whole body scanning', *Proc Int Conf Recent Advances in 3D Digital Imaging and Modeling (Cat. No.97TB100134)*, Los Alamitos, CA, USA & Ottawa, Ont., Canada, IEEE Comput Soc Press, 1997.
37. Corner B and Hu A, 'Effect of sway on image fidelity in whole body digitizing', *Proc SPIE*, Ottawa, Ontario, Canada, The International Society for Optical Engineering, 1998, 3313, 90–9.
38. Geisen G R, 'Automatic detection, identification, and registration of anatomical landmarks from 3D laser digitizer body segment scans', *IEEE 17th Annual Conf 1995*, San Jose, CA, USA, Engineering in Medicine and Biology Society, 1995.
39. Lewark E A and Nurre J H, 'Automated fudicial labeling on human body data', *Proc SPIE*, Montreal, Quebec, Canada, The International Society for Optical Engineering, 1998, 3313, 82–9.

9

Human anthropometrics and sizing systems

W YU

9.1 Terms and definitions

9.1.1 Anthropometrics

Anthropometrics can be defined as the science concerned with the measurement of man.[1] The name was derived from the Greek 'anthro' and 'metreein' which mean human and measure, respectively. Pheasant further expanded this definition to 'applied anthropometrics', which included numerical data concerning size, shape and other physical characteristics of human beings and could be applied in the design context .[2]

9.1.2 Anatomy

According to the *Columbia Encyclopedia*, anatomy is a branch of biology concerned with the study of body structure of various organisms, including humans. In Gray's classic publication, the term human anatomy comprises a consideration of the various structures which make up the human organism.[3]

9.1.3 Landmarks

Landmarks are located by anatomical points and grouped according to their positions on the body. This provides a predetermined order to permit greater speed in body measuring. Figure 9.1 shows 21 anatomical points[4] and Fig. 9.2 indicates 19 key landmarks.[5]

Clear landmarks with logical coding would be useful to explain all critical measurements for basic pattern development. From landmark points to body lines, all definitions and measuring methods should be standardised and commonly agreed. To obtain the data with acceptable consistency, reproducibility and reliability, structured methods of landmarking and recording will help to make the measuring process more efficient and effective.

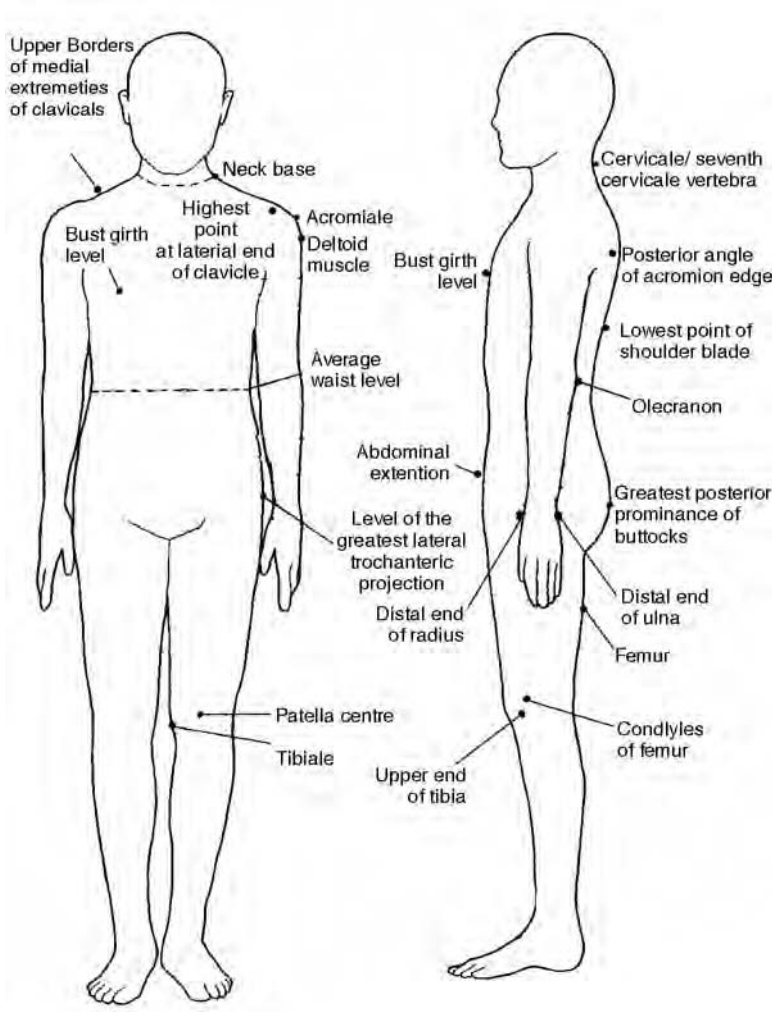


Figure 9.1 Critical anatomical points.

9.1.4 Body measurement

The classic terminologies and methods of body measurement for the clothing field were first published by the Joint Clothing Council.[4] A standard reference for body measurements was later made available.[6] Body measurements were divided into four groups: stature, segment length, body breadth and circumference. In 1996, Beazley suggested a procedure for undertaking a size survey using ISO 8559:1989 (E) which included a natural sequence of body measurement comprising three types of data: horizontal, vertical and others.[5] In Japanese Body Size Data 1992–1994, the definitions, equipment, methods and

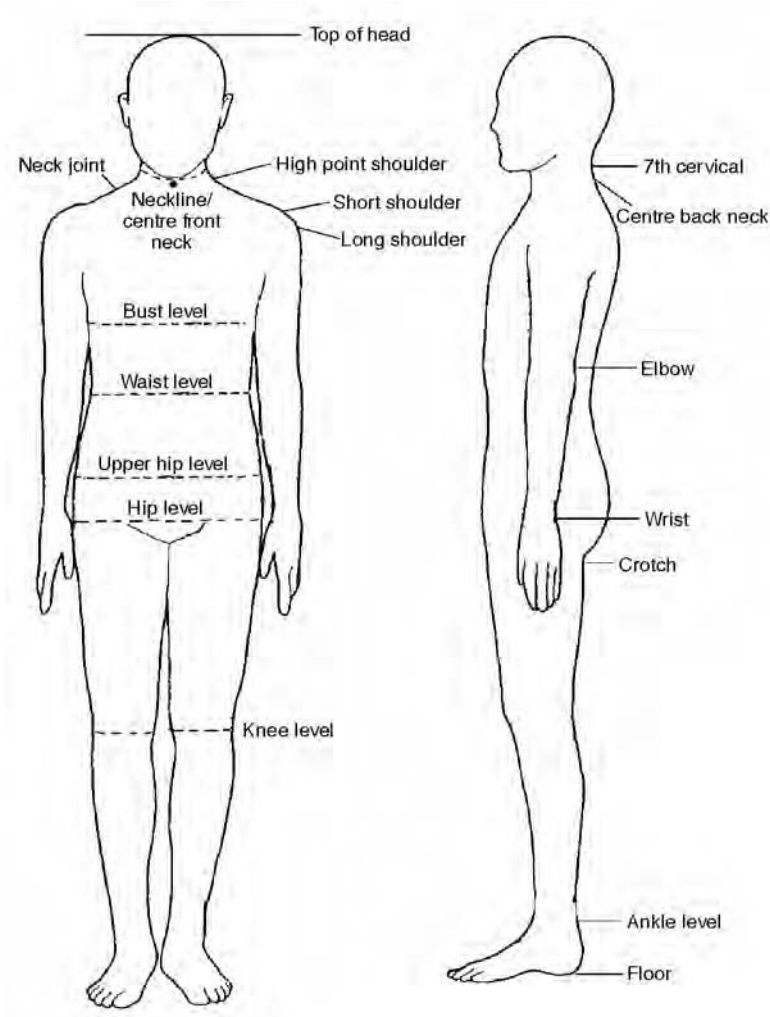


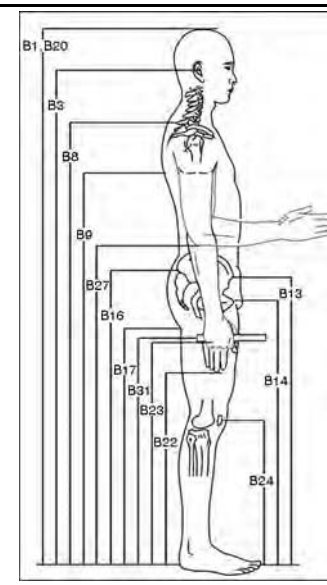
Figure 9.2 Key body landmarks.

procedures of body measurements were described in detail. An example of the vertical measurement is illustrated in Fig. 9.3.

9.2 Traditional anthropometry

A detailed account of the problems and methods of anthropometry was given by Cameron who outlined the historical development of anthropometry and gave a detailed comparison of equipment and methods of body landmarking. He also explained the dynamic relationship between subjects being measured, the measuring instruments and the measurer.[8]

Code	Measurement item	Definition of measurements
B1	Height	
B2	Entocanthion height	
B3	Tragion height	
B4	Suprasternale height	
B5	Fossa jugularis height	
	Nipple height (male) /	
B6	Bust height (female)	
B7	Substernale height (male) /	
	Underbust height (female)	
B8	Cervicale height	
B9	Axilla height	
B10	Iliocristal height	
	Height of minimum	
B11	abdominal circumference	
B12	Omphalion height	
B13	Iliospinale height	
B14	Symphysion height	
B15	Trochanterion height	
B16	Iliospinale posterius height	
B17	Gluteal furrow height	



B18	Crotch height	
B19	Acromiale height	
B20	Radiale height	
B21	Stylion height	
B22	Dactylion height	
B23	Phalangion III height	
B24	Mid-patellar height	
B25	Tibiale height	
B26	Height of calf circumference	
B27	Elbow height	
B28	Dactylion height, over head	
B29	Dactylion height, over head, heel raised	
B30	Maximum height	
B31	Fist height, grip axis	
B32	Gnathion height	
B33	Phalangion height, over head	
B34	Trunk length	

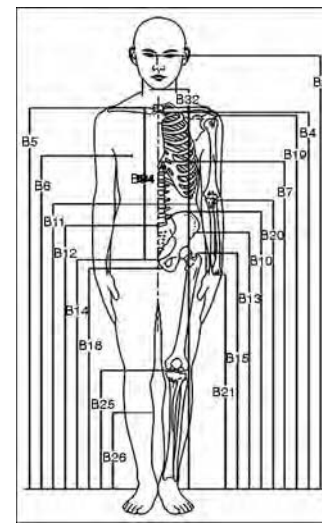


Figure 9.3 Definition of vertical body measurements. Source: Makiko Kouchi and Masaaki Mochimaru, 2002: Japanese body dimensions data 1997-1998, English version. Digital Human Laboratory, National Institute of Advanced Industrial Science and Technology.[7]

9.2.1 Anthropometric tools

Anthropometry deals with the methods of precise measurement of the human body. The methods and tools of anthropometry have been developed to make valid and reliable measures of individuals in a population for the design of clothing. The tools include anthropometers (a standing tool which measures straight linear distances), calipers, and calibrated measuring tapes. Linear heights are taken with anthropometers, while linear depths and widths are taken with calipers. Landmarks are carefully located (usually by feeling for bones beneath the skin) and marked on the body to identify anchor points for the measuring tools and to ensure that measurements are taken consistently and accurately.

9.2.2 Preparation

The environment for anthropometric measurement was suggested to be a quiet room without undue haste and the absence of unnecessary people. Before measurement, the researcher should select the measurements to be taken, acquire the correct instruments and design a recording form. The researchers who will collect the data must be trained so that they will arrive at the same measurement consistently.

9.2.3 Sampling

Identification of a representative sample of the population is critical in order to collect data which reflects the population as a whole. Age, ethnicity and body type must all be considered. Statistical methods can be used to identify a representative sample but finding subjects for every category could be challenging.

9.2.4 Challenges

Many factors come into play during the measurement of the subjects, which could be the source of numerous errors. Some important sources include posture, identification of landmarks, instrument position and orientation, and pressure exerted by the measuring instrument. Due to the difficulty in controlling all potential sources of error, true values are seldom obtained in anthropometry. Accuracy and precision of anthropometric measurements are at the mercy of the researcher who takes them.

Human errors

Manual measuring of a human body is not an easy task. Accuracy depends upon the touch and eye judgement of the researcher. The measurements may vary

with different landmarks on the body, positioning of the equipment and the tension of the tape measure.

Varied definitions
In the apparel industry, different definitions of body measurements are used in the various pattern-making methods. The differences in terminology and methods significantly impact on the measurements. Unclear landmarks of waist level can cause differing lengths and therefore result in obvious variations in fit.

Time-consuming process
Generally the collection of anthropometric data has been an extremely complex process which is time-consuming, expensive and requires skilled personnel. Recent technologies, such as 3D body scanning and automated measurement, may change this.

9.3 Historical development of sizing systems

In the latter part of the eighteenth century, most clothing was custom-made by tailors. Various sizing methods were developed by professional dressmakers and craftsmen. Their techniques for measuring and fitting their clients were unique. In the 1920s, the demand for the mass production of garments created the need for a standard sizing system. In the 1930s, mail-order houses became popular. This led to frequent returns of ill-fitting garments. Hence, a large anthropometric survey of 10,042 women was conducted to develop a sizing system for women's apparel.[9] During the last decade, very extensive data were made available for fitting general clothing as well as military wear and equipment. Specific large-scale studies are summarised chronologically below:

1901 The US federal government created the National Bureau of Standards (NBS), a non-regulatory agency, for the purpose of standardising measurements for science and industry.[10]

1902 In the Sears Catalog, dresses were coded with bust girth and age.[11]

1921 The first report was published of an American anthropometric survey with clothing sizing which was conducted on some 100,000 men during demobilisation at the end of First World War.

1937–41 A US size survey of some 147,000 boys and girls was conducted on a nationwide basis.

1939–1940 A further study on some 150,000 American women was conducted by the same team. The report entitled 'Women's measurements for garment and pattern construction' was published in 1941 by the US Department of Agriculture.

1945 The Mail Order Association of America recommended a commercial standard CS151 for the clothing industry.

1947	The British Standard Institution developed standards relating to garment sizing in a series of product standards, such as women's blouses (BS 1345).
1950s	The British Board of Trade published the results of a survey of 5000 women. It indicated that 126 sizes were required to cater for 98% of the adult female population.
1954	The Denmark Standards Association published a national standard DS923 for women's sizes.
1955–59	The Polish Academy of Science, in conjunction with the Central Laboratory of the Clothing Industry, conducted anthropometric surveys to establish a national sizing system.
1957	The United Kingdom published a report of a sizing survey collected from UK military personnel.[4]
1957–58	Germany published its first size table of body measurements.
1957–65	The former USSR carried out extensive surveys on the principal population groups, including men, women and children in various regions of the country.
1958	The US-based voluntary standard CS215-58, titled 'Body Measurements for the Sizing of Women's Patterns and Apparel', was published by NBS, based on further analysis of the 1939–40 data.[12]
1961–62	The German Research Institute conducted a survey of women for the clothing industry to produce properly fitting garments for the population.
1963	The German Hohenstein Research Institute published fairly extensive surveys for the preparation of women's and girls' outerwear size tables.
1963	The Netherlands Standards Institute (NNI) reported a standard sizing system for men's clothing.
1965–66	In France, the Centre d'Etudes Techniques des Industries de l'Habillement (CETIH) surveyed 7283 male subjects between the ages of 22 and 64.
1966	The German Textile Distributors' Association published size tables of outerwear for men and boys after a survey on some 10,000 subjects which constituted over 80,000 measurements.
1966–67	The Japanese JIS Standard reported a size survey of 35,000 subjects.
1969	CETIH in France compiled women's measurements with the exception of foundation garments. A survey was carried out on 8037 adult females between the ages of 18 and 65 years, and another on 14,000 boys and girls of 4 to 21 years of age.
1969	The first Australian survey of 11,455 women was carried out.
1970	The US Voluntary Products Sizing Standards PS 42-70 was published for commercial pattern sizing. Grading of sizes was

	arbitrarily set at 1 inch increments for girth and 1½ inch increments for height.[13]
1972	A Swedish national anthropometric survey was carried out on about 1000 subjects, and involving 40,000 measurements. This is a small sample but the population was fairly homogeneous.
1972	South Africa published a Code of Practice SABA 039 'Standard Size Ranges for Men's Clothing'.
1973	Body size tables PC 3137 and PC 3138 were published in the former USSR.
1974	The BS 3666 'Sizing Coding Scheme for Women's Outerwear' was published.
1974	China started to prepare a sizing standard for clothing, known as GB 1335–81, which was then implemented in 1981.
1975	The International Organisation for Standardisation (ISO) developed a new size labelling system with key dimensions and pictograms of figure types which would aid the consumers in size selection.[14]
1977	The Swedish Textile Research Institute (TEFO) and the Clothing Industries Federation (KIF) published a sizing system for women's garments which included market distribution charts.
1978–81	A further study was carried out in Japan on 50,000 subjects of both sexes and all ages.
1980–86	Size charts for the clothing industry in Netherlands were developed from measurements of 10,000 men and women.[15]
1981	The Chamber of Mines of South Africa Research Organisation reported an anthropometric survey on 669 black mine-workers.
1981	South Korea labelled garment sizes with arbitrary codes, but did not indicate body measurements.[16]
1981–82	Germany undertook further measurements of 10,000 women and girls.
1982	The British Standards Institution developed a series of size systems BS 3666 for women's wear, 3728 for children's wear and 5592 for men's wear.
1983	A sizing system was developed in Germany by adapting the ISO system.[17] The sample size was 9402 women and the result provided 57 sizes, catering for 80% of the female population.
1985	The Japanese JIS L4005 'Sizing Systems for Women's Garments' was published.
1986	A Hungarian standard sizing system, MSZ 6100/1, was developed.[17]
1987	To update the GB 1335-81 version for clothing applications, a Chinese national size survey was carried out to measure more than 14,000 men, women and children from ten different provinces.
1988	An anthropometric study for US army personnel, known as ANSUR, involved body measurements on 1774 men and 2208 women for the design and sizing of military clothing and equipment.[18, 19]

1989	The European Association of Clothing Industries (AEIH) provided sets of body dimensions for men and women of three height groups and six other body dimensions.
1990	A standard size labelling system was developed in South Korea.[20]
1991	A Chinese Sizing Standard GB 1335–91 was published after lengthy discussion among the clothing academia, industrialists and experts.
1992–94	34,000 Japanese people, aged from 7 to 90, were measured in two buses that travelled from south to north, equipped with a 3D body scanner.[21]
1994	The American Society of Testing and Material (ASTM) committee – published an updated standard known as D5585-94. It was not derived from new anthropometric data, but was compiled from designers' experience and market observations in the USA.[19]
1995	A survey of over 6000 women aged 55 and above was completed and found inappropriate representation of fit concerns for older women. A new standard ASTM D5586-95 was therefore established for this group.[22]
1997	The Chinese sizing standard was further updated to a new version GB 1335-97 with consideration of international practice.
1999–2002	The UK Government started a national sizing survey known as 'Size UK', using a [TC^2] 3D body scanner.[23]
2002–2003	'Size USA' commenced with similar methods and procedures as used for 'Size UK'[24] and completed the survey of 10,800 people in 13 cities across the United States in December 2003.
2004	A comprehensive national survey of 6600 men and women in Mexico is planned to be carried out, using a TC^2 body scanner.

People have changed in body shape over time. Workman[25] demonstrated that the problem of ageing contributes to the observed changes in body shape and size, more than any other single factor, such as improved diet and longer life expectancy.[26] Sizing concerns will grow as the number of ageing consumers is expected to double by the year 2030. This presents a marketing challenge for the clothing industry since poor sizing is the number one reason for returns and markdowns, resulting in substantial losses. Therefore, sizing systems have to be updated from time to time in order to ensure the correct fit of ready-to-wear apparel. Many countries have been undertaking sizing surveys in recent years.

9.4 Latest national size survey using a 3D body scanner

Along with the rapid development of a 3D body scanner, the international communities have already made headway in conducting anthropometric surveys using the state-of-the-art technologies in helping to reduce the time and labour

involved in the collection of anthropometric data. The intention is to have accurate and automated 3D body analysis information delivered to the apparel industry in a form which is immediately useful. The system measures body size, shape and volume in ways which can be customised for each apparel segment and even allows for the direct creation of garment patterns from 3D data, avoiding the interpretation step of using measurements and shape.

9.4.1 Japanese size survey (1992–1994)

Japan was probably the first country to use a 3D body scanner to conduct a large-scale national size survey. The statistical results of the survey are available in *Japanese Body Size Data 1992–1994*, published by the Research Institute of Human Engineering for Quality Life (HQL). About 19,000 Japanese males and 15,000 females aged from 7 to 90 were measured. Some 178 measurement items were obtained from the Voxelan laser 3D body scanner and traditional methods.

The major motivation for this sizing survey was to understand the changes that have occurred in body size and shape in Japan. It revealed that human stature decreased after the Kofun period, and was shortest at the end of the Edo period. Since then, it has increased very rapidly. The main reason for the observed changes is considered to be environmental factors relating to nutrition, rather than to genetic factors. Figure 9.4 shows the relation between the birth year and the mean stature of people aged 20. The mean stature of Japanese people has increased by more than 10 cm over the last 100 years. The rate of increase was especially high for the generation born in the 1940s, and became very low for the generation born in the 1970s. The inter-generation differences in stature are partly due to ageing, although the older generation was shorter than the younger generation even when they were young adults.

9.4.2 CAESAR (1998–2002)

The Working Group of the CAESAR project (Civilian American and European Surface Anthropometry Resource) consisted of the Computerised Anthropometric Research and Development Laboratory at Wright Patterson Air Force Base, the National Research Council from Ottawa, Canada, Iowa University, Department of Human Sciences at Loughborough University, and TNO. It used Cyberware's whole body scanner technology and funds from companies who each contributed US$40,000. The Working Group collected over 10,000 scans in North America and Italy. The subjects comprised various weights, ethnic groups, gender, geographic regions and socio-economic status. The survey included three laser scans per person, one standing and two in a sitting position (Fig. 9.5), as well as 40 traditional body measurements taken with a tape measure and calliper.

