Ministry of Science and High Education of Russian Federation
Ivanovo State Polytechnic University

Trial print

Yan Jiaqi

DEVELOPMENT OF E-BESPOKE MEN'S SHIRT VIRTUAL DESIGN WITH PREDICTABLE FIT

Scientific specialty 05.19.04 − Technology of sewing garments

Dissertation for the degree
of PhD (technical sciences)

Scientific adviser -
Doctor of Sc., Prof. Victor Evg. Kuzmichev

Ivanovo − 2021

CONTENT

LIST OF ABBREVIATIONS 5
LIST OF TABLES 9
LIST OF FIGURES 11
FULL INTRODUCTION 15
BRIEF INTRODUCTION 21
1. CURRENT SITUATION OF REAL AND VIRTUAL DESIGN OF CUSTOMIZED CLOTHING 23
1.1. Customization as the primary trend in clothing industry 24
1.1.1.Difference between RtW, MtM, and bespoke tailoring 24
1.1.2. Trend of customization 26
1.1.3. Contemporary methods of clothing customization 26
1.2. Morphology and anthropometry of male bodies 34
1.2.1. Essential morphological features of male bodies 34
1.2.2.Existing body measurements reflecting the male body morphology 41
1.2.3. Application of 3D body scanning technology 44
1.3. Men's shirt and its pattern construction 50
1.3.1.Men's shirt and its styles 50
1.3.2.Contemporary methods of pattern drafting 52
1.3.3. Methods of adapting pattern to body morphology 57
1.4. Methods of achieving and evaluating clothing fit 59
1.4.1. Factors that influence on the clothing fit 60
1.4.2.Evaluation and criteria of the clothing fit 62
1.5. CAD for clothing design 73
1.5.1. 2D CAD 73
1.5.2. 3D CAD 75
1.6. Main aim and steps of research 82
2. ANTHROPOMETRIC DATABASEOF MALE TORSO. 86
2.1. Methods of research 86
2.1.1. Instruments and software 86
2.1.2.Acquisition of virtual clones of male bodies 87
2.1.3. Method of obtaining body measurements in Rhinoceros 88
2.1.4. Statistic validation of the body measurements 90
2.2. Morphological features of male torso 92
2.2.1. Proportions of anteroposterior main torso 93
2.2.2.Spatialshape of neckline 96
2.2.3. Spatial location of shoulder line 98
2.2.4. Morphology of arm 99
2.3. New body measurements 100
2.3.1. Raw new body measurements 100
2.3.2. Converted pattern-oriented body measurements 104
2.4. Geometric modeling of male torso 105

2.4.1. Geometric modeling of neckline and shoulder line 105
2.4.2. Geometric modeling of main torso and arm 109
Conclusion after Chapter 2 111
3. CRITERIA FOR VIRTUAL FIT EVALUATION 112
3.1. Methods of research 112
3.1.1. Instruments and software of research 112
3.1.2. Consumers' opinions from the Internet 113
3.1.3.Photos of men's shirts from the Internet 114
3.1.4.Digital twins and real samples for validation 115
3.2. Initial databases for subjective evaluation 118
3.2.1. Database of consumers' opinions 118
3.2.2. Database of misfit photos 119
3.3. Criteria for evaluating men's shirt 121
3.3.1. Constructive reasons 122
3.3.2. Fit indicators with real validation 124
3.3.3.Final criteria of fit evaluation 128
Conclusion after Chapter 3 130
4. DEVELOPMENT OF E-BESPOKE MEN'S SHIRT PATTERN . . . 131
4.1. Methods of research 131
4.1.1.Software 131
4.1.2. Subjects of research 132
4.1.3. Objects of research 134
4.2. Patterns of men's shirt 135
4.2.1. Database of ease allowances 135
4.2.2. Generation of shirt patterns 138
4.2.2.1. E-bespoke shirt patterns 138
4.2.2.2. RtW and MtM shirt patterns 140
4.2.3. Comparison between shirt patterns 141
4.2.4. Fit prediction with patterns 144
Conclusion after Chapter 4 148
5. VIRTUAL E-BESPOKE MEN'S SHIRT 149
5.1. Methods of research 149
5.1.1.Instruments and software 149
5.1.2. Properties of textile materials 150
5.1.3. Subjects of the research 150
5.2. Generation of e-bespoke shirt 150
5.2.1. Virtual twins of male bodies 151
5.2.2. Digital twins of textile materials 154
5.2.3.Digital twins of e-bespoke shirts 155
5.3. Evaluation of virtual e-bespoke shirt 157
5.3.1.Subjective evaluation 157
5.3.2. Objective evaluation 164
5.3.3. E-bespoke shirts in different styles 167
5.3.4. E-bespoke shirts made of different fabrics 169
5.4. Practical production testing 170