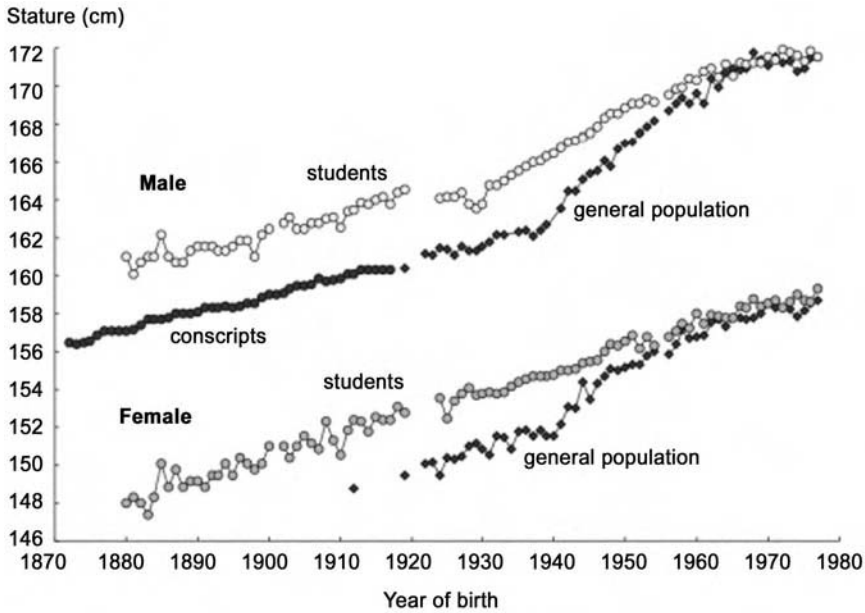


Figure 9.4 The year of birth versus the average stature of Japanese people aged 20. Source: Makiko Kouchi, 1996: Secular change and socio-economic difference in height in Japan. Anthropological Science, 104: 325–340.[27]

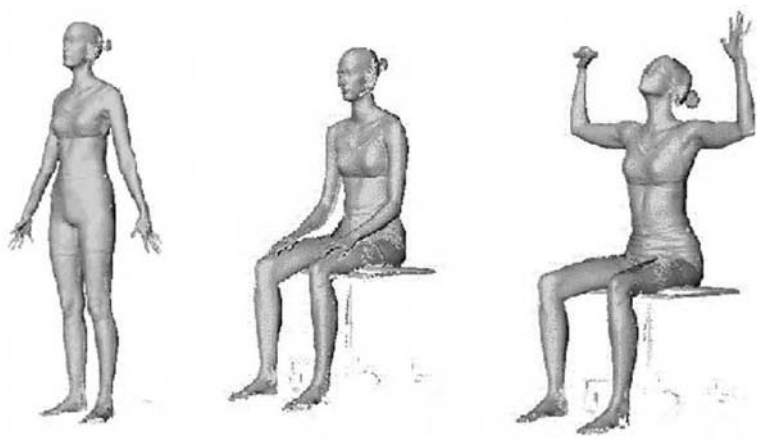


Figure 9.5 Three measuring postures. Source: Robinette, K., Blackwell, S., Daanen, H., Fleming, Boehmer, M., Brill, T., Hoeferlin, D., and Burnsides, D., (2002) Civilian American and European Surface Anthropometry Resource (CAESAR), Final Report, Volume I: Summary, AFRL-HE-WP-TR-2002-0169, United States Air Force Research Laboratory, Human Effectiveness Directorate, Crew System Interface Division, 2255 H Street, Wright-Patterson AFB OH 45433-7022.[28]

9.4.3 Nedscan (2000–2002)

Over the last fifty years, the Dutch people in the Netherlands have gained about 8 cm in height. The average height of 1.84 m for a male and 1.71 m for a female make them the tallest in the western world and they are still increasing in stature. Therefore, exact body dimensions are necessary to design and develop products which fit them and thereby improve the products of the apparel industry.

NedScan was a part of the CAESAR project, measuring the body dimensions of the Dutch population. In August 1999, the NedScan project started with over 2000 subjects in Soesterberg and planned to finish measurements in the Netherlands in September 2000. They then started measurements in Italy from June 2000 to 2002. TNO used the Cyberware 3D body scanner to take measurements of 42 body parts of 1255 Dutch men and women aged between 18 and 65.[29]

9.4.4 Size UK (1999–2002)

In 1999, the UK government launched a national research project and established the Centre for 3D Electronic Commerce. The project was sponsored by a group of commercial companies and leading clothing retailers. The project had three main parts: virtual shopping, custom clothing and the UK national sizing survey which is known as 'Size UK'. It was the largest and the first national survey in the UK since the 1950s. The cost of the UK Sizing Survey has been stated as $1.2 million. Three TC^2 body scanners were used in eight different locations around the UK. Over 140 measurements were automatically extracted for each subject, requiring only ten measurements to be taken manually.

Size UK demonstrates the use of 3D body scanning in a large-scale 3D size survey, with the aim of providing consumers with better fitting clothes. The London College of London and University College London have played a major role in the project, and a total of 10,000 women and men were scanned.

Bodymetrics was selected to be the exclusive seller for the National Sizing Survey data obtained from 'Size UK' in 2003. Therefore it is now responsible for analysing the body data of 5000 women and 5000 men and marketing the research data. From the analysed 3D shape data, the services to be offered include virtual try-on, and the supply of size charts and tailor dummies. They are also involved in the Body Craze program in Selfridges which has installed a TC^2 body scanner which scans its customers and digitally matches them with their ideal jeans. The results are fed into a denim data bank containing details of famous brands, such as Calvin Klein, D&G and Versace.

9.4.5 Size USA (2002–2003)

Following successful experience with the TC^2 body scanner in the Size UK survey, Size USA[30] has been able to use the same technology[31] in the American national size survey. It completed 10,800 scans of subjects by 16 December 2003. Top-level sponsors are being granted access to the initial survey data in quarterly increments. Apparel products influenced by the Size USA results already appeared on the market during 2003.

9.4.6 African body dimensions (2004–onward)

African body dimensions (ABD)[32] was a joint venture initiative to establish a South African national anthropometric database to address the specific requirements in the areas of clothing size and fit. Ergonomics Technologies and the University of Potchefstroom are the custodians of the South African National Defence Force (SANDF) anthropometric database, currently the largest South African anthropometric database and possibly the largest in Africa. The University of Pretoria hosted the Clothing Size and Fit Symposium held in 2000, which was the springboard that eventually led to the ABD initiative. A whole body scanner was housed in a mobile unit to allow measurements to take place all over the country. The requirements from the clothing and textile industry have become more urgent as the demographics of the consumer have changed rapidly within South Africa in recent years due to globalisation, growth in the informal market and the emergence of new consumer profiles.[33] The clothing and textile industry has recognised the need for a national South African anthropometric database and has excellent insight into the problems that arise in producing garments which are designed to provide a satisfactory fit for the diversity of consumers.

9.4.7 Women's size survey in mainland China

Donghua University has jointly established a Human Science Research and Development Centre in Shanghai with the Wacoal Corporation. During 1997–1999, 1100 Chinese women were measured with their upper body naked.[34] During 1999–2000, Zhang undertook a research project 'Body Shape Study for the Comparison between Korea and China' for Seoul University.[35] 2800 women from East, North and South China were surveyed up until 2002, using traditional Martin measuring techniques. Sixty-two body positions were considered and 12 body parameters were drawn of the female torso. A silhouetter and the American TC^2 non-contact body scanner were also applied in the survey.[36] A specially-made Voxelan 3D laser scanner was also installed in 2004 for the detailed measurement of the bust region.

In the Beijing Institute of Clothing Technology, a Human Engineering Research Centre was established in 1999. A comparison of body types between Chinese and Korean college women was carried out.[37] In 2003, a size survey of Chinese women was undertaken in collaboration with a local lingerie brand. A Japanese Voxelan 3D laser scanner was installed towards the end of 2003.

9.5 International sizing

9.5.1 National size designations

Many countries have conducted large-scale size surveys on a national basis, and have revised their size standards several times. The most updated size designations are summarised in Table 9.1.

9.5.2 Standardisation of sizing systems

International Organisation for Standardisation (ISO)

Since sizing practices vary from country to country, in 1968 Sweden originated the first official approach to the International Organisation for Standardisation (ISO) on the subject of sizing of clothing, it being in the interest of the general public that an international system be created. Sweden suggested a discussion on the terminology and definitions, dimensions and tolerances, and selection of sizes. The ISO then set up a new technical committee TC133 entitled 'Sizing

Table 9.1 Examples of latest size designations in various countries

Country	Last update	National standard	Body measurements			
			Men	Women	Children	Infants
Australia	1997	AS 1182		✓	✓	✓
Canada	1992	CGSB 49.5-M85-CAN/CGSB		✓	✓	✓
China	1997	CSIC GB/T 1335.1-97	✓	✓	✓	
France	1987	NF G03-008	✓	✓	✓	
Germany	2002	DIN EN 13402		✓		
Hungary	1986	MSZ 6100/1	✓	✓		
Japan	2001	JIS L4001 to 4005	✓	✓	✓	✓
Korea	1990	KS K0050 to 0052	✓	✓	✓	✓
New Zealand	1973	NZS 8774, 5	✓	✓		
Philippines	1988	BPS 114		✓	✓	✓
Singapore	1982	PSB SS262 part 1–6	✓	✓	✓	✓
Slovak	1981	SUTN STN 80 5023	✓	✓	✓	
South Africa	1982	SABS 039	✓			✓
Spain	1974	UNE-40229 to 31	✓	✓	✓	
UK	1989	BSI BS 3666	✓	✓	✓	✓
USA	2001	ASTM D 4910	✓	✓	✓	✓
ISO	1991	ISO/TR 10652	✓	✓	✓	✓

Systems and Designations for Clothes'. There were 17 country members participating actively in the work and the committee had its first formal meeting in 1970.[38]

After lengthy discussions and many proposals, the term 'Mondoform' was agreed on as a suitable title to cover size designation implementation work. At the completion of the fifth meeting in 1979, members submitted documents relating to secondary body dimensions, their definitions and methods of measuring. This eventually resulted in the publication of ISO 8559 'Garment Construction and Anthropometric Surveys – Body Dimension', which is currently used as an international standard for all types of size survey.[39] The ISO is now a worldwide federation of national standards bodies from more than 140 countries. The latest version of international standard for clothes is found in ISO/TR 10652:1991.

The ISO system suggested describing garment sizes in a 'pictogram' in which an illustration of key dimensions is shown. These size-labelling systems will let consumers select their garment sizes by comparing their measured body size with that labelled on the garment. It is expected that consumers will be able to find their correct garment size easily without trying on too many garments. The system will also reduce manufacturers' and retailers' costs associated with the frequent returns of ordered garments and damaged garments after fitting trials.

European size standard

Further attempts to establish a uniform European size designation have been made by several organisations, these only being found in the literature, and not in practice.[40] In 1994, the first steps towards a European standard in TC 248 failed. In a second attempt in 1996 the Working Group was set up with experts from 12 countries. It revised the Mondoform to such an extent that important body measurements (height, waist and hips) could be associated, in a more flexible manner, with size series. For cost and logistical reasons, agreement has been reached on the fact that the code must not consist of more than three digits. A four-part standard (EN 13402) has been drawn up:

Part 1: Definition of the uniform body measuring procedure, and the corresponding measuring positions on the basis of pictograms.
Part 2: Agreed primary and secondary dimensions.
Part 3: Appropriate starting points and intervals between individual sizes.
Part 4: For committee agreement if there is a system compliance.

The corresponding standard was fully approved in 2003 and was published in 2004.[40]

Acceptance of standard sizing systems

Body shapes and proportions may differ significantly. Body shapes vary not only from country to country but also within countries. It might not be feasible

to construct a single set of body sizes which could be universally applied. What has been developed is a systematic format which is sufficiently open and flexible to cater for this variability, and uses certain preferred numbers and fixed intervals to render it internationally applicable. This commonality will make sizes recognisable and comparable around the world.[41]

Although the standards were reissued and updated periodically, manufacturers preferred having flexibility to change measurements quickly to suit consumer needs without reference to rigid standards.[42] According to LaBat and Delong,[26] manufacturers have resisted accepting the US sizing code. They preferred to define their own target markets through small consumer surveys. Department stores, such as Sears, J.C. Penney, Montgomery Ward and Spiegel, have developed their own specifications, better to satisfy the needs of their specific buying public. However, commercial data were collected from narrow company-specific populations and the data remained confidential.[43]

Another commercial practice is to use commercial dress forms for initial style development, the body being assumed to be symmetrical and balanced with standard body proportions. Yet these could not represent the average person in the population. Fit models play a critical role in sizing, once initial sample garments constructed from the dress forms are adjusted to the specifications of a fit model, before production begins. These specifications affect all sizes, since garments are graded from the fit model size. Goldsberry *et al*.[22] revealed that the size specifications for fit models have changed less than actual body measurements in the population.

Different manufacturers have had different size-defining systems. Even for the same size code, body measurements have changed over time. Consumers are dissatisfied with the search process needed to identify their sizes.[44] Some clothing manufacturers and retailers even deliberately downsized clothing codes from a larger size to a smaller size, in order to promote sales by appealing to customers who felt happier with smaller sizes. It brought confused sizing into the market.

To conclude, manufacturers in most countries are slowly adopting size standards and each continues to have its own specific size chart. This creates some questions[17] concerning the sizing system:

- Is the classification and selection of key dimensions reasonably done?
- Do consumers in various countries prefer to use a common sizing system?
- Are consumers able to use a sizing system which includes a list of body measurements?

9.6 Principles of sizing systems

Problems with regard to clothing sizing and fit continue to be identified globally for consumers.[33,45–48] Manufacturers and retailers incur excessive costs due to

poor prediction of stock levels.[49] Solutions can be addressed more effectively with the application of interpreted data from a national anthropometric database and sizing system.

9.6.1 Important aspects

In 1975, French suggested that sizing should have three principal aspects:[14]

1. Relationship between one dimension and another in a particular garment.
2. Size intervals by which one garment is larger than the *next* smaller garment.
3. What the size should be called, so as to identify it.

In 1993, Chun-Yoon and Jasper reviewed the sizing systems of several countries, giving detailed examples[17] according to:

- how they defined figure types
- how they described garment sizes
- which key dimensions are used for the sizing system
- how they grouped garment types.

In 1997, Winks[38] concluded that the essential elements of a sizing system comprised:

- predetermined size ranges
- specified size intervals
- a standard method of size designation
- size labelling.

The goal of any sizing system is to choose size groups in such a way that a limited number of sizes will provide ready-to-wear clothing which fits most individuals in the population. Although sizing systems developed by different countries vary in the body dimensions chosen to divide the population, the basic structure of most sizing systems is very similar.

9.6.2 Definition of figure types

To create a sizing system, the population is first divided into different body types, based on dimensions, such as height or ratios between body measurements. A set of size categories is developed, each containing a range of sizes from small to large. The size range is generally evenly distributed from the smallest to the largest size.

Women's body types
Most countries, such as England,[4] Germany[50] and Hungary,[51] developed sizing systems which classified figure types according to height and drop value. Drop value is the difference between hip and bust circumference.[17] In the UK, the

Joint Clothing Council defined three figure types according to height: short, average and tall. Within each group, five figure types were classified according to bust measurements.[4] In Germany, the height and hip types defined nine figure types. Heights were grouped into average height (normal), short (kurze) and tall (lange). Each group is divided into three hip types; slim hip type (schmalhuftig), average hip type (normalhuftig) and full hip type (starkhuftig).[50] Similarly, the Netherlands classified women's figures into three heights – 1.60 m, 1.68 m and 1.76 m, with three hip sizes – small, normal and wide. This resulted in nine sizing charts.[15] The Hungarian sizing system (MSZ 6100/1-86) defined only two female figures: normal and full, as classified by height and body-build.[51]

In the United States, early commercial standard CS215-58 defined 20 figure types according to height and hip size determined by drop values.[52] It was then revised to the product standard PS 42–70 in 1970. The figure types are classified as junior petite, junior, misses petite, misses, misses tall, women's and half-sizes. Austria sells women's wear made for two height groups: kurze (short) and normale (normal).[17] The Korean Industrial Standard Association developed a standard sizing system, which classified body figures into five height groups: 150 cm, 155 cm, 160 cm, 165 cm and 170 cm.[16] In Canada, three height groups of 155, 163 and 171 cm have three body types (junior, misses and women).[38] Czechoslovakia suggested coding the figure types as A, B and C which have drop values of 6–10 cm, 4–12 cm and 7–8 cm, respectively.

ISO developed a revised sizing system in 1991. It classified body types into A type, M type, and H type also according to the drop values (difference between bust and hip circumference) as shown in Fig. 9.6.

Men's body types

For men's wear, the body length and drop value are the two main measurements characterising the definition of figure type. Maier has compared existing sizing systems throughout the world.[40]

In the UK, BSI identified three body heights; short (166 cm), regular (174 cm) and tall (182 cm). Each has two figure types; mature (drop – 14 cm) and athletic (drop – 17 cm). The German sizing system places men's figure types into eight different categories: athletic, slim, normal, stocky, large, short stocky, large waist and short large waist as reported in Table 9.2.

In the United States, three body heights, regular, tall, and extra tall, are normally identified with two types of figure: regular and large, as reported in Table 9.3. The French identify five main body heights in cm; 162, 168, 174, 180 and 186 and seven types of figure: athletic, slim, normal, stocky, large, stout and large waisted (Table 9.4).

In Argentina, Czechoslovakia, Denmark, the Netherlands and Finland, men's figures are all categorised according to drop values. The slim figure has a drop value of 12–16 cm, while corpulent men have up to −2 to −6 cm drop.[38]

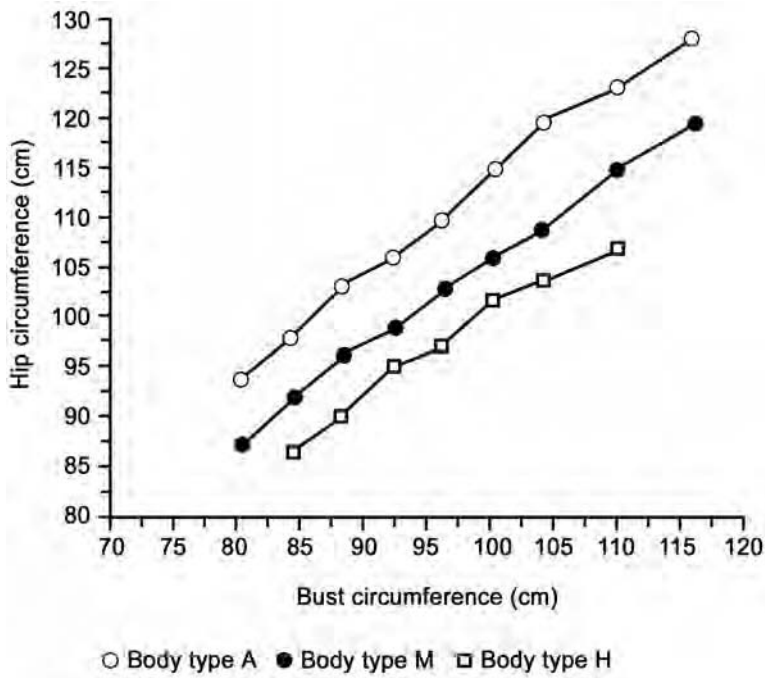


Figure 9.6 Distribution of figure types in ISO (1991). Source: Chun-Yoon and Jasper, 1993.[17]

9.6.3 Selection of key dimensions

Key body dimensions are chosen to divide the population into size groups.[19] The selection of key dimensions must satisfy the following requirements:[53]

Table 9.2 German men's figure type categorisation

Type of figure	Size making	Drop	Body height
Athletic	440–1060	−16 cm	168–190 cm
Slim	90–110	−12 cm	177–190 cm
Normal	44–58	−12 cm to −8 cm	168–186 cm
Stocky	22–29	−8 cm to −6 cm	162–180 cm
Large	144–156	−8 cm to −6 cm	168–184 cm
Short stocky	225–295	−6 cm to −4 cm	156–174 cm
Large waist	47–59	+4 cm/+6 cm/+8 cm	166–178 cm
Short large waist	495–575	+4 cm/+6 cm/+8 cm	162–170 cm

Source: Maier 2000.[40] By courtesy of Professor Angela Maier (Mrs), Dean of the Textile Department of The University of Applied Sciences, Reutlingen, Germany. Printed first by *Knitting Technology*, 22(1), p. 32.

Table 9.3 American sizing system

Sizes	Designation	Body height	Drop
S-XXL	Regular	173–182 cm	–15 cm
MT-XXLT	Tall	183–192 cm	–15 cm
MXT-3XIXT	Extra Tall	193–201 cm	–15 cm
2XL-5XL	Big Regular	173–182 cm	–10 cm
2XLT-5XLT	Big Tall	183–192 cm	–10 cm

Source: Maier 2000.[40] By courtesy of Professor Angela Maier (Mrs), Dean of the Textile Department of The University of Applied Sciences, Reutlingen, Germany. Printed first by *Knitting Technology*, 22(1), p. 32.

Table 9.4 Classification of the French tables according to types

Types of figures	Designation	Drop	Body Height in cm
Athletic sizes	Athletique	–16 cm to 14 cm	168/174/180
Slim size	Elance	–12 cm to 8 cm	180/186
Normal size	Normal	–12 cm to 8 cm	168/174/180/186
Stocky size	Fort	–8 cm to 4 cm	174/180
Large size	Trapu	–8 cm to 4 cm	162/168
Stout sizes	Corpulent	–4 cm to +/–0 cm	162/168/174
Large waist sizes	Ventru	+4 cm/+6 cm/+8 cm	162/168/174/180

Source: Maier 2000.[40] By courtesy of Professor Angela Maier (Mrs), Dean of the Textile Department of The University of Applied Sciences, Reutlingen, Germany. Printed first by *Knitting Technology*, 22(1), p. 32.

- convenient to measure
- an integral part of the garment
- have a high degree of correlation with other dimensions important in sizing
- not highly correlated with each other.

The BSI, ISO, KS and JIS systems suggest the use of different key dimensions for various garment types.[17] The Japanese example is shown in Table 9.5.

9.6.4 Designation of size labelling

Size labelling is a tool for assisting consumers to choose apparel which fits their body properly. However, garment sizes are indicated by arbitrary numbers which may represent different key measurements in different systems. Table 9.6 shows how various countries differ in the combinations of body measurements in relation to similar bust sizes of 92 cm on average.

Table 9.5 Japanese garment types and key dimensions

Garment types	Key dimensions
A. Coats, dress, and upper-body garments	Bust C, hip C*, and height
B. Skirt	Waist C, and hip C
C. Pants	
• Long pants	Waist C, hip C* and leg-inseam length
• Other pants	Waist C, and hip C*
D. Garment at work	
• Whole body garment	Bust C, and height
• Upper body garments	Bust C, and height
• Lower body garments	Waist C
E. Sweater, jacket, blouse, shirts, and sleep-wear	Bust C and height
F. Underwear (bra and foundations are excluded)	
• Whole body	
1. Slip	Bust C, and length of slip
2. Other	Bust C and hip C
• Upper body	Bust C, and underbust C
• Lower body	
1. Petticoat	Hip C. and garment length
2. Others	Hip C
G. Swimwear	Bust C, hip C

Note: Data in this table are from Japanese Industrial Standard JIS L 010, p. 8, published by Japanese Standard Association (1990).
* Hip circumference is a key dimension for fitted garment.
'C' Stands for circumference measurements

Source: Chun-Yoon and Jasper, 1993.[17]

9.6.5 Size interval

All sizing systems have both similarities and differences, although size intervals are usually classified according to height and drop value.

For women, drop value was defined as the difference between the hip circumference and the bust circumference.[17] The drop value for average women's sizes can vary from 2.5 to 8 cm, according to the particular country.

For men, Maier defined drop value as the difference between the chest and the waist measurement.[40] A comparison of the size interval and drop value for men in various countries is given in Table 9.7. In the United States, the gap between sizes is 5 cm. In Europe, size changes every 4 cm. The drop value of each size remains constant in some countries (e.g. 12 cm in Japan, 14 cm in China, 15 cm in the United States). In other countries, such as Switzerland and Scandinavia, the drop value of the smallest size is 15 cm, but it decreases by 1 cm for every one size up.

For children, countries are using age as the determinant for size. In the Fourth National Growth Study in Netherlands, 20,000 children were measured, from

Table 9.6 Size labelling and body measurements in various countries

Country	Size label	Measurements (cm)			
		Bust	Hips	Height	Waist
Australia	14	90	95	160–170	70
Bulgaria	81	92	96	164	69.9
Czechoslovakia	3AA45	90	98	166	68
Finland	NC40 or C38	92	98	161–166	70
Germany	40	92	98	164	72.5
Hungary	164/80/94	90	94	164	68
Ireland	12	–	91–95	158–168	–
Israel	40	92	100	165–167.5	70.5
New Zealand	14	92	97	157–165	72
Poland	164/92/96	92	96	164	–
South Africa	92/96/164	92	96	165	72
Spain	42 + 2/L	92	96	167	67
Sweden	C40	90	98	163–170	–
UK	14, 38, or 8	90–94	95–99	160–170	–
USA	12 or 14	93	98	165	70
USSR	164/92/96	92	96	164	–
Yugoslavia	40	92	100	162	72

Source: Winks, 1997.[38]

which it emerged that children's height and age no longer appeared to increase in step with one another. That is why the Dutch clothing sizing system for children is no longer based on age, but on height. In the new sizing tables for children, there are 24 height categories, from 50 to 194 cm, each spaced at 6 cm intervals.[15]

In the 1970s and 1980s, ISO developed a new size labelling system in which body measurements of key dimensions are listed. Many countries revised their sizing systems by adopting the system developed by the ISO. Standard size-labelling systems were developed in the UK in 1982, in Hungary in 1986 and in South Korea in 1990. They suggested describing garment sizes in a sequence of numbers, a table form, or a 'pictogram' in which an illustration of key dimensions is drawn. These size-labelling systems will let consumers select their garments size by comparing their measured body size with the body size labelled on a garment. It is expected that consumers will find their correct garment sizes a lot easier, without having to try on too many garments, even though each manufacturer continues to have its own body measurements for each size code.[38]

9.7 Conclusion

Definitions of human anthropometrics and related terms have varied from country to country and from time to time. This chapter provides a review of

Table 9.7 Comparison of size interval and drop value of men in different countries

Germany									
Size	44	46	48	50	52	54	56	58	
Body height (cm)	168	171	174	177	180	182	184	186	
Chest measurement (cm)	88	92	96	100	104	108	112	116	
Waist measurement (cm)	76	80	84	88	92	98	102	108	
Drop (cm)	−12	−12	−12	−12	−12	−10	−10	−8	
Swiss Fashion									
Size	88	92	96	100	104	108	112	116	120
Body height (cm)	176	176	176	176	176	176	176	176	176
Chest measurement (cm)	88	92	96	100	104	108	112	116	120
Waist measurement (cm)	73	78	83	88	93	98	103	108	113
Drop (cm)	−15	−14	−13	−12	−11	−10	−9	−8	−7
France									
Size	44−38	46−40	48−42	50−44	52−47	54−50	56−52		
Body height (cm)	174	174	174	174	174	174	174		
Chest measurement (cm)	88	92	96	100	104	108	112		
Waist measurement (cm)	76	80	84	88	94	100	104		
Drop (cm)	−12	−12	−12	−12	−10	−8	−8		
Great Britain									
Size	34	36	38	40	42	44	46	48	50
Body height (cm)	174	174	174	174	174	174	174	174	174
Chest measurement (cm)	88	92	96	100	104	108	112	116	120
Waist measurement (cm)	74	78	82	86	90	98	102	106	110
Drop (cm)	−14	−14	−14	−14	−14	−10	−10	−10	−10
Netherlands									
Size	44	46	48	50	52	54	56	58	60
Body height (cm)	182	182	182	182	182	182	182	182	182
Chest measurement (cm)	88	92	96	100	104	108	112	116	120

Table 9.7 Continued

Waist measurement (cm)	75	80	85	90	95	100	105	110	115
Drop (cm)	−13	−12	−11	−10	−9	−8	−7	−6	−5
Scandinavia									
Size	C44	C46	C48	C50	C52	C54	C56	C58	
Body height (cm)	176	176	176	176	176	176	176	176	
Chest measurement (cm)	88	92	96	100	104	108	112	116	
Waist measurement (cm)	73	78	83	88	93	98	103	108	
Drop (cm)	−15	−14	−13	−12	−11	−10	−9	−8	
USA									
Size	S/34	S/36	M/38	M/40	L/42	L/44	XL/46	XL/48	
Body height (cm)	178	178	178	178	178	178	178	178	
Chest measurement (cm)	86	91	96	102	107	112	117	122	
Waist measurement (cm)	71	76	81	86	91	97	102	107	
Drop (cm)	−15	−15	−15	−15	−15	−15	−15	−15	
China									
Size	170/88A	108/92A	170/96A	170/100A	170/104A				
Body height (cm)	170	170	170	170	170				
Chest measurement (cm)	88	92	96	100	104				
Waist measurement (cm)	74	78	82	86	90				
Drop (cm)	−14	−14	−14	−14	−14				
Japan									
Size	88A5	92A5	96A5	100A5					
Body height (cm)	170	170	170	170					
Chest measurement (cm)	88	92	96	100					
Waist measurement (cm)	76	80	84	88					
Drop (cm)	−12	−12	−12	−12					

Source: Maier 2000.[40] By courtesy of Professor Angela Maier (Mrs), Dean of the Textile Department of the University of Applied Sciences, Reutlingen, Germany. Printed first by *Knitting Technology*, 22(1), p. 32.

various methods of body measuring and sizing systems. The traditional manual methods have been commonly used for many years but have many limitations. With the rapid growth of 3D body scanning technologies, many clothing researchers in several countries have initiated the need to update the national size standards which were developed in the 1940s and 1950s. The various large-scale sizing projects have been summarised in a chronological list, and the most recent national size surveys described in detail. However, the standardisation of sizing systems has been debated for a long time, and the acceptance of such a standard is sometimes in question. Even so, the principles of sizing systems, such as figure types, key dimensions, size intervals and size labelling can be drawn up as a reference for clothing education and research.

9.8 References

1. Kunick P, *Modern Sizing and Pattern Making for Women's and Children's Garments: A Scientific Study in Pattern Construction and a Standard Textbook for the Clothing Industry*, London, Philip Kunick Publications, 1984.
2. Pheasant S, *Bodyspace Anthropometry Ergonomics and Design*, London, Taylor & Francis, 1986.
3. Gray H, *Anatomy of the Human Body*, Lea and Febiger, Philadelphia, 1918.
4. Kemsley R, *Women's Measurements and Size – A Study Sponsored by the Joint Clothing Council Limited*, London, HMSO, 1957.
5. Beazley A, 'Size and fit: procedures in undertaking a survey of body measurements', *J Fashion Marketing and Management*, 1997 **2**(1) 55–85.
6. Lohman T G, Roche A F and Martorell R, *Anthropometric Standardization Reference Manual*, Human Kinetics Books, Illinois, 1998.
7. Kouchi M and Mochimaru M, *Japanese Body Dimensions Data 1997–1998*, English version, Digital Human Laboratory, National Institute of Advanced Industrial Science and Technology, 2002.
8. Cameron N, *The Measurement of Human Growth*, Sydney, Croom Helm, 1984.
9. Devarajan P, Istook C L and Simmons K P, 'U.S. sizing standards and the U.S. female consumer', *Proc of IFFTI Conf, Fashion and Text: the New Frontiers – Design, Technology and Business*, Hong Kong, 7–9 Nov., 2002.
10. Armstrong H J, *Patternmaking for Fashion Design*, New York, Prentice Hall, 2000.
11. Swearingen E, *Theoretical Model for Apparel Design Curriculum: Fit Satisfaction, Body Cathexis and Creativity*, MSc Thesis, California State University, Fresno, 1999.
12. National Bureau of Standards Commercial Standard CS215-58, *Body Measurements for the Sizing of Women's Patterns and Apparel*, Washington, D.C., U.S. Department of Commerce, U.S. Government Printing Office, 1958.
13. National Bureau of Standards Commercial Standard PS42-70, *Body Measurements for the Sizing of Women's Patterns and Apparel*, Washington, D.C., U.S. Department of Commerce, U.S. Government Printing Office, 1970.
14. French G E, 'International sizing', *Cloth Inst J*, 1975 **23**, 155–162.
15. TNO magazine, 'New clothes sizing charts: fitting selection offered to the consumer', URL: http://www.tno.nl/en/news/tno_magazine/march_2002/

em1_12_13.html, 2002.
16. KS K0068, *Sizes for Women's Blouse*, Seoul, Korean Industrial Standard Association, 1981.
17. Chun-Yoon J and Jasper C R, 'Garment sizing systems – an International comparison', *Int J Cloth Sci Technol* 1993 **5**(5) 28–37.
18. Gordon C C, Bradtmiller B, Clausner C E, McConville J T, Tebetts I and Walker R A, 'Anthropometric survey of US army personnel', *Technical Rep NATICK/TR-89/044*, Natick, MA, US Army Natick Research, Development, and Engineering Center, 1988.
19. Ashdown S P, 'An investigation of the structure of sizing systems – a comparison of three multidimensional optimized sizing systems generated from anthropometric data with the ASTM standard D5585–94', *Int J Cloth Sci Technol*, 1998 **10**(5) 324–341.
20. KS K0051, *Sizing System for Women's and Girl's Garment*, Seoul, Korea Standard Association, 1990.
21. National Institute of Bioscience and Human Technology, *Japanese Body Size Data 1992–1994*, Osaka, National Institute of Bioscience and Human-Technology, 1997.
22. Goldsberry E, Shim S and Reich N, 'Women 55 years and older: Part I. current body measurements as contrasted to the PS 42–70 data', *Cloth Text Res J*, 1996 **14**(2), 108–120.
23. Bougourd J P and Treleaven P C, 'Capturing the shape of a nation: Size UK', *IFFTI Int Conf*, Hong Kong, 2002.
24. Fashion Business International, 'US launches national sizing survey', *Fashion Business Int*, 2002 (June/July) **32**.
25. Workman J E, 'Body measurement specification for fit models as a factor in apparel size variation', *Cloth Text Res J*, 1991 **10**(1) 31–36.
26. LaBat K L and Delong M R, 'Body cathexis and satisfaction with fit of apparel', *Cloth Text Res J*, 1990 **8**(2) (Winter) 42–48.
27. Kouchi M, 'Secular change and socioeconomic difference in height in Japan', *Anthropological Sci*, 1996 **104** 325–340.
28. Robinette K, Blackwell S, Daanen H, Fleming, Boehmer M, Brill T, Hoeferlin D, and Burnsides D, 'Civilian American and European Surface Anthropometry Resource (CAESAR)', *Final Rep, 2002 Volume I: Summary, AFRL-HE-WP-TR-2002-0169*, United States Air Force Research Laboratory, Human Effectiveness Directorate, Crew System Interface Division, 2255 H Street, Wright-Patterson AFB OH 45433-7022.
29. Nedscan, URL: www.nedscan.nl, 2001.
30. Size USA ([Online]), 'Let's Size up America', URL: http://www.sizeusa.com.
31. TC^2, 'Size USA Moves to the West Coast', URL: http://www.tc2.com/RD/RDNews.htm, 2003.
32. MacDuff L and Smith J R, ([Online]) 'African Body Dimensions – A South African Anthropometric Initiative', URL: http://cyberg.wits.ac.za/cyberg/sessiondocs/physical/anthro/anthro4/anthro4.htm.
33. Dunne N, *Understanding the South African Clothing Manufacturing Sector' from the Perspective of Leading South African Clothing Retailers*, Industrial Restructuring Project, School of Development Studies, University of Natal, Research Report No. 31, 2000.
34. Human Science Research and Development, Brochure of Wacoal (Shanghai) Human

Science R&D Co Ltd 2003.
35. Program & Event, *IFFTI International Conference, Fashion and Textiles: the New Frontiers – Design, Technology and Business*, 7–9 Nov., 2002, Hong Kong, 2002 p. 6.
36. Zhang W Y, Li K & Dai W, 'Analysis of Chinese female body shape', Keynote Speech, *IFFTI Int Conf Fashion and Text: the New Frontiers – Design, Technology and Business*, 7–9 Nov., 2002, Hong Kong, 2002.
37. Sohn H S, Lim S, Kim H S, Son H J, Kim Y S, Jang H K & Jung R, *A study on the comparison of body types between Chinese and Korean college women*, Costume Culture Assoc, Korean, 1999 2(1) 43–53.
38. Winks J, *Clothing Sizes – International Standardization*, Manchester, The Textile Institute, 1997.
39. ISO 8559 *Garment Construction and Anthropoetric Surveys – Body Dimensions*, International Organization for Standardization, 1989.
40. Maier A, 'International size chart comparison for men', *Knitting Technol*, 2000 **22**(1) 32–36.
41. Wicks J, 'Mondoform – the breakthrough in the sizing of apparel', *Apparel Int*, 1991 32.
42. Simeon B, 'Berlei size right survey', *British Clothing Manufacturer*, 1973 **9**(4) 32.
43. Bougourd J P, Dekker L, Ross P G and Ward J P, 'A comparison of women's sizing by 3-D electronic scanning and traditional anthropometry', *J Text Inst*, 2000 **91**(2), 163–173.
44. LaBat K L, *Consumer Satisfaction/Dissatisfaction with the Fit of Ready-to-wear Clothing*, University of Minnesota St Paul, 1987.
45. Desmarteau K 'Let the fit revolution begin', URL: www.findarticles.com, 2000.
46. Senanayake M M and Little T J, '''Measures'' for a new product development', *J Text Apparel Technol Management*, 2001 **1**(3) 1–10.
47. Snyder R G, Scheider L W and Owings C L, 'Infant, child and teenager anthropometry for product safety design' *Advances in Consumer Res*, 1978 **5**.
48. Chun-yoon J and Jasper C R, 'Consumer preferences for size description systems of men's and women's apparel', *J Consumer Affairs*, 1995 **29**(2) 429–441.
49. Kuma M, *The Development of a Design Guide for the Plus-size Body-form*, MSc Thesis, Technikon, Pretoria, 1999.
50. DOB-Verband *DOB-Grossentabellen (Women's Outer Garment Size Chart)*, Germany, Cologne, 1983.
51. MSZ 6100/1-86, The Office of Hungarian Standards, Budapest, Hungarian People's Republic State Standards, 1986.
52. National Bureaus of Standards CS 215-58, *Body Measurements for the Sizing of Women's Patterns and Apparel*, Washington DC, U.S. Department of Commerce, N. B. O. S. N., US Government Printing Office, 1958.
53. McConville J T, Tebbetts I and Churchill T, 'Analysis of body size measurements for US navy women's clothing and pattern design', *Naval-Cloth Text Res Facility*, 1979.

10

Garment design for individual fit

M Y KWONG

10.1 Introduction

Pattern making is the process of transforming three-dimensional designs into their two-dimensional constituent pattern pieces. Traditionally, pattern making in the apparel industry involves the process of obtaining the linear measurements over the body surface with a tape measure, and then applying these measurements to draft the pattern based on a mathematical foundation and approximation. The body form comprises both convex and concave surfaces, and no two bodies are identical. As noted by Whife,[1] however many measurements are taken from a human body and however carefully they may be applied to a pattern, this will not guarantee a perfectly fitted garment since measurements alone cannot fully determine the shape of the human body. An 'observation' and 'judgment' of shapes and contours must be applied in order to achieve a good fit.

According to Bray,[2] defects in garments are connected with, and conditioned by, a variety of circumstances; the shape of the figure is one of the concerns apart from the texture of the fabric, and type of garment and the way it is worn.

Anglais[3] also stated that most of the fitting problems are due to figure abnormalities. Therefore, the activities of garment cutting and fitting include correct measurements and figure observations – careful cutting and accurate fitting.[4]

Body contour, posture, body proportion and symmetry affect the fit of clothing. Patterns are designed for an average symmetrical body shape, with standard posture and body proportions. Very few individuals are the same size and shape as this standard model; therefore, pattern alterations need to be made before garment pieces are cut and fitting adjustments are also made during the assembly process.[5]

10.2 Pattern alteration for fit

Barnes[6] stated that making clothing which really fits is one of garment making's greatest challenges – and crucial successes. No matter how lovely the fabric,

how fine the garment design, or how expert the sewing, the results are disappointing if the garment fits poorly. Bray[7] pointed out the difficulty of applying contour measurements to a flat surface and stated that results are bound to be somewhat approximate, and inaccuracies have to be allowed for.

There are numerous texts containing studies of the body form and illustrated methods of pattern alteration for different figure types to achieve fit, especially based on the problems relating to different figure types.

10.2.1 Study of the human anatomy

Analysis of ladies' figures

Whife[1] investigated three female figures and found that although the circumferential measurements of bust, waist and hips of the three figures might appear similar, the shapes of these figures were quite different and would require different shaped garments to give an accurate fit. Whife[1] also found that although all three figures had exactly the same chest girth and might have the same bust girth, the bust shape clearly differed from one figure to another and the distances between the bust line and chest line were also different. The figures had different bust lengths from the shoulder, and the distances between the breast and waistline also differed considerably. It was clearly evident from the figures that chest and bust girths are not in themselves indicators of chest and bust shape.

Perry[8] noted that improper posture might cause clothing fitting problems. The rigid or extremely erect figure shortens the distance from the back of the neck to the shoulder blade, and lengthens the distance from the base of the neck to the apex of the bust thereby causing fitting problems. The opposite of this rigid posture is a slumped figure, which will cause fitting problems due to rounded shoulders, dowager's hump, sway back and protruding abdomen.

Rasband[9] classified ladies' body shapes into eight types: ideal, triangular, inverted triangular, rectangular, hourglass, diamond-shaped, tubular and rounded.

Researchers found that as the body ages, certain predictable physical changes take place. Goldsberry and Reich[10] noted that the more obvious changes are the expansion of the waist and abdominal girth, coupled with a shortening of the spinal column. Katou and Nakaho[11] found that the lower half of the body of elderly women, especially the abdomen and hips, undergo noticeable changes as they grow older. Similarly, Le Pechoux and Ghosh[12] found that elderly women will tend to become larger around the waist, hips and thighs, with spinal column curving and shortening. From the age of 50 onwards, the body fat of women decreases at a rate of 1% annually, also indicating that their overall body dimensions are becoming smaller. Studies conducted by NTC (National Textile Center) Project No. I01–A27 indicate that body dimensions vary according to posture and shape, especially as people become older.[13]

Larson[14] found that the fit of trousers is affected not only by how accurately the pattern pieces reflect the wearer's measurements and contours but also by her posture. It is entirely possible for the pattern pieces for two people having the same hip and waist measurements to be quite different.

Analysis of men's figures

In a text for men's tailoring, Whife[15] classified men's figures into nine different figure types, namely: 1 Stooping, 2 Short neck, square, 3 Normal, 4 Long neck, sloping, 5 Head forward, 6 Erect, 7 Corpulent, 8 Tall and thin, and 9 Large shoulders. A similar approach was adopted by Waisman.[16] The authors of both textbooks stressed that figure abnormalities cause fitting problems.

To analyse men's figures, Frederic[17] suggested that the customer first be viewed from the front to ascertain whether he is sloping or square shouldered, and to ascertain the development of his muscles to check whether the figure is broad or narrow chested. Thereafter the customer is viewed from the side to determine and stipulate to what degree he stoops, or is erect, or to what degree the head leans forward or backwards. Then, he needs to be viewed from the back to determine and stipulate to what degree the customer has large or small shoulder blades or a long or short neck. Frederic found that there might be a combination of two or more figure types in one subject. For example, a man can be both sloping and stooping. He can also be sloping, stooping and have large shoulder blades, and then also have a long or short neck; or he can be square, with small shoulder blades and erect, etc.

Another study[18] categorises men's figures into four main body types, A, B, C and D. Body type A is a figure of average build with a normal drop and rise. Body type B is a figure of slender build, with narrow and sloping shoulders, and a flat chest. This figure has an average drop, but generally a short rise. Body type C represents a figure with narrow and sloping shoulders, shallow chest and a full waistline. This figure generally requires suits with a small drop and high-rise trousers. Body type D represents a figure with broad and square shoulders, deep chest and heavy shoulder blades. This figure usually has a flat stomach and small waist, requiring a high drop suit and high-rise trousers. As noted by Boswell,[19] 'drop' is defined as the difference between the chest and the waist and the 'rise' refers to the distance from the waist to the top of the inseam.

10.2.2 Methods of pattern alteration

Traditionally, alteration of garment patterns is an essential step in producing attractive and accurately fitting clothing from patterns which already exist. There have been numerous publications by tailoring experts on how to alter garment patterns for different figure forms. Texts of pattern alterations for ladies include those by Perry[8]; Bray[2, 7]; Liechty *et al.*[20]; Brackelsberg and Marshall[5]; Aldrich[21]; Rasband[9]; Barnes[6]; Betzina[22] and others. Tests for pattern alterations

for men's tailoring include Marcus[23]; Wilson[4]; Doblin and Frank[24]; Anglais[3]; Whife[15]; Frederic[17]; Anon[18]; Aldrich[25] and Brinkley.[26] Brumbaugh and Mowat[27] provided step-by-step self-instructional guidelines for altering women's and men's tailoring patterns.

Alterations can be done by using measurements, taken by a tape measure and incorporating them onto a paper pattern using the slash, seam or pivot methods.[20] In the instructions provided by Liechty *et al.*,[20] fitting by measurement is accomplished by comparing the body measurements, with an ease allowance added to the measurements on the pattern. Measurements may also be obtained by measuring a basic garment or personalised basic pattern. The body measurements, with the ease allowance added, are then compared to the corresponding locations on the pattern piece, adjusting the pattern where body measurements agree or where they extend beyond the pattern edge.

Taylor[28] reported that most of the problems concerning the fit of the rest of the garment, that is the bust, waist and hip measurements, can be resolved simply by increasing or decreasing the size of the garment part proportionally according to the style details.

10.2.3 Pattern alteration for flattering the figure

The fitting itself should be conducted in such a way that it will achieve a good and accurate fit, pleasing style lines and satisfy the customer.[4] One of the greatest functions of clothing is to hide figure problems and to make the most of good features, also creating optical illusions and camouflage.[27] The ultimate goal is to design clothing that fits and looks beautiful on the person, by adding ease to garments worn by larger women and to camouflage the body shape.[29]

Some tailors consider shoulders to be the key to a well-fitted jacket. Hutchinson and Munden[30] maintained that the critical area of the body concerning fit was around the shoulders. They stated that if garments fit the figure perfectly between the neck and the horizontal line encircling the figure at the lowest level of the armhole, then the main fitting difficulties would be overcome. Roeher[31] supported this view, maintaining that jackets are not close-fitting garments at the bust and sleeves, and that many figures can be fitted to perfection with only shoulder corrections plus minor length and circumference adjustments at the hem and side seams. There are also no definite rules for the shoulder width. Shoulders on some oversized jacket patterns extend as much as three inches on either side past the normal shoulder measurement. Roehr[31] further advised that shoulder pads could not adequately support a jacket for more than 1½ inches beyond the normal shoulder level without making creases, as many shoulder lines are exaggerated.

In the fitting of trousers, Larson[14] specified that a proper fit is the result of recognising an individual's prominent contours and draping the trousers so that they skim the body's profile. Regardless of the figure, good fit involves a

combination of three basic issues: the garment function, its style and its structure. Trousers should move comfortably with the body when sitting, standing, bending, walking or climbing. There should be no restriction of movement or uncomfortable binding. The style of the trousers should be proportional to the body. Slim cigarette trousers look much better on a slim figure than on a heavy one. Beautifully fitted trousers skim the body, hiding its flaws and accentuating the good points.

10.2.4 Pattern alteration for non-standard figures

Clothing companies usually design with standard figures in mind, based on the company's background and the statistical average of many figures. Such standards are considered as 'ideal' in terms of proportions, contours, symmetry and posture. However, due to heredity, ethnic origin, growth patterns, disease or accident, the figure of the individual may vary from the standard.[20]

For asymmetrical variations, Liechty *et al.*[20] noted that when the left side of the body differs significantly from the right side, the fitting pattern must be duplicated to have a pattern for each side of the body. Each side is then altered where necessary. This results in different pattern outlines for each side of the body for the bodice, skirt, or sleeve units. This approach is also supported by Komives *et al.*[32]

For a wearer with a curved spine and asymmetrical body, Komives *et al.*[32] suggested making a four-part pattern, especially for the bodice, which fits separately to the left and right fronts and backs, and then joining the pattern pieces at centre front and centre back, making the back closure (if any) perpendicular to the ground rather than following the spine. She pointed out that a tightly-fitting garment on an imbalanced body could often draw attention to the irregularities. Garments which hang from the shoulder are the most flattering and require minimal fitting, while separates tend to accentuate physical misalignments.

Tam Wong[33] suggested that garment design and cutting must not only enhance the appearance of disabled people, but also cope with individual disabilities. Women suffering from Down's syndrome encounter clothing problems due to their non-standard figures. Proper design and cutting may help to improve the wearer's ability to care for themselves. Similarly, authors have suggested the necessary adjustments for trousers to be worn by persons with artificial limbs[15] and Komives *et al.*[32] tried altering trousers, so that they can be worn comfortably by people who have to sit in wheelchairs and need to wear the trousers over diapers, by lengthening the back crotch and widening the seat of the trousers using the slash method.

The Fashion Institute of Technology (FIT) and the National Osteoporosis Foundation (NOF) established a competition, called 'Beauty in All Forms', which aimed to design a line of clothing for women whose body shapes have

changed because of osteoporosis. The specific feature of clothing for people with osteoporosis was that the back length of the jacket might be a little bit longer than the front, giving it a slightly different style line and shaping.[34]

10.2.5 Pattern alteration with experimental methods

To reduce trial and error in fitting and measuring, and to expand the use of the computer as a tool for quantification and plotting, many researchers have contributed to the evolving scientific methodology of pattern alteration as an alternative to the hand-drafted empirical approach.

Douty[35, 36] applied 'graphic somatometry', in which silhouettes of female subjects were projected through a grid screen. These somatographs were analysed for posture, general body mass, proportion, contour, balance and symmetry of body. This method helps to identify body variations in forms and shapes. Later, Douty and Ziegler[37] used 'graphic somatometry' to identify configurations of problem figures and to quantify the alterations needed for adjusting patterns. They developed an experimental method which they compared with the traditional method for pattern alterations. The experimental method included detailed measurements to establish dimensions, and somatographs to show proportions of body segments, for contour analysis and angle measurements. It was concluded that the experimental method achieved better results for most figures.

Farrell-Beck and Pouliot[38] found that it was not easy to alter trousers to fit the contours of hips and thighs as neither the shape nor the contour can be determined from traditional methods of measurement. They then compared two sets of trousers altered by traditional and experimental methods, respectively, in order to develop a method for alteration of trousers that incorporates body measurements, graphing techniques and the body angle. Data points from somatographs were used to plot full-scale body contours for 36 female subjects. The quadratic interpolation and cubic spline interpolation were developed to correct and plot full-scale representations of the body curves. One muslin garment was cut from a pattern altered by the experimental method and the second muslin garment from a pattern altered by the traditional method. Results showed that the experimental method was preferred over the traditional method for front waist placement, front waist dart size, back crotch curve and horizontal grain. For all other criteria, the fit produced by the two methods was rated as equal. Farrell-Beck and Pouliot[38] concluded that no one method of alteration solves all problems efficiently. Some pattern corrections can be made quite satisfactorily by traditional methods, especially changes in length and circumference. The experimental method offers a means of calculating the amount and location of changes when figure variations demand adjustment of angles.

Brackelsberg *et al.*[39] developed an experimental method of pattern alteration for a set with the bodice attached to the skirt. Information on body angle was

added in addition to the length and circumference measurements used by conventional alteration methods. These angle measurements were obtained from computer-drawn plots of the body profile and were used to alter the dart size and length and slope of the shoulder seam. This experimental method was then compared to the conventional method of alteration. The results indicated that models with deep body angles were more satisfactorily fitted when using the traditional methods, whereas models with shallow body angles benefited more from the use of the experimental methods.

Brackelsberg *et al.*'s results[39] were further clarified by Winakor *et al.*[40] who pointed out that the bust has a rounded or domed shape rather than the pointed shape of the geometric models. The bust angle was measured by placing the straight edge on the surface of the breast which makes the apex of the angle lie beyond the bust point. A space was formed between the bust point and the apex of the angle which therefore caused excess fullness in the bust region.

Heisey *et al.*[41] developed a method of pattern alteration using mathematical analysis of the graphic somatometry. The angle of a dart or a seam was determined from angles measured on the silhouette somatographs of the body. An exact geometric relationship between the angle measured on the photograph and the angle of the dart or seam on the pattern was derived for those areas of the garments that can be modelled with cones. Although Heisey *et al.*'s approach of modelling the body as a series of conical shapes seems valid in theory, it is not entirely satisfactory for any area in which the garment must curve in more than one direction, e.g. the side seams of the skirt and trousers and possibly the shoulder area of the bodice.

The somatometry approach has been used to describe the graphical human body shape by researchers in the development of a methodology for pattern alterations. Though success with this methodology has been limited, the approach offers the potential for providing more accurate measurements than the traditional method of body measurement.[42]

10.2.6 Pattern alteration using computer-aided design (CAD) programs

Experienced pattern markers have developed a set of heuristics that enable them to make pattern changes rapidly. Nevertheless, computer systems do not have the 'experience' or background knowledge which experienced pattern markers have to accomplish rapid alterations. Although CAD systems cannot learn by experience, once the heuristics have been developed within a CAD system, it can process the information and perform the functions more rapidly, accurately and consistently than the most experienced pattern marker.[43]

Most apparel CAD systems (Gerber Technologies, Lectra Systems, Investronica, Assyst, PAD and Optitex) have several preparatory activities in common which will allow automatic pattern alterations based on individual

measurements. Although each system has a different interface to the others, the basic underlying theory is the same. These preparatory activities are laborious in the beginning, but ultimately allow the automatic alteration of existing garment patterns.[43]

The mass production strategies of the past decades have categorised whole populations by a relatively small number of sizing systems which have made it virtually impossible to meet the needs of those individuals who have special fitting requirements. Developments in information technology have increased the probability of mass customisation (defined as the mass production of customised goods by Davis[44]) being adopted as an acceptable business strategy. CAD alteration systems will enable the creation of garments, customised for fit, very quickly and accurately. These customised garments can be inserted into normal production lines as an additional 'size' and produced like every other garment of the same style.[43]

10.3 Prediction of garment patterns from body measurements

Clothing design and pattern development sources have referenced various body types with corresponding pattern alteration techniques. Pattern alteration would, of course, greatly depend on one's experience and ability clearly to visualise the shape of the figure.[2] This approach is essentially an intuitive visual analysis of the body with major assumptions made about their relationship to the pattern shape.[45]

10.3.1 Pattern generation using photographic and anthropometric data

Similar to Heisey *et al.*'s approach[41] for pattern alteration using a series of right circular cones and graphic somatometry, Winakor *et al.*[40] developed and tested a pattern for the lower part of the female bodice by using quasi-conical surfaces which have a hyper-elliptical cross-section which represents a horizontal cross-section through the body as shown in Fig. 10.1. The cones that modelled the body form can be unrolled to form flat surfaces without loss of information. Figure 10.2 shows the computer draft experimental pattern.

Data for analysis came from measurements of rigid body forms and somatographs of these forms. A computer was used to calculate and plot the patterns. The experimental patterns were compared to the patterns draped on the body forms. It was found that although a reasonably good fit was obtained for some forms, the quality of fit was limited by difficulties in obtaining consistent data from the measurements and somatographs. It was found that the cone-shaped draft could be extended to the back bodice and the skirt. Winakor *et al.*[40] concluded that this research demonstrated that a simple geometric model, when

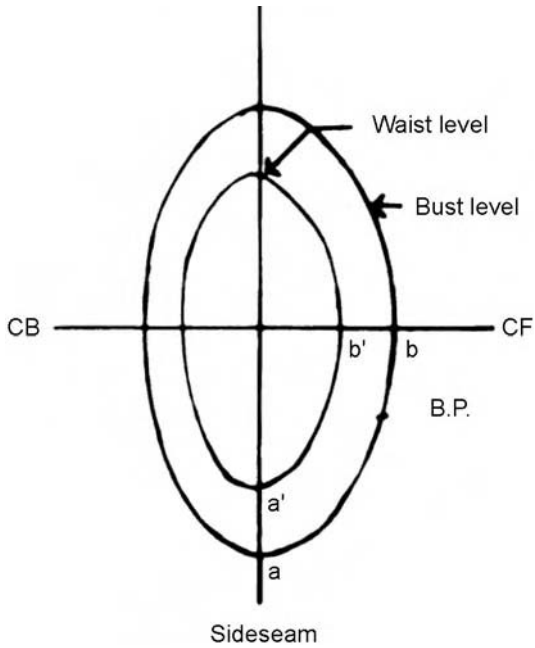


Figure 10.1 Cross-sectional view of the geometric model for the experimental pattern. Source: Winakor *et al.,* 1990.[40]

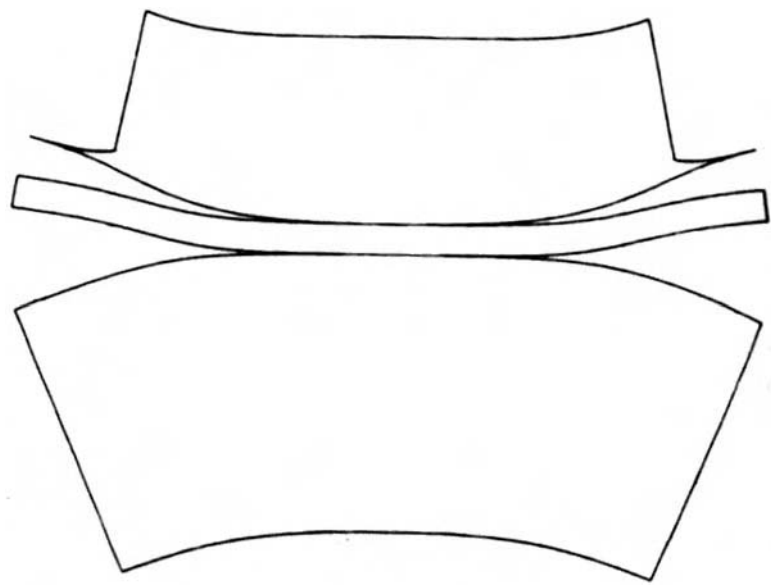


Figure 10.2 Computer pattern draft of experimental pattern. Source: Winakor *et al.,* 1990.[40]

based on geometrically consistent measurements, provides a reasonable estimate of the lower bodice dart opening and dart angle.

The imprecise nature of taking linear body measurements with a tape measure and then applying such measurements for pattern drafting is evidenced by the need for repeated trials and fittings of the garment by a skilled technician after the pattern has been cut from cloth. Experience has shown that these linear body measurements are not directly applicable to pattern dimensions and are useful primarily as approximations. Gazzuolo *et al.*[45] therefore carried out research to develop garment patterns from photographic and anthropometrical measurements of the body. They developed statistical regression models to predict the dimensions of a planar pattern (i.e. a close-fitting experimental garment pattern for the bodice of the female body form) from both traditional linear and photographic body measurements. In their study, photographic data were compared with linear anthropometric data as predictors of pattern dimensions. The statistical regression models developed indicated that, while linear measurements were slightly more accurate in predicting a few of the pattern dimensions, the photographic measurements were more accurate in predicting others, particularly pattern angles. Gazzuolo *et al.*[45] concluded that photographic measurements held promise as an alternative to the more intrusive linear measurements for predicting pattern dimensions. Schematic diagrams showing the locations of photographic measurements are given in Fig. 10.3.

The approach of Douty,[36] involving the somatograph technique to help identify body variations in forms and shapes, was also adopted by Shen and Huck[42] to determine body angles and curves. They utilised the captured two-dimensional photographic image in conjunction with the models to estimate body measurements and shapes.

In the research of Shen and Huck,[42] the geometric nature of 12 female bodices with various configurations was obtained using photographic data and physical measurements. A computer program was written to generate block patterns for the female bodices using the data. A conventional pattern drafting

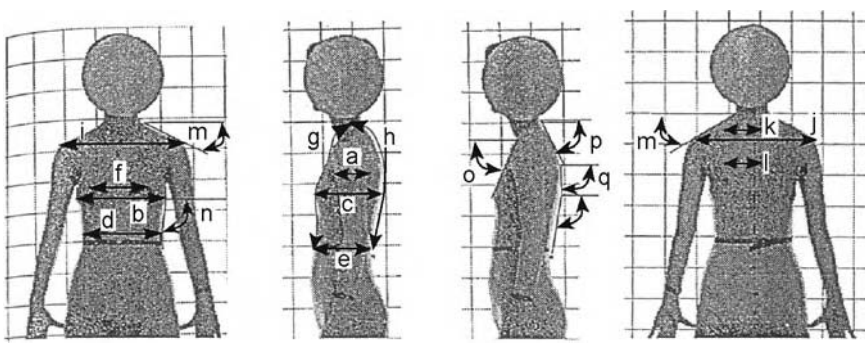


Figure 10.3 Locations of photographic measurements. Source: Gazzuolo *et al.*, 1992.[45]

method was used to develop hand-drafted bodice patterns. An evaluation scale, which included 25 fitting criteria, was developed to compare the fit of the experimental bodices with that of the hand-drafted bodices. For 12 of the 25 items on the scale, the experimental bodices were judged to have a better fit than those produced by the hand-drafted method. For two items on the scale, the hand-drafted bodices provided a better fit. No statistically significant differences were found for the remaining 11 items on the fit scale. This methodology showed potential for providing accurate, quickly generated bodice patterns.

Research has been carried by Chan *et al.*[46] to predict shirt patterns from 3D body measurements. The pattern parameters of men's shirts were correlated with the body measurements of the model generated from a Tecmath laser body scanner. A high correlation was found between the parameters of the two-dimensional shirt patterns and the three-dimensional body measurements. It was revealed that prediction equations could be established, using multiple linear regressions, to predict important pattern parameters. The authors concluded that the prediction equations could be improved by using Artificial Neural Network.

10.3.2 Pattern generation from 'made-to-measure' systems

A research team at the University of Maryland has developed an open-ended Clothing Design Expert System (CDES) which can process the codified expertise of garment design and alterations and generate patterns for made-to-measure garments. Two tools were developed in this system: The Alteration Definition Tool (ADT) is a CAD-like environment in which the user generates and stores sets of alteration sequences which will modify a pattern geometrically. The Pattern Requirement Language (PRL) executes the alteration sequences generated with the ADT and converts the data contained in a customer's order to enable a custom-made garment to be produced. The system can also create new base patterns by altering existing patterns. Through the development of CDES, the alteration of made-to-measure garments has shifted from a manual procedure to a computerised set of procedures.[47]

Made-to-measure software is available from Gerber, Lectra and other commercial CAD/CAM garment systems; these are, however, more costly and more complex to operate. In view of this, Turner[48] developed a PC-based CAD system, called MICROFIT, for producing made-to-measure garment patterns in the commercial environment of a bridal wear manufacturer. The main structure of the system contained functions which could generate made-to-measure patterns through digitising and grading and then plotting the resultant pattern pieces. The fundamental elements of the made-to-measure system were based principally on making structured inquiries from customers to find out their body measurements, specific body form and dictated style specifications. The computerised 'made-to-measure' system was developed to allow the pattern to be drafted more effectively for non-standard sizes.

Since the made-to-measure system should have the capability of producing patterns for a well-fitted garment based on customer's body measurements, Turner and Bond[49] recommended the use of default formulae rather than mathematical interpolation of size charts when one or more of the customer's measurements were missing. Turner and Bond[49] then derived specific default formulae for the German DOB 'regular' and 'outsize' charts and also for the full range of 'height' categories and 'bust to hip' relationships, so that all sizes and shapes of customer are catered for. The German DOB system of charts was chosen because it is the most comprehensive national system and is also the basis for the European Standards. These derived default formulae, when applied to a given size chart set, enable measurements to be determined efficiently over wide-ranging customer sizes in terms of both stature and girth.

10.4 Three-dimensional (3D) apparel design systems for pattern generation and garment fit

Garment patterns have traditionally been produced from two-dimensional (2D) data consisting of lengths, widths and circumferences. Little information about the three-dimensional (3D) form of a body is contained in a typical data set. Pattern makers have supplemented data with qualitative descriptions of body variation for more accurate specifications of the body form, but such descriptions have obvious limitations in pattern production. The inadequacy of such data for drafting individual patterns has long been recognised.[50]

The CAD systems which have been developed have certain limitations in representing the complex 3D shape of the human body in terms of a 2D drawing. Studies on the computerisation of the garment design process have focused mainly on the generation of accurate flat patterns.[51, 52] Research has therefore been carried out to develop more realistic 3D methods which could produce optimum patterns and achieve good fit.

10.4.1 Pattern generation from 3D data

Appel and Stein[53] produced a bodice pattern using a pair of photographs representing data of the human body from the front and side views; a blouse formed with various planes being manually superimposed onto the photographs. In order to make certain that the points on the plane are coplanar, either triangle or trapezoid planes were used as shown in Fig. 10.4. The vertices of the planes were digitised and Cartesian coordinates determined for each vertex. The three-dimensional design was displayed on a computer for visual verification. The planes were then projected and assembled to complete the pattern. The resultant pattern was well fitted to the subject with only one minor alteration necessary at the shoulder.

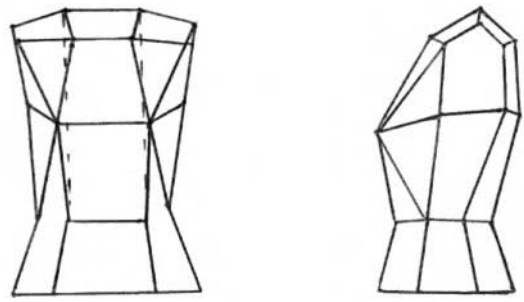


Figure 10.4 Design of blouse superimposed onto photographs of the human body. Source: Appel and Stein, 1978.[53]

Hutchinson and Munden[54] revealed that the workroom stands which are used as the standards for modelling garments in the industry were significantly different in their three-dimensional characteristics from those of the subjects measured. Hutchinson and Munden[30] therefore developed a method of assessing body shape, which consisted of moulding the body in polyethylene foam sheeting. The moulds were then cut at selected places so that they took the form of two-dimensional shapes. From these shapes an average shape was derived which was used to produce an average block pattern. It was found that the average block pattern provided a better fitting garment than the industrial block pattern.

Efrat,[55] however, found that Hutchinson and Munden's method, apart from the angle and forward slope of the shoulder, appeared not to be completely satisfactory for all body parts. The pattern shape was still the most important aspect to be evaluated. He then suggested a method to produce patterns of acceptable fit for the female bodice.

Efrat[55] developed the conical principle, which was intended to establish two-dimensional co-ordinates for the crucial pattern shaping points. The bodice was specified with 26 crucial shaping points, as shown in Fig. 10.5, which included the apex of the bust, the apex of the shoulder blade, and three or four points on either side of the pattern perimeters; the waist, side, neck, armscye (armhole) and shoulder. The bodice was then defined by 31 triangular planes; 16 for the front and 15 for the back panels. The bust and shoulder blades were the two prominent points, which were used to generate these triangular planes. A schematic diagram is shown in Fig. 10.6. Each triangle was formed by connecting two adjacent perimeter points and the appropriate apex. Orthogonal projections of the triangles were assembled to produce front and back bodice patterns; proportional corrections were made in the back shoulder area for the difference between the Euclidean distance calculated from coordinates and the actual curvature of the back.

Efrat[55] concluded that the problems associated with achieving good-fitting garments are caused by the unsatisfactory nature of the measurements obtained

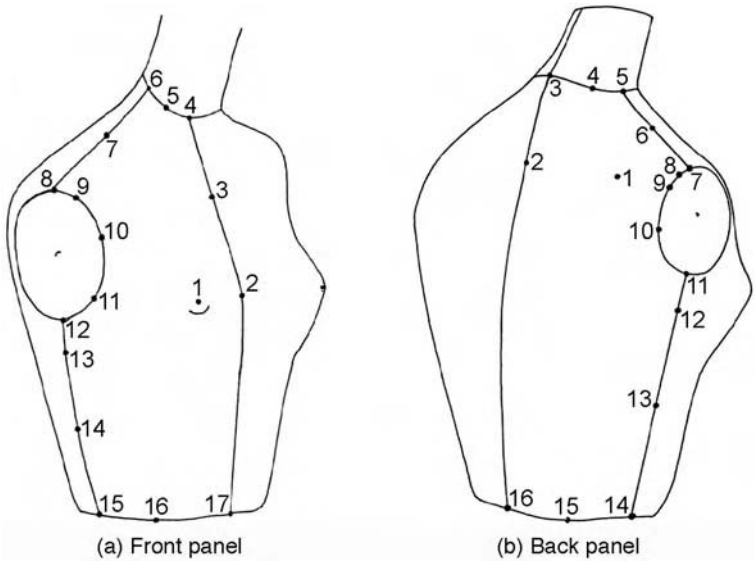


Figure 10.5 Location of the crucial shaping points. Source: Efrat, 1982.[55]

when measuring the human body by the traditional methods, and that the traditional methods of body shape determination are far from accurate. Therefore, a scientific investigation into the problems of achieving a two-dimensional block pattern which accurately reflects the three-dimensional nature of the human body, could well be of extreme significance to the clothing and tailoring trades.

Appel and Stein[53] and Efrat[55] examined the use of computers to draft the bodice patterns from 3D data with satisfactory results. Nevertheless, their work has not been extended or explored further.

Because fitting a fabric to the surface of a 3D object is a time-consuming art, Heisey and Haller[56] developed a computational method for fitting 3D surfaces with flat fabrics, using a mapping algorithm based on Mack and Taylor's[57] definition of fit; namely, 'the fabric is everywhere in contact with the surface.' They thought that a better understanding of the relationship of a 2D fabric fitted to a 3D object could aid in the automation of the customised production of garment patterns.

Heisey *et al.*[58] initiated a theoretical framework for drafting individually fitted patterns based upon modelling the physical process of draping a 3D garment. They noted that the 3D form of a garment does not exactly duplicate the surface of the body. Some parts of a garment may lie parallel to the surface of the body while others may be indirectly related to the underlying surface of the body. Figure 10.7 shows the mapping of a garment which lies parallel to the lateral surfaces of the bust and the back, and bridges the hollows between the breasts. Once the 3D form of a garment has been approximated then a projection

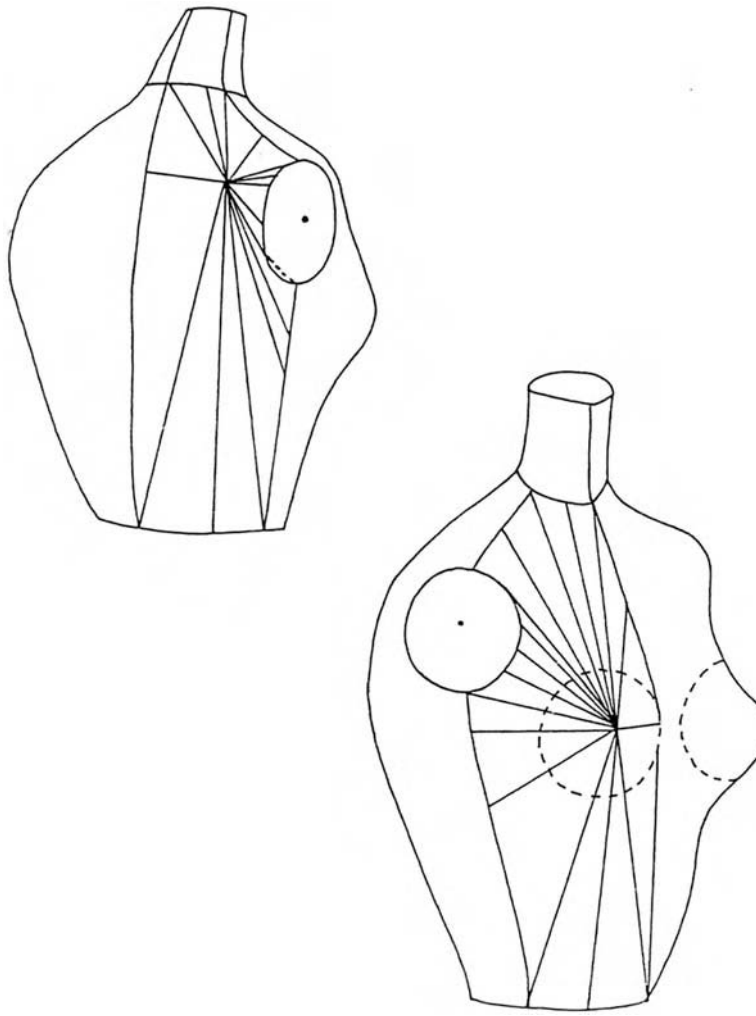


Figure 10.6 Division of the body into triangular sections. Source: Efrat, 1982.[55]

could be carried out to flatten it into a 2D pattern. They acknowledged that a sphere or any other dual curved surface is not applicable to a planar surface without distortion. It was difficult to define a projection which causes distortion to be acceptable or compatible with the end use. They also found that different fabrics might have different mappings and that very little work has been done on how fabrics conform to 3D surfaces. Their research may be regarded as the earliest published theoretical development of a 3D pattern design for garments.

Heisey *et al.*[50] found that the form of the garment which could be produced was typically restricted by arbitrary flattening procedures, which were not based on modelling the physical mechanisms of a fabric to conform to a 3D form and

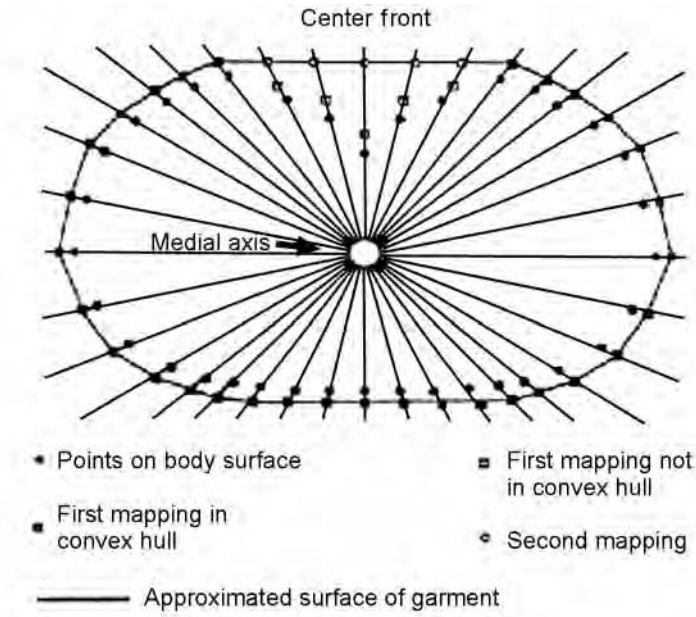


Figure 10.7 The mapping of the garment at the bust level. Source: Heisey *et al.* 1988.[58]

human judgement was needed to specify each individual garment. To overcome these restrictions, Heisey *et al.*[50] further developed an algorithm for computationally drafting patterns from 3D data based on their own theoretical framework.[58]

The procedure that Heisey *et al.*[50] developed to model the flattening of a woven fabric covering was basically a projection consisting of three steps: approximating the surface to be fitted with a mesh of polygons, projecting each individual polygon onto a plane, and combining the polygons to form a continuous pattern. They demonstrated the application of the algorithm in drafting coverings for a spherical object. A functional relationship for the fabric-flattening step of that framework for a woven fabric was developed. They found that the only factor which restricted the form to be fitted was the physical characteristics of the fabric.

Heisey *et al.*[59] further demonstrated their previously developed projection methods[50] in producing a 2D basic skirt pattern. In their research, they used the term 'last', which is used in the manufacture of shoes, to denote the form of an individually fitted garment. Such a 'last' rarely duplicates the area of the body to be fitted exactly, but rather specifies the space to be enclosed. They revealed that the functional relationship between the 'last' and the body is determined by a complex interaction of the garment, the form of the underlying body and the physical and mechanical characteristics of the fabric from which the garment is

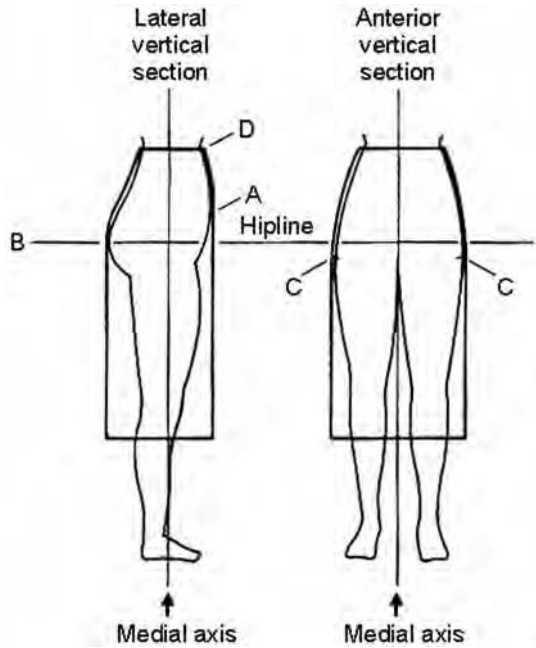


Figure 10.8 Diagram of two vertical cross sections of the body and a 'last' for a basic skirt. Source: Heisey *et al.,* 1988.[59]

sewn. A change in the form of the 'last' would change the style of the garment. The definition of a 'last' and style details for a basic skirt were used in mapping an individually fitted 'last' and projecting the 'last' to produce a pattern.

Heisey *et al.*[59] defined a 'last' for the basic skirt as a convex form from the waist to the point that was farthest from the medial axis (see Fig. 10.8). The 'last' followed the body's convex curves smoothly and bridged the concavities. The point on each vertical cross-section that was farthest from the medial axis was referred to as the rotational maximum for the section. Below the rotational maximum, the skirt hung parallel to the medial axis. Figure 10.9 shows a diagram of a basic skirt 'last'. The curve connecting points A, B and C connect the rotational maximum on each vertical section; this curve was referred to as the rotational ridge. Only the data corresponding to the specific region of the body was needed for mapping. The 'last' and style details for the skirt were mapped and the surface of the 'last' was projected using the developed algorithm.[50] It was demonstrated that the developed algorithm worked well.

Using a concept similar to that of Heisey and Haller,[56] Aono *et al.*[60] considered the fitting of a 2D cloth to a 3D surface so that it is everywhere in contact with the surface. They developed a mapping method to model surfaces, having double curvature, using flat patterns, assuming that the 2D cloth is deemed to have a limited deformational capacity, with inextensible vertical and

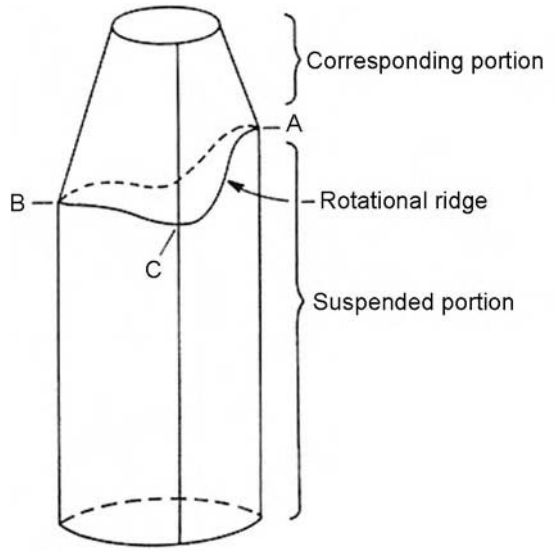


Figure 10.9 Diagram of a 'last' for a basic skirt. Source: Heisey *et al.,* 1988.[59]

horizontal threads, no curvature between thread crossings but with an ability to shear.

The above research was inevitably limited due to the difficulties in the acquisition of 3D measurement data. However, they provided a step to understand the relationship between the 2D shape of a pattern and the 3D form of the body.[61] With the advanced development of non-contact measurement methods, the use of quantitative data of the actual human body has become practical in many 3D CAD applications.[62]

10.4.2 3D apparel CAD developments

The main function of a 3D apparel CAD system is to provide a design environment for both garment and pattern development. The essential elements considered in the 3D software development are the access of a 3D human model by inputting the selected garment stand using a 3D digitiser or scanner for characterising the garment form; flattening from the 3D garment form to the 2D garment pattern; simulating the 2D pattern assembly and for a 3D visualisation of the garment design with fabric drape characteristics which help the designer earlier in the pre-production stage and for assessing the garment fit.

The computer generated 3D human model for accessing the garment form
Both manual and 3D CAD systems require a human model for pattern generation. The 3D human model can be generated by 3D contact or non-contact digitising techniques, both of which provide groups of set points to identify the

3D form. The 3D digital digitiser determines and records the co-ordinates of the intersections of the points on the stand at set latitudes and longitudes. A surface can then be created using this array of co-ordinates. Systems using 3D contact digital digitising techniques include those of Asahi AGMS-3D,[63] Okabe *et al.*,[64] Ito *et al.*,[65] Hinds and McCartney[66] and McCartney and Hinds.[67]

In developing the human model generator, Kang and Kim[68, 69] divided the human body model into several virtual cross-sections parallel to the floor, from the neck to the thigh, and the shape of each section was measured using a sliding gauge. Each cross-sectional shape was divided into 60 sectors and the radius obtained by image analysis, whereafter the body model is reconstructed in the cylindrical co-ordinate system using this data. The selected cross-sectional values, such as the neck, bust and hip from the anthropometric data, were used as the standard to develop a resizable human body model generator. Different growth ratios of the selected sections were considered from the statistical anthropometric data to obtain a realistic body model. Figure 10.10 shows the selection of base sections and an example of different growth ratios for the bust section. This resizable human body model is easily used in garment drape shape prediction as well as in the validation of the pattern grading process for mass production in commercial applications.

It has been concluded that although the 3D contact digital digitising technique provides an accurate model, the digitising process is very slow and for accuracy can only be performed on an inanimate object.[70]

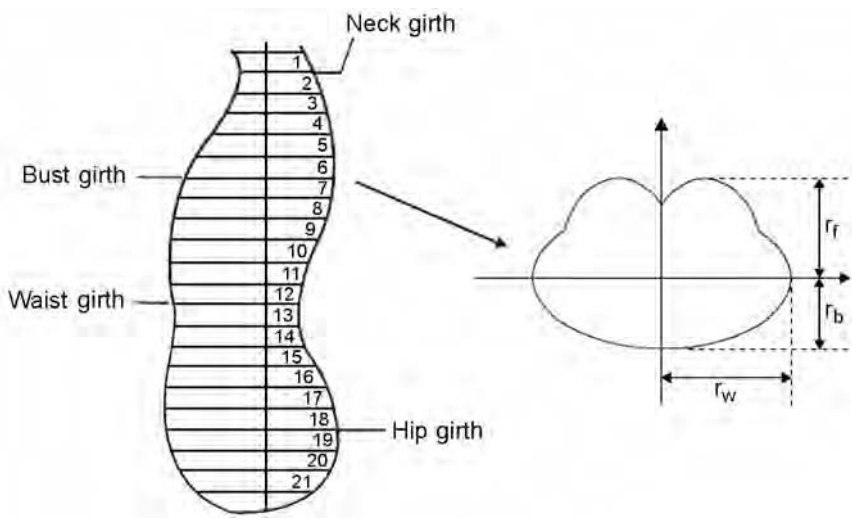


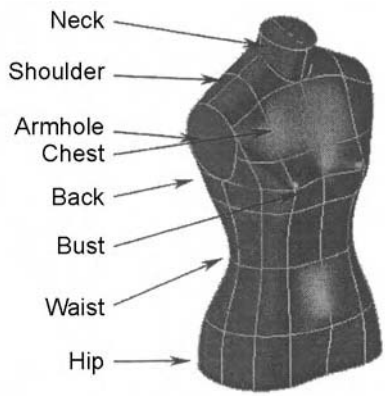
Figure 10.10 The selection of base sections and an example of a different growth ratio for the bust section. Source: Kang and Kim, 2000.[68]

With the development of the 3D non-contact digitising technique, the use of real body data has become practically feasible. There are several systems using 3D non-contact digisiting techniques for 3D human model generation. Fozzard and Rawling[71, 72] used the 3D human model from a computer interface. Hinds and co-workers[73, 74] used the Loughborough Anthropometric Shadow Scanner system (LASS),[75] to improve the accuracy of the image captured and to develop a 3D model in their 3D CAD garment design system.

As reviewed by Chen,[76] the CDI-3D system of 'CDI Technologies Inc.' first generated a 'Wireframe' garment stand using 3D contact or non-contact digitising techniques. The garment stand generated in this system can be resized using a 'resize' program, which offers a proportional modification rather than an individual requirement. The 'surface' program generates a concrete 3D garment form surface onto which style lines can be placed. The form type, posture, shape and proportion can be visualised and manipulated to meet individual demands from the solid form garment stand at this stage. The 'Curve' program by 'NURBS' (Non-Uniform Rational B-Spline – a mathematical method for constructing curve lines in a CAD environment), offers different types of curve lines to be drawn as style lines onto the surface of the garment form surface.

A feature-based human model, consisting of the major features of the torso for garment design, was created by Au and Yuen[77] in a 3D apparel CAD project initiated and led by Yuen in Hong Kong in 1996.[78] A feature recognition algorithm was used to recognise the features of a human torso represented by a cloud of points to create the feature-based human model. Figure 10.11 shows an example of the generic feature model of a mannequin with detailed features listed. The feature-based human model can also be defined parametrically. The alteration of the dimensions can be 'input' through a standard user interface. The feature recognition algorithm can be used in designing tailored garments for a specific person, while the parametric feature model can be used for mass production.

Kim and Kang[61] refined an automatic garment pattern design system using 3D body scan data. A WB4 whole body scanner, developed by Cyberware of USA, was used to obtain the 3D body data. A body model was generated from the scanned data using segmentation and the Fourier series expansion method. Finding that it was difficult to make garment patterns directly from the body model, a bodice (garment) model based on the surface geometry of a standard garment dummy used in the apparel industry was then generated by a stereovision technique. Two CCD cameras which simulate human vision were used to capture the four panels (two fronts and two backs) of the dummy marked with grids. The stereovision algorithm was used to calculate the spatial co-ordinates of the grid crossing points. A bodice model, as shown in Fig. 10.12, was reconstructed by assembling the four panels using specially designed stereovision software.



Features	Neighbouring features	Feature geometry: Form	No. of Vertices	No. of Surfaces
Neck	Shoulder		6	2
Shoulder	Neck, Back, Chest, Armhole		9	4
Chest	Shoulder, Armhole, Bust		6	2
Armhole	Shoulder, Back, Chest, Bust		5	4
Bust	Armhole, Chest, Back, Waist		12	6
Back	Shoulder, Armhole, Chest, Waist		14	7
Waist	Bust, Back		21	12
Hip (F_g)	Waist		14	6

Figure 10.11 The generic feature model of a mannequin with detailed features listed. Source: Reprinted from *Computer-Aided Design*, 31, Au and Yuen, 'Feature-based reverse engineering of mannequin for garment design', 751–759, Copyright (1999), with permission of Elsevier.[77]

3D CAD systems for 3D garment form generation

According to Sato,[63] a commercial 3D CAD 'AGMS 3D' system, which was developed by the Asahi Chemical Industry Company in Japan, can convert 3D images into 2D patterns and 2D patterns into 3D images. It can make a pattern in a short time whilst obtaining the actual image. The system can display pattern and 3D images simultaneously and the design can be made with either 2D patterns or 3D figures. The prototype stage can be viewed in the form of 3D images.

Chen[76] reported that another commercially developed software, 'The CDI Design Concept 3D' (CDI-3D), which was developed by 'CDI Technologies Inc.' in the United States, and then taken over by Lectra in 1997, can obtain

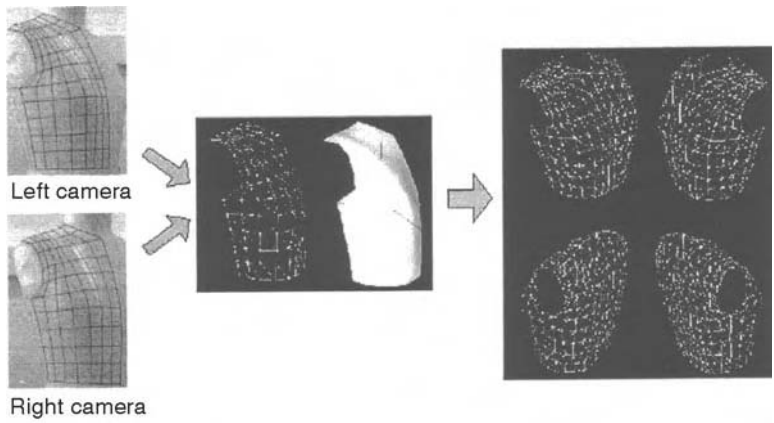


Figure 10.12 The generation of the bodice dummy; (a) a pair of images captured by two cameras; (b) reconstructed mesh structure and shaded surface for right front panel; (c) assembled bodice model with four panels. Source: Reprinted from *Computer-Aided Design*, 35, Kim and Kang, 'Garment Pattern Generation from Body Scan Data', 611–618, Copyright (2002), with permission of Elsevier.[61]

'contact-fit' patterns from 3D surfaces through five major programs, namely; the 'resize' program, the 'surfaces' program, the 'curves' program, the 'regions' program and finally the 'draping' program. The first three programs are used to develop the garment stand to generate the 3D garment forms. The latter two programs are used to flatten the 3D form into 2D patterns and for visualisation of the final result.

There are other commercial 3D CAD systems available, such as Gerber Technology, PAD, Investronica Inc., Optitex and Lectra. These systems incorporate the ability to apply a flat pattern to a 3D form or fit a model to see how a pattern will look when stitched together. Hence, fit problems can be identified and the flat pattern can be altered before an actual garment is cut and sewn. Nevertheless, published information is scarce.[79,80]

In the CIMTEX (Computer Integrated Manufacture in Textiles) project, Fozzard and Rawling[71,72] proposed developing a software system for garment CAD which could simulate pattern shapes from a conventional 2D CAD system in a 3D garment visualisation environment. The concept of the system allows marks to be made on the garment after dressing and draping in 3D. These marks can be examined on the corresponding panel in 2D and vice versa. The development can allow modifications made to a flat panel piece to be viewed in the completed garment without a physical prototype.

Okabe *et al.*,[64] developed what they regarded as 'the first 3D apparel CAD system', the core of which is a simulator which estimates the 3D form of a garment placed on a body from its paper pattern (2D to 3D process) as well as developing a program which minimises the energy required to deform the given

3D shape to obtain the 2D pattern (3D to 2D process). The system allows the designer to design in 2D or 3D, and to adapt shapes in the 3D environment to automatically generate the new patterns. As a consequence of the mechanical calculation in the system, the visualisation of distortion and stress in the garment panels can be used as a measure of the body contact pressure to assess garment fit.

Ito *et al.*[65] proposed an approach to develop an automatic pattern making system which could generate an appropriate garment pattern by inputting an initial designer sketch of a garment and to simulate the generated pattern to provide a 3D garment visualisation in the computer. Any alterations made to the original design sketch by the designer can be reprocessed into an improved pattern generation. The conceptual approach proposed was to develop an expert system which would transfer the designer's concept and a corresponding extensive garment description database for automatic pattern generation and visualisation of 3D garments. As concluded by Ito *et al.*,[65] the simulation was basically made by the interpolation of the actual measurements; a theoretical treatment method should be developed to realise the system for general use.

Hinds and McCartney[66] developed a method to provide a 3D tool for the designer to create a garment as a series of connecting panels around a 3D generated human form. A panel is defined as a generated surface which follows the contours of the underlying body form and bound by a series of edges. Points along the edges of each garment panel and the offset, which is defined as the length of the surface normal from the body to a point above the body surface, specified garment 'fit'. When the points along an edge are specified, the edge can be generated using curve-fitting algorithms. They concluded that the proposed method of garment design offers the way for storage of the 3D data and offers the opportunity for automatic pattern generation.

McCartney and Hinds[67] considered the garment pieces to be designed as a surface offset from a human form. Surface points on the dummy were mapped onto curvilinear coordinates to describe the body form. The B-spline method was used for 3D surface fitting. The Bezier form was used for user-defined geometry manipulation of the curves in 3D in the 3D CAD system which was developed. When garment design is considered, some degree of fullness may be added or an offset surface may be required for a particular region of the 3D surfaces due to a significant effect of the material thickness for garment piece generation. The curve-fitting process of the system can be extended to include editing of the offset behaviour. Then, an accurate panel periphery can be designed in 3D which incorporates variable offset values along individual edge curves of the panel. McCartney and Hinds[67] claimed that the developed 3D CAD system could rapidly specify complex garment pieces with variable fit.

Later, Hinds and McCartney[74] improved the computer hardware, which enabled realistic garment images to be created within acceptable time scales, for designers in the clothing industry. The software allowed the relatively complex

shapes and textures of garments to be specified with the minimum input of data by the designer.

In order for a CAD system to be of practical use to garment designers and manufacturers, McCartney *et al.*[81] proposed two approaches in their development. With an accurate drape algorithm, the 2D patterns of a chosen fabric can be attached to the mannequin for 3D garment visualisation. The 2D patterns can be altered and re-run when changes are necessary. Another approach is to specify garment pieces in 3D with advanced drawing tools. Then the expert rules are used to process the 3D garment piece for the 2D shape with constructional details required to achieve the final form. To achieve this, McCartney *et al.*[81] proposed that the garment specifications should be divided into fit and drape areas. In the 3D CAD development, they outlined a framework for a possible computer integration approach which would accomplish the integration of the design interface, the pattern flattening and the fabric drape engine. The design interface enables 3D specifications of the garment to be created. The 3D specification provides an accurate surface description in areas where fit is important. The 3D surface representation of the garment provides a 3D framework within which panel relationships of garment composition can be defined. It also provides a reasonable starting point for drape simulation. The flattening process flattens the fitted areas differently from the draped areas, with the anisotropic nature of fabric characteristics being considered.

Kang and Kim[68, 82] developed a comprehensive apparel CAD system and integrated it into a 3D garment drape shape prediction system with a resizable human body model generator. The integrated 3D CAD system can perform automatic flat garment pattern drafting and can generate grading rules as well as engineering patterns, which can be used in the prediction of the final draped shape of a designed garment on the human body.

Later, Kang and Kim[69] developed a direct pattern generation method, using a body-garment shape matching process, to substitute the traditional trial and error garment fitting process in developing the 3D apparel CAD system for automatic garment pattern generation. A typical garment model was replicated by applying stereoscopy on a general-purpose dummy model, which is usually used in pattern making. Then, an algorithm was developed to adjust the shape of the garment model to fit the human body thus obtaining an individually optimum fit garment pattern. Finally, a pattern-flattening algorithm which flattened the adjusted garment model into 2D patterns was developed which also considered the anisotropic properties of the fabric to be used.

An algorithm has been developed to adjust parametrically a garment piece to fit a particular body while maintaining its styling. Any misfit of the garment can be fine-tuned by using the Free Form Deformation (FFD) algorithm to control the dimensions of the garment at different positions by altering and adjusting the control grid. The garment can also be adjusted interactively on screen, and the new pattern for the adjusted garment thus generated.[78]

Wang *et al.*[83] further used the feature-based approach for intuitively modelling a 3D garment around a 3D human model using 2D sketches as input. It aimed at providing a 3D design tool to create garment patterns directly in the 3D space through 2D strokes. The approach consists of three parts: a feature template is first constructed for creating a customised 3D garment according to the features on a human model; the profiles of the 3D garment are specified through 2D sketches; and finally, a smooth mesh surface, interpolating the specified profiles, is constructed.

Wang *et al.*[83] introduced a prototype model to show the various modification operations of the system. Strokes could be input by the user to specify the silhouette of the extruded surface. Strokes marked across the contour of the model in the cutting operation mode represented the cutting off of some part of the model. Seam lines could be painted in using drawing strokes within the model silhouette. The whole model could be separated into component parts according to the painted seam line and finally flattened into 2D patterns. Figure 10.13 shows the overview of the system operations.

Wang *et al.*[83] concluded that this system could regenerate patterns automatically when creating the same style of garment for other human models, as the garment patterns are constructed in relation to the features of the human

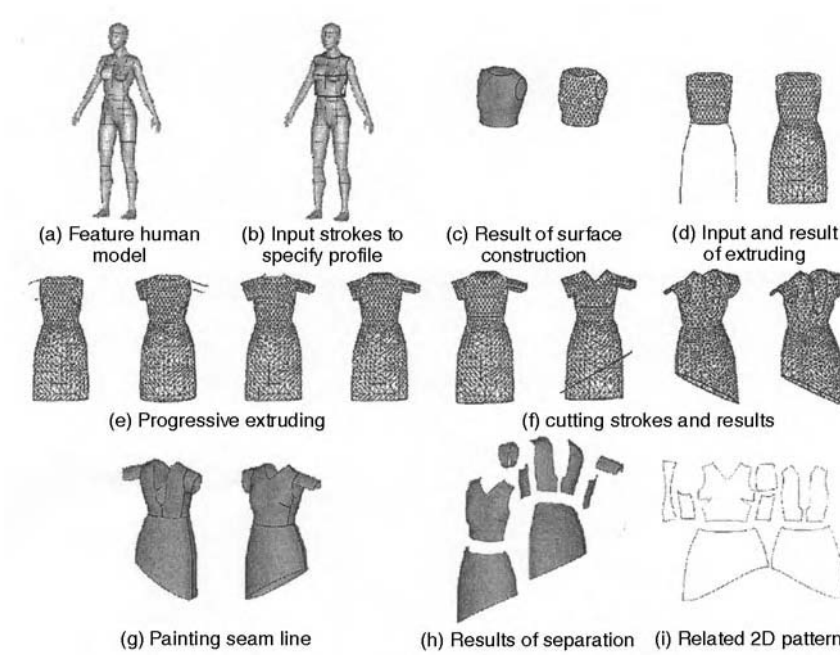


Figure 10.13 The overview of the 3D garment design system operations. Source: Wang *et al.*, 2002.[83]

model. Also, easing space is provided between the specified profiles and the cross-section of a human model; tightly fitting garments as well as loosely fitting garments can be constructed using this approach.

The flattening of the 3D garment form into a 2D garment pattern

Automatic pattern generation is seen as a major aim of 3D CAD system development, requiring a method to generate the 2D pattern shapes from the 3D prototype. Noting that the process to flatten a curved surface into a plane is different from the process to force a pattern from a plane surface into the curved shape of a garment, Okabe *et al.*[64] proposed using cylindrical mapping to derive the panel shape, which can be refined after meshing and re-simulating the position of the panel into 3D space.

Hinds *et al.*[84] demonstrated an approach to derive garment pattern pieces from the designed 3D models at a CAD station. An offset surface with respect to the underlying body form which represents a piece of a garment was created. A grid of points was necessary for pattern development for this surface. Primary and secondary spines were first defined. Using these spines and starting out from the origin, a grid on the 3D surface could be formed. A Newton-Raphson algorithm was used to iterate the intersection of an approximately equal-sided mesh to the complete surface of the garment as shown in Fig. 10.14. The mesh grid was trimmed later for the garment pattern as shown in Fig. 10.15. The small darts on the pattern were grouped together to form a single dart at a specific location. An alternative to the Newton-Raphson algorithm was a radial-mesh development as shown in Fig. 10.16. Hinds *et al.*[84] concluded that the developed methods were based on the simple concept of modelling a doubly curved surface as an assembly of triangular platelets. Groups of such platelets can be flattened onto the plane to obtain the overall pattern, which reflects the type of curvature on the original 3D surface.

Hinds *et al.*[73] developed a software aimed at improving the '3D to 2D' flattening and simulating '2D to 3D' drape. This development enables the cursor to move around the surface of the body form on the screen in the design system. The editing features developed for the system become a means of defining the 3D shape of the garment pieces with respect to the underlying body form. The 3D shape is then flattened depending on the degree of double curvature and type of curvature.

McCartney and co-workers[81, 85] developed an algorithm for flattening 3D surfaces described in terms of a list of triangles. By selecting groups of these platelets as strands of the pattern, each group could be flattened onto a two-dimensional plane. The resulting pattern contained darts and gussets, which could be approximated to provide a more realistic pattern shape in the fitting process for garment design purposes.

A flattening algorithm developed by McCartney *et al.*[85] was used for 2D flattening in the 3D CAD system developed by McCartney *et al.*[81] The

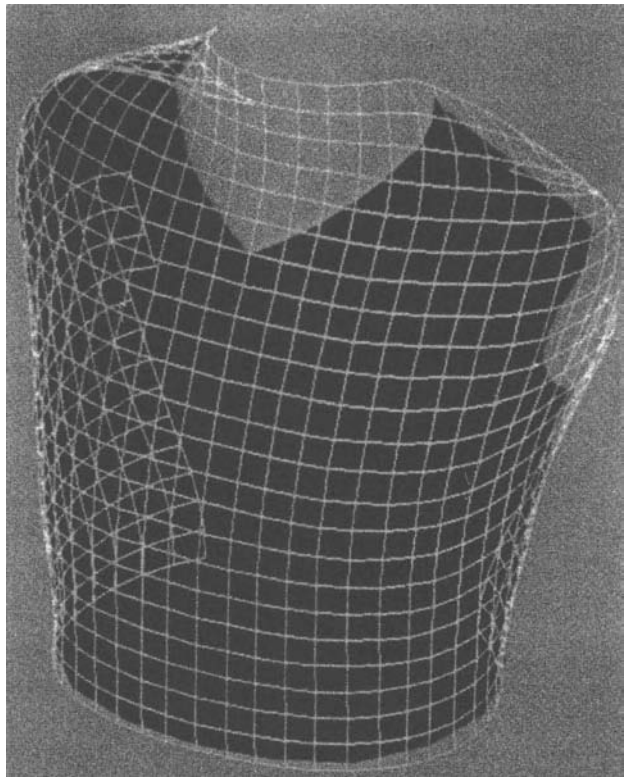


Figure 10.14 Garment piece with a superimposed equimesh grid. Source: Reprinted from Computer-Aided Design, 23, Hinds *et al.*, 'Pattern development for 3D surfaces', 583–592, Copyright (1991), with permission from Elsevier.[84]

algorithm was capable of handling the arbitrary siting of seams, darts or gussets depending on the nature of the curvature involved. The 2D flattening specifications involved a full interior description of how the garment was mapped from 3D to 2D, which would enable the reverse process to be achieved when the draping was considered. Examples of the integration of the design interface, the pattern flattening and the fabric drape engine are shown in Fig. 10.17.

Kim and Kang[61] developed the surface-wrapping algorithm to make an equalised geometry of a body model and the garment model, and a multi-resolution mesh generating algorithm together with an optimum planar pattern mapping algorithm were used to generate the optimum 2D patterns for individual body shape. They revealed that these automatically generated patterns were somewhat different in overall line shape or dart location compared with the manually designed patterns, which may be due to the limitations of conventional methods to reflect accurately the 3D features of the human body in flat patterns.

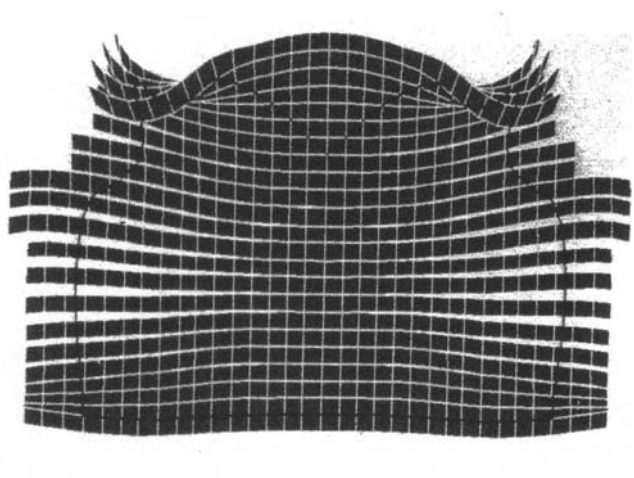


Figure 10.15 Multistrand garment-piece pattern. Source: Reprinted from Computer-Aided Design, 23, Hinds *et al*, 'Pattern development for 3D surfaces', 583--592, Copyright (1991), with permission from Elsevier.[84]

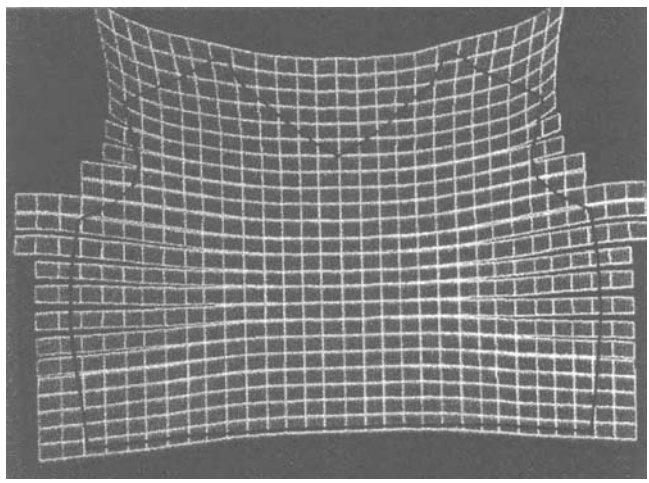


Figure 10.16 The Overlaps eliminated by the spreading out of strands. Source: Reprinted from *Computer-Aided Design*, 23, Hinds *et al.*, 'Pattern development for 3D surfaces', 583–592, Copyright (1991), with permission from Elsevier.[84]

Wang *et al.*[86] demonstrated a method for 3D surface flattening to be used in the 3D CAD system developed by them.[83] A facet model was used to present a complex model. Then a spring-mass model based on energy functions was used to flatten the resulting mesh surfaces into 2D patterns. They believed that the method can efficiently solve the flattening problems for complex surfaces.

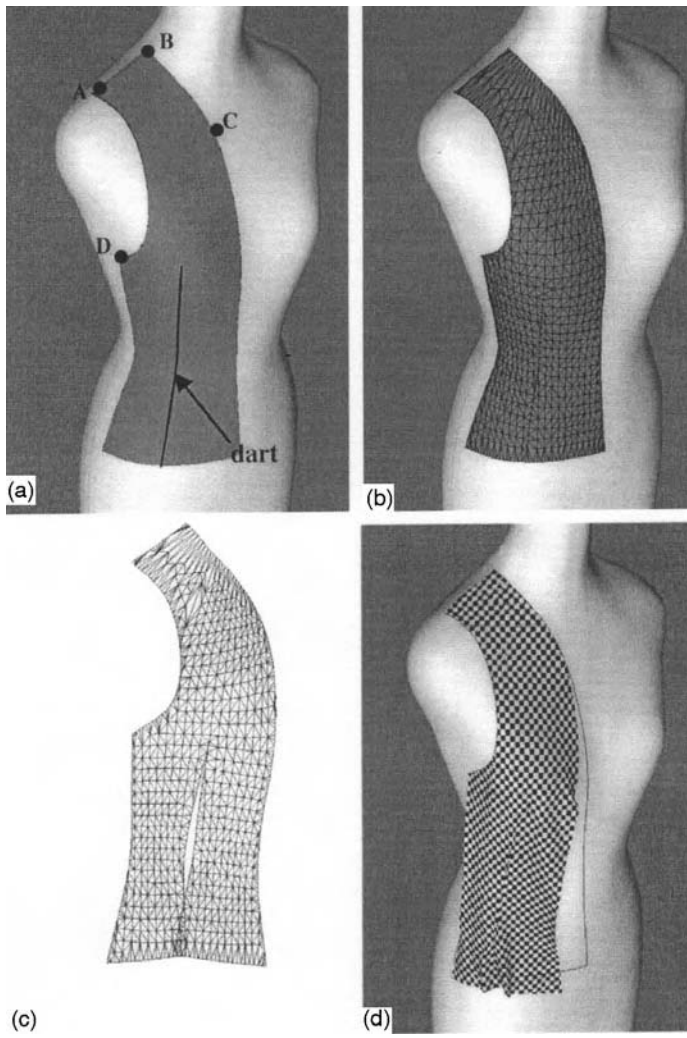


Figure 10.17 The integration of the design interface, the pattern flattening and the fabric drape engine, a) stylished 3D garment panel design with dart, b) garment panel triangulation with dart, c) 2D flattening of panel with dart, d) 3D drape of panel with texture rendering. Source: Reprinted from *Journal of Materials Processing Technology*, 107, McCartney *et al.*, 'Dedicated 3D CAD for garment modelling', 31–36, Copyright (2000), with permission from Elsevier.[81]

The fabric model and garment fit

Fabric selection is an important part of garment design. The fabric model is required to predict the shape of the draped fabric in real time with links to mechanical data to enable different fabric types to be modelled. Fozzard and

Rawling[71, 72] identified a drape algorithm for incorporation into a dressing visualisation system into their CIMTEX project. To simulate fabric drape in the system, the finite element modelling technique combined with NURBS surfaces were used. A fabric objective measurement database was developed within CIMTEX for interfacing with the system.

In the work proposed by Okabe *et al.*,[64] the specific anisotropy of the mechanical properties of fabrics is considered in both the 3D to 2D and 2D to 3D processes. In the 2D to 3D process, the contact problems with body and geometrical nonlinearity are also taken into account. As a consequence of the mechanical calculation, the distributions of the distortion and stress in garment panels are also visualised, which can be used as a measure of body contact pressure to assess garment fit.

Hinds *et al.*[73] revealed that adjustments are required for plane 2D materials to fit a 3D surface. They concluded that material might be added to create drape in some cases and might be absorbed in other cases. In their work, they found that the distortion or stretch of the fabric helped the fitting process.

To visualise the actual draped shape of the garment on a human model, the finite element analysis method was developed as well as computer graphics to obtain and demonstrate the 3D drape shape. The flat pattern pieces were divided into fine quadrilateral elements using a specially coded mesh-generating program and appropriate sewing conditions are assigned to transform 2D patterns into 3D shapes. The strain reduction and pseudo-drape methods are used in the garment drape shape prediction system. Kang and Kim[68] concluded that the final drape shape prediction was determined from the solutions of the contact condition with the human body; deformations, and the weights of the elements constituting the garment pieces, as well as the surface texture of the fabric. They also revealed that the precise variables for material behaviour are tensile strain energy constants, in the warp and the weft direction; shear strain energy constant; out-of-plane bending energy constant; and potential energy resulting from fabric mass. The model, which embodied these energy and geometric modelling elements, was termed a drape engine.

In the 3D software developed by Yuen,[78] the pattern from a 2D CAD system was inputted into the computer using the standard DXF format. Sewing, fabric and positional information were also inputted to allow the construction of the garment by assembling the patterns around the feature-based human model.[77] The assembled garment could be shown in its constructed or draped format, with a choice of fabric properties and texture. Fast collision detection and self-collision detection algorithms were used to facilitate the draping process and show the draping effect of different fabric garment properties and textures. In the system, the facility of viewing the assembled garment in translucency and the fabric stressing display mode provided a useful tool to evaluate the fitting of pattern and garment and the choice of fabric.

10.5 Virtual fitting on the Internet

Today's consumers have less time to shop around for proper fitting garments. They are more likely to carry on buying at retailers who consistently offer products which fit them. Some consumers may enjoy the convenience of catalogue or Internet shopping, but many may not purchase apparel this way because they are sceptical as to whether the garment will fit once it is delivered. Apparel fit problems are costly and frustrating, not only for consumers but also for apparel manufacturers and retailers, the costs resulting from returned merchandise, lost sales, brand dissatisfaction or time wasted in the fitting room.[79, 87, 88] Moreover, nowadays the apparel industry has changed from mass production to customised and versatile production in order to satisfy the consumer's desire for more individuality, thus the waste of resources and time and the traditional fitting trials become a major problem.

It has been found that the major source of fit problems are:

- lack of standardisation
- problems with size standards and grading rules
- shortcomings in pattern making
- manufacture-driven conflicts
- consumer and industry perceptions of the body.

With the super-rapid pace of technology advances and the promise of new sizing data on the horizon, solutions are beginning to abound.[87, 89]

10.5.1 The Web-enabled body scanner

To overcome the problems of lack of size standardisation and inappropriate grading rules, and the different perceptions of body shape from consumers and industry, apart from industrial surveys and studies to update consumer size, shape and fit preference data, automated body scanners have become one of the most powerful tools for obtaining 3D shape data to improve garment fit. Several advanced body scanners have been developed to be Web-enabled. The scanned data thus obtained can be transmitted via the Internet to a central database or to manufacturing locations from remote scanner locations.

The 'ImageTwin' (TM) system, which was formed by the joint venture between the Textile Clothing Technology Corporation (TC^2) and Konover Property Trust, was the first to deploy body scanners in commercial retail settings. The 3D body scanners were installed at various retail mall locations to obtain measurement data from consumers. The scanned data was then entered into a confidential database, which can be accessed by partner retailers for order fulfilment and by other retailers and manufacturers on an anonymous, data-for-fee basis. The consumer can access his or her scanned data for order placement via the Internet, or via a store or catalogue for clothing items.[87, 90]

The Tecmath AG's 3D body scanner from Germany, integrated with measurement software, can collect and automatically download scanned data into programs, such as made-to-measure systems.[91] There are other Web-enabled 3D body scanning technologies, such as the system from Clarity Fit Technologies, which can take scanned data and convert it into custom 2D patterns.[92] The Battelle Pacific Northwest National Laboratory (PNNL) has invented a high-speed body scanner 'Battelle' which can obtain human body measurements through clothing, thereby eliminating the need for a changing room.[93]

10.5.2 Services from Web-enabled scanning

ImageTwin's proprietary 'Best Fit' size prediction software can help the consumer to identify the best fitting garments for sale from partner retailers and brands from the scanned data. The Tecmath enables retailers to offer customised clothing options to consumers. Clarity Fit Technologies offers services for helping firms to improve their size standards and patterns. The Clarity Fitting Room of the firm assists consumers in online apparel shopping. Clarity Fit's solution can provide size recommendations based on consumer measurement data, fit preference data and the manufacturer's or retailer's garment specification data. The Clarity Fitting Room's proprietary visualisation technology displays how garments could fit an individual consumer in various sizes, such as loose, tight, recommended, etc. The 3D Custom Fit Corporation has developed a process utilising the 3D relational-geometry principle to automatically mould 3D basic blocks to fit over individual body scans. These 3D blocks are then flattened into 2D garment patterns which can be incorporated into standard CAD packages to create perfectly fitting garments without the use of measurements.[87]

IC3–D (Interactive Custom Clothes) is beginning to produce custom-made jeans based on information from body scanners. Brooks Brothers embraces the use of theTC^2 body scanner in its flagship store to act as a 'digital tailor' for its customised clothing business. This technology enables detailed measurements of their customers to be captured at the time of sale, thus ensuring a better fit, higher production efficiency and ultimately higher customer satisfaction.[88]

10.5.3 The virtual fit engines

Most consumers remain reluctant to buy garments online because they cannot try them on to ensure proper fit. Internet retailers have begun to implement virtual fit technologies on their websites to attract more shoppers to these sites, improve fit prediction, and decrease the number of returns. The virtual fit technology enables consumers to develop a 'virtual model' which 'looks' like

them by entering a series of measurements and shape parameters, and then choosing from a variety of facial, hair, and skin types to design a 'virtual model'. The consumer can click on garment images at a retailer's site while visiting participating retailers online and see how the clothing looks on the virtual model.

There are many virtual fit developments online offering 3D cyber mannequins for virtual trying-on, such as Browzwear's C-me, Clarity Fitting Room of Clarity Fit, DigiTex and DigiGarments of DigiBits Interactive, WebFitting of DigiBits Interactive, Vtryon of Enfashion, My Virtual Model and Virtual Dressing Room (VDR) of yourfit.com. In addition, Imaginarix's Click&Dress uses the consumer's own photographic images and Virtual 3D uses 3D images for visual effects. The Digital Fitting Room of MySize Systems can tie in with other 3D cyber mannequin solutions. Though EZsize and TheRightSize do not use a 3D cyber mannequin for visual effects, the EZsize provides a five-star fit rating and comments based on consumer's measurements while TheRightSize performs data analysis to recommend products based on what the consumer wears.[94]

Browzwear's C-Me combined with its flagship product, V-stitcher, can provide a 3D simulation of a 2D flat pattern. Manufacturers can see fit problems in virtual space before the sample is cut and made up. Problems can be identified and then corrected on the 2D pattern, thus saving time and development costs.[88]

'My Virtual Model', which is based in Montreal, and 'PlusSize.com' websites offer virtual trying-on or virtual fitting rooms. Consumers just need to enter a limited set of variables, such as weight and height and then choose a type of body shape from a few picture references to develop their virtual model virtually for trying on an outfit, and to mix-and-match styles. My Virtual Model provides personal shopping guidance by making clothing recommendations based on the individual's information and previously chosen styles. My Virtual Model's database on the size and fit of consumers is collected and aggregated and may eventually feed back to their retail partners so that they can gain a better understanding of the size, shape and consumer preferences in their target market.[87, 88]

Firms, such as EnFashion, EZsize, TheRightSize and YourFit.com, are targeting the size prediction marketplace. EZsize works with Saks Inc., Ann Taylor and Esprit de Corp. to integrate their merchandise offerings into the EZsize database. Consumers who input their measurements online via the EZsize service will be digitally matched with different garment choices.[87, 89] Furthermore, EnFashion considers not only consumer measurements but also the apparel manufacturer's DFX image of the paper pattern, fabric weight and elasticity and garment strength characteristics. The light and shadow renderings from computer simulation can illustrate the hang and drape of the fabric. The 'see-through' mechanism enables the consumers to see how well the garment fits in any dimension.[87]

Companies, such as Virtual 3D, are offering infrastructural tools which enable online retailers to display 3D images of products on their websites. The tools allow e-consumers to see, touch and feel a product through rotating, zooming and interacting with the images.[79]

10.5.4 Customisation from the Internet

Lectra has developed a solution called 'FitNet' which aims at addressing the needs for mass customisation. FitNet enables pattern makers not only to view their pattern constructed on a 3D model, but also to make adjustments to the garment in 3D and see those changes translated automatically onto the 2D pattern. It includes a server which allows each company to create its own collections, either online or through a sharing network. Consumers can design their own garments by selecting the viewed style, fabric, colour, trim, etc., available at point-of-sale, and then inputting their measurements through either measurement scales (chest, waist, hip, etc.), alterations to existing styles, or through body scanned data. The information can be sent electronically to a Modaris pattern-making system, where a customised pattern is produced and picked up by the Diamino marker making system, and a marker is automatically cut by the TopSpin cutting system. All these systems are linked through FitNet, garment fit can be ensured while production and delivery times can be reduced to a minimum.[88]

In addition to FitNet, there are a number of other solutions on the market which offer quick alterations to existing patterns to fit customisation and production automation. These include offerings from Optitex, Gerber Technology and PAD Systems.[80, 88]

10.6 References

1. Whife A A, *Designing and Cutting Ladies' Garments*, London, The Tailor and Cutter, 1965 1–16.
2. Bray N, *Dress Fitting: Principle and Practice*, London, Lockwood, 1978.
3. Anglais F, *Alterations and How to Make Them*, New York, Kogos Publications, Apparel Institute, 1967.
4. Wilson J K, *The Art of Cutting and Fitting*, London, The Tailor and Cutter, 1966.
5. Brackelsberg P and Marshall R, *Unit Method of Clothing Construction*, 7th edn. Prospect Heights Ill: Waveland Press, 1990.
6. Barnes M G (ed.), *Fitting Solutions: Pattern Altering Tips for Garments that Fit*, Newtown, Conn.: The Taunton Press, 1996.
7. Bray N, *Dress Pattern Designing – the Basic Principle of Cut and Fit*, 5th edn. Oxford: Blackwell Scientific, 1994.
8. Perry P, *The Vogue Sewing Book of Fitting*, *Adjustments and Alternations*, New York, Butterick Fashion Marketing Co., 1972.
9. Rasband J, *Fabulous Fit*, New York, Fairchild Publication Co., 1994.

10. Goldsberry E and Reich N, 'It either fits or it doesn't', *ASTM Standardization News*, Sept. 1989 42–44.
11. Katou C and Nakaho Y, 'Shapes of abdomen and hips of elderly women for the drafting pattern of basic blocks', *Japan Res Assoc Text End-Uses*, 2001 **42**(4) 251–261.
12. Le Pechoux B and Ghosh T K, 'Apparel sizing and fit', *The Text Inst*, 2002 **32**(1) 3.
13. Connell L J, Ulrich P and Ashdown S, 'Body scan analysis of posture and body shape for reengineering', URL: http://www.ntcresearch.org/current/yearII/I01–A27.pdf.
14. Larson M H, 'Pants for every body', *Threads*, Aug./Sept., 1994 **54** 50–55.
15. Whife A A, *A First Course in Gentlemen's Garment Cutting*, London, The Tailor and Cutter, 1968.
16. Waisman A, *Modern Custom Tailoring for Men*, Chicago, the Master Designer, 1974.
17. Frederic T C, *The Blue Book of Men's Tailoring*, Van Nostrand Reinhold Company, Variations, 1977.
18. Anon, *The Art of Simple Fitting*, Chicago, Alternation Consulting Inc., 1987.
19. Boswell S, *Menswear: Suiting the Customer*, Englewood Cliffs, N.J.: Prentice Hall, 1993.
20. Liechty E G, Pottberg D N and Rasband J A, *Fitting and Pattern Alteration: A Multi-method Approach* New York, Fairchild Publication Co., 1986.
21. Aldrich W, *Metric Pattern Cutting*, 3rd edn, Blackwell Science, 1994.
22. Betzina S, *Fast Fit: Easy Pattern Alterations for Every Figure*, Newtown, CT, Taunton Press, 2001.
23. Marcus J, *Fitting Men's Ready-to-wear Clothes*, London, The Tailor and Cutter, 1961.
24. Doblin F C and Frank C D, *The Modern Mitchell System of Men's Designing*, Chicago, Master Designer, American-Mitchell Fashion Publishers. Inc., USA, 1966.
25. Aldrich W, *Metric Pattern Cutting for Menswear,* 2nd edn, Blackwell Science, 1994.
26. Brinkley J, *Altering Ready-to-wear Fashions*, Peoria, Ill., C. A. Bennett Co., 1976.
27. Brumbaugh J and Mowat J, *His and Hers Tailoring: A Self-instructional Guide*, Anna Publishing, Incorporated, Winter Park, FL, 1977.
28. Taylor G, 'Patterns vs. people', *Bobbin*, April, 1979 170–182.
29. Hackler N, 'What is good fit?' *Consumer Affairs Update*, published by Consumer Affairs Committee of American Apparel Manufacturers Association, May, 1984 **2**(1).
30. Hutchinson R and Munden D L, 'The geometrical requirements of patterns for women's garments to achieve satisfactory fit, Part 2', *Cloth Res J*, 1978 **6**(3) 119–129.
31. Roehr M, 'Fitting jacket shoulders', *Thread Magazine*, Oct./Nov., 1993 62–65.
32. Komives M, DuMont D and Gale J, 'Fitting', *Threads*, April/May 1992 **40** 8, 10.
33. Tam Wong H Y, 'Pattern construction rules for Down's syndrome females', *Int J Cloth Sci Technol*, 1991 **3**(4) 25–32.
34. Abend J, 'Clothing for osteoporosis sufferers affords new niche', *Bobbin*, Oct., 1997 pp. 8, 10.
35. Douty H I, 'Objective figure analysis', *J Home Econ*, 1954 **46**(1) 24–26.
36. Douty H I, '''Visual somatometry'' in health related research', *J Alabama Academy of Sci*, Jan., 1968 **39** 21–34.

37. Douty H I and Ziegler, 'An engineered method for fitting garments to problem figures', *ACPTC National Meeting Proc*, 1980 58–59.
38. Farrell-Beck J A and Pouliot C J, 'Pants alteration by graphic somatometry techniques', *Home Econ Res J*, Sept., 1983 **12**(1) 95–105.
39. Brackelsberg P, Farrel-Beck J and Winakor G, 'Comparing fit of basic bodices and skirts altered by traditional and experimental techniques', *Cloth Text Res J*, 1986 **5**(1) 34–41.
40. Winakor G, Marvin S B and Part S, 'Using geometric models to develop a pattern for the lower bodice', *Cloth Text Res J*, 1990 **8**(2) 49–55.
41. Heisey F, Brown P and Johnson R F, 'A mathematical analysis of the graphic somatometry method of pattern alternation', *Home Econ Res J*, 1986 **15**(2) 115–123.
42. Shen L and Huck J, 'Bodice pattern development using somatographic and physical data', *Int J Cloth Sci Technol*, 1993 **5**(1) 6–16.
43. Istook C L, 'Enabling mass customisation: computer-driven alteration methods', *Int J Cloth Sci Technol,* 2002 **14**(1) 61–76.
44. Davis S M, *Future Perfect*, Reading, Mass, Addison-Wesley, 1987.
45. Gazzuolo E, DeLong M, Lohr S, LaBat K and Bye E, 'Predicting garment pattern dimensions from photographic and anthropometric data', *Applied Ergon*, 1992 **23**(3) 161–171.
46. Chan A P, Fan J and Yu W M, 'Garment pattern design based on human body's anthropometric data', *Proc 82nd World Conf Text Inst*, Cairo, Egypt 2002.
47. Stein D C and Magrab E B, 'Expert system for the design and manufacture of made to measure clothing', *Manufacturing Rev*, 1991 **4**(1) 126–138.
48. Turner J P, 'Development of a commercial made-to-measure garment pattern system', *Int J Cloth Sci Technol*, 1994 **6**(4) 28–33.
49. Turner J P and Bond T, 'Made-to-measure garments for ladies–catering for wide ranging stature and length measurements for standard and outsize ladies', *Int J Cloth Sci Technol*, 1999 **11**(4) 216–225.
50. Heisey F, Brown P and Johnson R F, 'Three-dimensional pattern drafting, Part I. Projection'. *Text Res J*, 1990 **60**(11) 690–696.
51. Collier B J and Collier J, 'CAD/CAM in the textile and apparel industry', *Cloth Text Res J*, 1990 **8**(3) 7–12.
52. Stjepanovic Z, 'Computer-aided processes in garment production features of CAD/CAM hardware', *Int J Cloth Sci Technol,* 1995 **7**(2) 81–88.
53. Appel A, and Stein A, 'The computer-aided design of a garment to fit a specific person', in *Conf Proc, Paperless Apparel Management*, Apparel Research Committee, American Apparel Manufactures Association, Atlanta, 1978.
54. Hutchinson R and Munden D L, 'The geometrical requirements of patterns for women's garments to achieve satisfactory fit, Part 1', *Cloth Res J*, 1978 **6**(2) 68–87.
55. Efrat S, *The Development of a Method for Generating Patterns for Garments that Conform to the Shape of the Human Body*, Doctoral dissertation, Leicester Polytechnic, 1982.
56. Heisey F and Haller K D, 'Fitting woven fabric to surfaces in three dimensions', *J Text Inst*, 1988 2 250–63.
57. Mack C, and Taylor H, 'The fitting of woven cloth to surfaces', *J Text Inst,* 1956 **47** T477–T488.
58. Heisey F, Brown P and Johnson R F, 'Three-dimensional pattern drafting: a theoretical framework', *Cloth Text Res J*, 1988 **6**(3) 1–9.

59. Heisey F, Brown P and Johnson R F, 'Three-dimensional pattern drafting, Part II, Garment modeling', *Text Res J*, 1990 **60**(12) 731–737.
60. Aono M, Breen D E and Wozny M J, 'Fitting a woven cloth model to a curved surface: mapping algorithms', *Computer Aided Design*, 1994 **26**(4) 278–92.
61. Kim S M and Kang T J, 'Garment pattern generation from body scan data', *Computer Aided Design*, 2002 **35** 611–618.
62. Lin C F and Lin C Y, 'A new approach to high precision 3–D measuring system', *Image Vision Computer*, 1999 **17**(11) 805–814.
63. Sato R, 'Asahi chemical apparel system with high performance software', *JNT,* Sept 1990 96–100.
64. Okabe H, Imaoka H, Tomiha T and Niwaya H, 'Three-dimensional apparel CAD system', *Computer Graph*, 1992 **26**(2) 105–110.
65. Ito I, Kawauchi K and Odagaki C, 'Three-dimensional computer system for automatic pattern making and simulation', *J Text Mach Soc Japan*, 1992 **38**(3) 68–77.
66. Hinds B K and McCartney J, 'Interactive garment design', *The Vis Computer*, 1990 **6** 53–61.
67. McCartney J and Hinds B K, 'Computer aided design of garment using digitized three-dimensional surfaces', *J Eng Manuf*, 1992 **206** 199–206.
68. Kang T J and Kim S M, 'Development of three-dimensional apparel CAD system: Part II: Prediction of garment drape shape', *Int J Cloth Sci Technol* 2000 **12**(1) 39–49.
69. Kang T J and Kim S M, 'Optimized garment pattern generation based on three-dimensional anthropometric measurement', *Int J Cloth Sci Technol,* 2000 **12**(4) 240–254.
70. Harderka C H M and Fozzard G J W, 'Towards the virtual garment: three-dimensional computer environments for garment design', *Int J Cloth Sci Technol*, 1988 **10**(2) 114–127.
71. Fozzard G J W and Rawling A J, 'Simulation of dressing and drape for garment CAD', *Proc 6th Int Forum on CAD*, 1991 157–162.
72. Fozzard G J W and Rawling A J, 'CAD for garment design effective use of the third dimension', *Proc Eighth National Conf Manuf Res*, 1992 183–198.
73. Hinds B K, McCartney J, Hadden C and Diamond J, '3–D CAD for garment design', *Int J Cloth Sci Technol*, 1992 **4**(4) 6–14.
74. Hinds B K and McCartney J, 'Three-dimensional design of garments and automated pattern construction', *The Appl of Computers to Manuf Eng, (SCME) Directorate*, Science and Engineering Research Council, Research Conference Proceedings, 1993 2–7.
75. Jones P, West G, Harris D and Read J, 'The Loughborough Anthropometric Shadow Scanner', *Endeavour*, 1989 **13**(4) 162–168.
76. Chen J H-C, *An Investigation into 3–dimensional Garment Pattern Design*, PhD Thesis, Nottingham Trent University, UK, 1998.
77. Au C K and Yuen M M F, 'Feature-based reverse engineering of mannequin for garment design', *Computer Aided Design*, 1999 **31** 751–759.
78. Yuen M, '3–D garment construction', *Textile Asia*, April, 2000 44–48.
79. Chapman K, 'Sizing up virtual fit technology', URL: http://www.techexchange.com/thelibrary/VirtualFit.htm, 2001.
80. URL: http://www.tx.ncsu.edu/3–Dbodyscan/pdf_docs/Document3.pdf.

81. McCartney J Hinds, B K, Seow B L and Gong D, 'Dedicated 3–D CAD for garment modelling', *J Materials Processing Technol*, 2000 **107** 31–36.
82. Kang T J and Kim S M, 'Development of three-dimensional apparel CAD system: Part 1. Flat garment pattern drafting system', *Int J Cloth Sci Technol*, 2000 **12**(1) 26–38.
83. Wang C C L, Wang Y and Yuen M M F, 'Feature based 3–D garment design through 2–D sketches', *Computer Aided Design*, 2002 **35** 659–672.
84. Hinds B K, McCartney J and Woods G, 'Pattern development for 3–D surfaces', *Computer Aided Design*, 1991 **23**(8) 583–592.
85. McCartney J, Hinds B K and Seow B L, 'The flattening of triangulated surfaces incorporating darts and gussets'', *Computer Aided Design,* 1999 **31**(4) 249–60.
86. Wang C C L, Smith S S F and Yuen M M F, 'Surface flattening based on energy model', *Computer Aided Design*, 2002 **34** 823–833.
87. DesMarteau K, 'CAD: Let the fit revolution begin', *Bobbin,* Oct., 2000, Columbia **42**(2) 42–56.
88. Chapman K, 'Sizing up fit issues', *AATCC Rev* **2**(10) Oct., 2002 33–36.
89. Moin D, 'Fixing the fit problem online', *WWD*, Aug., 23 2000.
90. URL: http://www.textileworld.com/News.htm.
91. URL: http://www.bekleidung-nach-mass.de/presse/englisch/htp_vitus_smart_eng.pdf.
92. URL: http://www.clarityfit.com/info.htm.
93. URL: http://availabletechnologies.pnl.gov/securityelectronics/body.stm.
94. URL: http://www.techexchange.com/thelibrary/resources/VirtualFitChart.htm.

Index

3D 52–4, 64–8, 72, 77, 80, 86, 87, 115, 117, 123, 125–31, 135–8, 140–50, 152–8, 161–6, 174, 177, 178, 180–2, 193, 206, 207, 209, 210–29
3D Electronic Commerce, Centre for 180
3D laser scanning system 64, 65
3D model 128, 155, 161, 215, 229
3D Model Maker 64, 66
3D virtual design 127
3D visualisation 125, 213

AATCC 15, 16, 19–22, 24, 25, 28, 48, 49, 51, 54, 61–3
Accumark 126, 144, 154
accuracy 35, 46, 51, 61, 65, 68, 125, 140, 142, 144, 152, 154, 155, 161, 163–5, 167, 173, 214, 215
aesthetics 15, 89, 91
African body dimensions (ABD) 181
air force 143, 154, 178, 179
algebraic mannequin 72, 78, 79
alignment 73, 161
American 20, 143, 174, 177–9, 181, 188
anatomy 31, 169, 197
anthropometric data 138, 146, 165, 174, 177, 178, 203, 205, 214
anthropometrics 166, 169, 190
anthropometry 154, 166, 171, 173, 178, 179
Apparel-Body-Construct 9
appearance 1, 8–20, 22–6, 28–32, 41, 43, 48, 49, 51, 52, 54, 58, 59, 61, 65–9, 71, 77, 85–97, 101–3, 105, 106, 108, 109, 111–14, 122, 126, 130, 135, 200
appearance of the clothed body 9
appearance retention 25, 26, 89, 109
appearance of seams 20, 22
assessment procedure 27, 28
assessment scale and rating technique 28
AssyCAD 144
ASTM 17, 19, 20, 22, 24, 59, 177
attractiveness rating 7
Australian 175
Auto-Mate 144
average displacement from the mean magnitude (R_a) 64

balance 31–3, 38, 97, 138, 159, 201
balanced 11, 39, 43, 184, 200
beauty 1–5, 33, 200
bending 90, 91, 93–102, 106–9, 115, 118–24, 131, 200, 225
bending length 97, 106–7, 115, 118, 119, 123
bending rigidity 97, 100, 102, 107–9, 119–22
bodice 38, 80, 200–9, 215, 217
body 1, 4–12, 25, 29, 31–7, 39–41, 45, 72, 73, 77–81, 83–6, 89, 93, 126, 130, 135–50, 152–6, 158, 159, 161–6, 169–78, 180–93, 196–203, 205–15, 217–19, 221, 222, 225–9
body attractiveness 1, 7, 9
body card 153
body cathexis 10, 11, 32, 33, 41
body image 1, 8–10
body mass index (BMI) 6
body measurements 85, 126, 130, 135, 137, 140, 153, 166, 170–2, 174–8, 183–5, 188, 190, 199, 201, 203, 205–7, 227
body morphology 148
body proportion 12, 32, 196
body scanner 35, 139, 141, 143, 149, 152, 153, 156, 177, 178, 180, 181, 206, 215, 226, 227

body scanning 77, 135, 138, 142–5, 161, 164, 166, 174, 180, 193, 227
body type 173, 198
bras 77
breadth 166, 170
British 175, 176, 195
Brooks Brothers 143, 227

CAD 35, 86, 123, 124, 125, 126, 131, 135, 141, 144, 145, 147, 153, 156, 162, 163, 202, 203, 206, 207, 213, 215–19, 221, 223–5, 227
CAD system 126, 144, 202, 206, 213, 217, 218, 219, 221, 223, 225
CAESAR 178–80
calibration 141, 142, 156, 161
calipers 173
cantilever method 115
CCD camera 45, 51, 52, 58, 59, 62, 117
charge coupled device (CCD) 159
children 138, 141, 175, 176, 182, 189, 190
China 140, 143, 176, 181, 182, 189, 192
circumferences 166, 207
Civilian American and European Surface Anthropometry Resource 178, 179
clothing appearance 10, 15, 31, 41, 43, 77, 86, 87, 135
comfort 31, 32, 34, 37, 39, 85, 89–94, 104, 105, 114
complex phase tracing 150
compression 90–6, 99, 100, 102, 106, 108, 166
computer-aided design (CAD) 202
contact methods 43, 45, 60, 61, 72
contour 43, 44, 61, 76, 82, 85, 115, 135–7, 145, 148, 151, 156, 196, 197, 201, 220
conusette 138, 139, 159, 162, 163
crease retention 25, 94
cross-sectional index 78–90
Cubic 140, 157, 161–3, 201
Cubicam 77, 141, 142, 148–50, 162–4
customisation 135, 138, 145, 203, 229
Cyberware 66, 143, 154, 155, 162–6, 178, 180, 215

dark room 52, 141
data extraction 154, 164–6
DCTA 144, 162
definitions 31, 114, 166, 169, 170, 174, 182, 183, 190
definitions of fit 31
Denmark 175, 186
deviation of the ratio of waist over hip from the ideal ratio (AWHR) 7
DigiScan 150, 151
digital human 35, 36, 172
digital image processing 51, 58
dimension 33, 46, 49–51, 54, 55, 57, 78, 150, 163, 183, 185, 189, 228
dimensional stability 25, 90, 93, 94, 96, 107, 108
drape 22, 32, 41, 65, 68, 72, 86, 89, 94, 99, 101, 102, 104, 114–26, 128–31, 135, 213, 214, 219, 221, 222, 224, 225, 228
drape coefficient 115–24
drape image 116, 125
drape models 130, 131
drape resistance 117
drapemeter 115–21, 124
dress 11, 22, 33–7, 41, 72, 80, 114, 125–7, 135, 181, 184, 189, 228
dress form 34–6, 126, 127
dress forms 33, 35, 41, 184
drop value 185, 186, 189, 191
dynamic fabric drape 122
dynamic visual appearance 122

ease 31, 38, 39, 79, 85–7, 99, 107, 128, 129, 199
EN 13402 183
equipment 16, 46, 53, 107, 170, 171, 174, 176
errors 166, 173
evaluation 10, 15, 19, 20, 22, 28, 32–5, 38, 39, 43, 47, 49, 54, 55, 58–66, 68, 72, 73, 77, 78, 80, 81, 84–6, 90, 92, 94, 95, 101, 102, 106, 122, 135, 206
evolutionary psychology 5
exercise routine 34
experimental method 201, 202
extensibility 91, 97, 100, 105, 107–9, 128
extension 90, 93, 95, 97, 100, 105, 107, 122

fabric 13, 15, 16, 18, 19, 25, 32, 35, 41, 43–9, 51–5, 58–62, 64, 65, 67, 80, 85, 89–103, 105–11, 114–28, 130, 131, 141, 196, 209–11, 213, 219, 222–5, 228, 229
fabric colour and pattern 16
fabric drape 115, 117, 119, 122–4, 131, 213, 219, 222, 224, 225
fabric drape engine 219, 222, 224
fabric handle 90, 91, 93–7, 101

fabric model 224
fabric objective measurement 91, 94, 96, 141, 225
fabric performance 89, 92, 93
fabric properties 41, 89–91, 93, 95, 96, 99, 101, 109–11, 117, 123, 124, 128, 225
fabric surface smoothness 15
fabric wrinkle 15, 45, 51–3
fabric wrinkling 43, 45, 49, 51–3, 61
face 3, 4, 11, 17, 143, 156
facial attractiveness 3
FAST 52, 63, 95, 96, 106–8, 110, 111, 121, 125, 127, 150, 225
Fast Fourier Transform (FFT) 63
FastScan 157, 158, 162, 163
female physical attractiveness 5–7
figural scale 9, 10
figure abnormalities 196, 198
figure types 176, 185–7, 193, 197, 198
finish stability 108
fit 4, 7, 11, 15, 31–5, 37–9, 41, 60, 72, 73, 76–8, 80, 81, 83–7, 89, 90, 114, 126, 135, 140, 143, 144, 156, 162, 174, 177, 180, 181, 184, 196, 197–201, 203, 206, 207–9, 213, 217–19, 224–9
fit engines 227
fit evaluation 33, 38, 39, 81, 135
fit testing 85
fitting 11, 31, 34, 38, 39, 41, 79, 80, 93, 141, 147, 152, 165, 174, 175, 180, 183, 196–201, 203, 205, 206, 208, 209, 212, 218, 219, 221, 225–8
five-point scale 37
flashlight 150
flattening 210, 211, 213, 219, 221–4
flattering 199, 200
FOM 91–6
formability 94–7, 107–9
fractal dimension 49–51, 54, 55, 57
France 144, 145, 175, 182, 191
friction 54, 90, 91, 94, 97, 99, 100, 124
Fujinon 138, 139, 162
fullness 11, 41, 90, 96, 101, 102, 109, 202, 218
fuzz 16, 54, 55, 57, 59, 60
fuzzy-neural network 125

garment design 125, 141, 196, 197, 200, 206, 207, 213, 215, 216, 218, 220, 221, 224
garment fit 39, 207, 213, 218, 224–6, 229
garment form 213, 215, 216, 221
garment pattern 138, 146, 205, 213, 215–19, 221
garment stand 213, 215, 217
garment types 185, 188, 189
Gemini 142
Gerber 126, 135, 153, 156, 202, 206, 217, 229
Germany 62, 145, 175, 176, 182, 186–8, 190–2, 227
GGT 144
girdles 77
golden proportion 2
golden ratio 2, 4
GOweb 144
grade 22–4, 26, 41, 46, 51–5, 58, 60, 63, 65, 66
grain 31, 38, 201
grey level 49, 51, 53, 54
grid 52, 73–5, 85, 123, 137, 149, 150, 155, 201, 215, 219, 221, 222
guideline 39
gypsum 136, 137

halogen 140, 152, 161, 162
Hamamatsu 138, 159, 162–4, 166
handle 15, 28, 29, 90–7, 101, 105, 106, 107
HKUST 140, 148
Hong Kong Polytechnic University 141, 149
hosiery 35, 86
human model 36, 148, 155, 213–15, 220, 221, 225
human solutions 145, 156, 162
human torso 215
Hungarian 176, 186
hygral expansion 91, 93, 94, 96, 97, 103, 107–9

ideal figure 9, 32
illumination 49, 51, 53, 60, 150, 161
illusion 11
image 1, 8, 9, 10, 43, 46, 49, 51–60, 62, 66, 72–5, 86, 87, 116–18, 125, 127, 140, 142, 148–50, 152, 154, 155, 157, 159, 161, 164–6, 205–16, 228
image processing 43, 49, 51, 52, 54, 55, 58, 66, 117, 150
infrared 135, 136, 138, 139, 142, 145, 157–9, 162
Inspeck 161–3
internet systems 125, 126

jacket 10, 41, 73, 75–7, 105, 107, 189
Japanese 3, 16, 19, 22, 25, 35, 72, 138, 170, 172, 175–9, 182, 188, 189
judgement 1, 7, 58, 91, 173, 211

Kawabata 63, 90–3, 95, 96, 98, 102–6, 122
KES-F 95, 96, 98, 99, 101, 102, 105, 122, 126
key dimensions 176, 183–5, 187–90, 193
kurtosis 55, 57, 65

ladies' figures 197
landmarks 35, 36, 135, 154, 166, 169, 171, 173, 174
lands' end 143
laser 43, 45–9, 54–6, 58, 62–6, 68, 135, 136, 138, 140, 142, 143, 145, 148, 154, 156, 157, 161, 162, 164, 165, 178, 181, 182, 206
laser scanning 43, 45–7, 54, 55, 58, 62–5, 135, 143, 154, 164
laser triangulation technique 46, 55
LASS 143, 146, 147, 162, 215
laying up 97, 107–9
LED (light emitting diodes) 158, 159
length 4, 22, 25, 43, 46, 48, 51, 53, 55, 57, 61, 62, 77, 97, 106–8, 115, 118–20, 123, 124, 136, 146, 154, 166, 170, 172, 186, 189, 199, 201, 202, 218
Levi Strauss 143
line 10, 18, 31, 38, 41, 44, 45, 47, 48, 55, 63, 75, 79, 81–3, 101, 127, 145, 150, 154, 162, 163, 197, 199–201, 220, 222
linear index 78, 79
linear measurements 79, 135, 148, 196, 205
lines 11, 13, 38, 52, 53, 63, 74, 76, 95, 159, 169, 199, 203, 215, 220
live models 33–5, 41
Loughborough University 143, 146, 178

made-to-measure 124, 143, 144, 156, 206, 207, 227
making-up 90, 91, 93, 95, 97, 98
mannequin 72, 73, 77–9, 84, 85, 115, 130, 135, 140, 141, 215, 216, 219, 228
mass customisation 138, 145, 203, 229
mass production 174, 203, 214, 215, 226
mean profile height 55
mean roughness CLA 55
mean roughness RMS 55
measurer 171
measuring tapes 173
men 3, 22, 24, 25, 28, 38, 65, 101, 128, 141, 174–7, 180, 182, 186, 187, 189, 191, 198, 199, 206
men's figures 186, 198
MICROFIT 144, 206
military 165, 174–6
missing data 165
mobility 31
model 12, 34–6, 51, 64, 66, 84, 86, 96, 123–5, 128, 130, 135, 148, 155, 156, 161, 162, 184, 196, 203, 204, 206, 211–17, 219–25, 227–9
modeling 35
moiré 73, 75, 139
moiré topography 141, 148–50, 162
'Mondoform' 183
moulding 97, 107–9, 136, 137, 208
movements 17, 34, 37, 79, 155

national size survey 176–8, 181
Nedscan 180
Netherlands 175, 176, 180, 186, 189, 191
neural network 51, 96, 106, 122, 125, 206
non-contact methods 43, 45, 61
non-standard figures 200
Nottingham Trent University 144
number of assessors 28
number of wavelet coefficients 55, 58

objective evaluation 43, 54, 55, 58, 60, 61, 63, 65, 66, 68, 72, 77, 86, 92, 94, 95, 102
OptiFit 145, 153
orientation 47, 124, 157, 173
overall garment appearance 43, 66, 68

pants 189
particle-based model 125
pattern 13, 16, 35, 46, 48, 51, 54, 59, 60, 62, 65, 72, 76, 77, 81, 86, 89, 97, 124, 126–8, 135, 138, 146, 148–51, 156, 169, 174, 175, 196–219, 221–6, 228, 229
pattern alteration 196–203
pattern generation 135, 203, 206, 207, 213, 217–19, 221
perceived body sizes 11
perception of body appearance 1, 9, 11
phase measuring profilometry 151
phase shift 148, 151, 162

photogrammetry 135, 145, 159, 162
photographic data 205
photographic pilling standards 59
photographic seam smoothness replicas 20
photometric stereo 53, 54
pictogram 183, 190
pill contrast 59, 60
pill density 59
pill feature 60
pill size 59
pilling 15–17, 19, 43, 54, 55, 58–60, 90, 91, 94
pilling propensity 16, 17
PMP 151
pointedness 65
polish 175
polygons 135, 161, 211
polynomials 180
portable 96, 142, 157
position sensitive detectors (PSD) 158, 159
posture 147, 165, 166, 173, 196–8, 200, 201, 215
posture and movement 165
power 7, 52, 55, 57, 60, 63, 85, 141, 142
prediction of static drape 117
pressure 3, 17, 44, 49, 72, 84–6, 173, 218, 225
procedures 20, 22, 25, 34, 171, 177, 206, 210
projecting grid technique 52
proportion 2, 11, 12, 32, 33, 196, 201, 215
proportion balance 33
pucker 22, 43, 60–5, 94, 97, 98, 107–9
pucker index 61, 62
pucker vision system 62
puckering 61, 68, 90, 99, 108, 109
puckering-severity index 61
Puckermeter 61

RAMSIS 155
rank 28, 35
ratio of the total area of pills and the number of pills 55
ratio of waist height over the chin height (WHC) 7
relaxation shrinkage 93, 94, 96, 97, 103, 107–9
reliability of subjective assessment 27
repeated home laundering 19, 25
resolution 46, 47, 61, 131, 150, 152, 155, 156, 167
reviews on drape 114
rigidity 97, 100–2, 107–9, 119–22, 124, 131
roughness ratio 52

sampling 47, 48, 173
SAWTRI Wrinklemeter 44, 45
scan 9, 64, 68, 154, 155, 157, 161, 164–6, 215, 217
seam appearance 20, 28, 29, 97
seam pucker 22, 43, 60–3, 65, 97, 98, 107
seamed fabric drape 122
set 3, 6, 31, 35, 37, 38, 41, 59, 61, 95, 108, 124, 137, 146, 147, 176, 182–5, 201, 202, 206, 207, 213, 214, 228
shadow moiré topography 72, 137, 148
shape 3–6, 10, 13, 15, 31, 32, 34, 35, 41, 47, 48, 52, 54, 60, 62, 63, 72, 73, 76, 77, 80–6, 89, 93, 94, 109, 114, 115, 121, 123, 124, 135, 137, 138, 141, 143–5, 148, 150, 151, 153, 154, 156, 159, 161, 165–7, 169, 177, 178, 180, 181, 196, 197, 199, 201–3, 207–9, 213–15, 218, 219, 221, 222, 224–6, 228
shear 90, 91, 93–100, 102, 105, 107–9, 114, 117–24, 131, 213, 225
shear hysteresis 96, 105, 120, 121, 124
shear rigidity 97, 100, 107, 109, 121, 131
shear stiffness 102, 115, 118, 120, 122
Shirley Stiffness Tester 118
signature curve 78, 80
silhouetter 35, 136, 137, 145, 181
Sivim Wrinklemeter 44, 45
size 11, 12, 17, 29, 31, 33–5, 45, 48, 49, 59, 74, 79, 81–4, 108, 109, 115, 116, 120, 121, 126, 135, 138, 143, 144, 148, 150, 153, 155, 163–6, 169, 170, 174–8, 180–93, 196, 199, 201–3, 207, 226–8
size chart 184, 207
size designation 183, 185
size intervals 185, 189, 193
size labelling 176, 177, 183, 185, 188, 190, 193
size survey 135, 170, 174–8, 180–3
‘Size UK’ 177, 180, 181
‘Size USA’ 177, 181
sizing 90, 92, 97, 108, 135, 169, 174–8, 180, 182–6, 188–90, 193, 203, 226
skewness 55, 57, 64, 65

skewness of the distribution 64
skin 5, 6, 12, 79, 84, 89, 137, 165, 173, 228
skirt 114, 122, 189, 200–3, 211–13
sliding gauge 136, 137, 214
social message 32, 41
soft mannequin 84, 85
software 49, 53, 58, 62, 64, 65, 67, 68, 86, 126–40, 142, 144, 145, 147, 150, 153–5, 157, 161, 164–6, 206, 213, 215–18, 221, 225, 227
somatograph 205
somatometry 86, 201–3
South Africa 176, 181, 182, 190
South Korea 176, 177, 190
standards 16, 17, 19, 20, 22–6, 28, 33–5, 41, 51, 59, 61, 174–6, 182–4, 193, 200, 207, 208, 226, 227
stature 170, 178–80, 207
Stevens' power law 7
stretch 85, 86, 109, 225
structure light 145, 148, 165
subjective evaluation 34, 49, 90, 122
surface area ratio 52, 53
survey 135, 136, 170, 174–8, 180–3
Swedish 176
SYMCAD 144, 145, 147, 162, 163
symmetrical 39, 40, 48, 76, 86, 184, 196
symmetry 3, 32, 57, 196, 200, 201

tailorability 90, 93–6, 101–3
tailoring 90, 91, 93–5, 98, 102, 104, 106, 108, 144, 198, 199, 209
Takasaki 148, 149
tape measure 166, 174, 178, 196, 199, 205
TC^2 143, 148, 151, 164, 165, 177, 180, 181, 226
Tecmath 145, 155, 164, 206, 227
Telmat 144, 145, 147, 153, 154, 162–4
tensile 86, 93, 96–100, 102, 119, 121, 123, 225
texture 10, 13, 51, 53, 55, 57, 60, 65, 67, 126–8, 131, 140, 146, 150, 155, 156, 161, 165, 196, 224, 225
three-dimensional 16, 22, 23, 47, 86, 99, 107, 115, 123, 124, 135, 140, 143, 148, 157, 196, 206–9
three-dimensional (3D) body data 143, 157, 215
three-dimensional (3D) design 196, 220
three-dimensional (3D) human model 36, 148, 155, 213, 215, 220
three-dimensional computer aided design (3D CAD) 123, 126, 213, 215–19, 221, 223, 224
traditional method 201, 202
training of assessors 27
TriForm 144, 152, 153, 162, 163
two-dimensional (2D) pattern 126, 210, 213, 218, 221, 228, 229
two-dimensional computer-aided design (2D CAD) 217, 225

ultrasonic wave technology 62

variance 7, 64, 65, 119
virtual fit 227, 228
virtual model 130, 227, 228
visual design principles 13
visualisation 125–7, 156, 166, 213, 217–19, 225, 227
volume height index (VHI) 6
volume index 78, 79
Voxelan 138, 140, 156, 157, 162, 163, 178, 181, 182

Wacoal 33, 137, 181
waist-hip ratio (WHR) 6
wash and wear 20
waveform 72, 81–3
wavelet energy 52, 58
wearer acceptability scale 34, 37, 38
web-enabled 226
Weber-Fechner law 63
Wicks and Wilson 144, 148, 152, 164
women 9, 11, 33, 72, 128, 141, 143, 159, 174–7, 180–2, 186, 189, 197, 199, 200
wrinkle 15, 16, 35, 43–9, 51–4
wrinkle density 48, 51, 52
wrinkle depth 49
wrinkle height 43, 44
wrinkle ratio 49
wrinkle roughness 48
wrinkle sharpness 48
wrinkle size 49
wrinkle slope 45
wrinkle wavelengths 45
wrinkles 15, 16, 31, 38, 40, 41, 45–9, 51, 52, 156
Wrinklemeter 43–5, 61

Young's Modulus 117, 123