Conclusion after Chapter 5 173
CONCLUSIONS 174
Final results of research 174
Recommendations, perspectives of future research 176
REFERENCES 177
APPENDIXA. Ease allowances of men's shirts 195
APPENDIXB. Body measurements of male bodies 200
APPENDIXC. Consumer s' opinions 207
APPENDIXD. Indicators of shirt misfit 210
APPENDIX E. Results of technology validation 223

LIST OF ABBREVIATIONS

2D	–	two-dimensional
3D	–	three-dimensional
AD	–	armhole depth
AF	–	angles of front contours
AFH	–	front contour of bodice in H silhouette
AFX	–	front contour of bodice in X silhouette
AG	–	armscye girth
AI	–	artificial intelligence
AL	–	arm length
ANN	–	artificial neural network(s)
AP	–	axilla point
APF	–	armpit point front
APB	–	armpit point back
AR	–	augmented reality
AW_F	–	across front width
AW_B	–	across back width
B	–	bending stiffness
BHB	–	back bottom height
ΔBHB	–	difference between profile and back bottom height of a shirt
BHF	–	back bottom height
ΔBHF	–	difference between profile and front bottom height of a shirt
BHP	–	profile bottom height
BL	–	back length
BM	–	body measurement(s)
BM_E	–	existing body measurement(s)
BMI	–	body mass index
BM_N	–	new body measurement(s)
BNP	–	back neck point
C2M	–	customer-to-manufacture
CAD	–	computer aided design
CG	–	chest girth
CG_F	–	front chest girth
CG_B	–	back chest girth
d	–	margin of error
D_{CW}	–	vertical depth from chest to waist
DE	–	dynamic ease
D_{BNP}	–	horizontal distance from back neck point to predefined vertical plane
D_{FNP}	–	horizontal distance from back front point to predefined vertical

plane
DN_F – depth of front neck
DN_B – depth of back neck
DT – digital twin
DT_M – digital twin of textile material
DT_S – digital twin of system “male body - shirt”
D_{SNP} – horizontal distance from side neck point to predefined vertical plane
D_{WH} – vertical depth from waist to hip
E – ease allowance
E_C – constant ease allowance
E_V – variant ease allowance
ECG – ease to chest girth
EHG – ease to hip girth
EMT – elongation under 500 cN/cm
EP – elbow point
E_P – predicted ease allowance
E_{P0} – predicted ease allowance which should equal to zero
E_{PC} – predicted constant ease allowance
E_{PV} – predicted variant ease allowance
EWG – ease to waist girth
F – tensile strength when elongation is 3%
FE – fabric ease
FL – front length
FNP – front neck point
G – shear rigidity
H_{BNP} – height of back neck point
H_{FNP} – height of front neck point
H_{SNP} – height of side neck point
H_C – height of chest
HG – hip girth
HG_F – front hip girth
HG_B – back hip girth
H_W – height of waist
H_H – height of hip
I_1 – pattern index 1 which equals to the raw body measurement
I_2 – pattern index 2 which equals to the sum of body measurement and constant ease
I_3 – pattern index 3 which equals to the sum of body measurement and variant ease
I_4 – pattern index 4 which equals to the variant ease
IoT – Internet of things

I_P	–	pattern index
KES-F	–	Kawabata Evaluation System for Fabric
LFNB	–	length from front waist line to back waist line across side neck point
LFNB	–	length from front waist line to back waist line across shoulder point
MtM	–	made-to-measure
n	–	number of samples
NG	–	neck girth
NG_F	–	front neck girth
NG_B	–	back neck girth
NW	–	neck width
NWP_F	–	profile width of front neck
NWP_B	–	profile width of back neck
PBH	–	pattern block in loose-fit style
PBX	–	pattern block in body-fit style
PM	–	pattern measurement
PPN_B	–	profile projection of back neck on the sagittal plane
PPN_{B-P}	–	predicted profile projection of back neck on the sagittal plane
PPN_F	–	profile projection of front neck on the sagittal plane
PPN_{F-P}	–	predicted profile projection of front neck on the sagittal plane
RT	–	tensile resilience
RtW	–	ready-to-wear
S	–	subject
SD	–	standard deviation
SE	–	style ease
SL	–	shoulder length
SLA	–	shoulder sloping angle
SM	–	shirt measurement
SNP	–	side neck point
SNW_F	–	surface length from side neck point to front waist
SNW_B	–	surface length from side neck point to back waist
SP	–	shoulder point
SS	–	shoulder sloping index
SSW_F	–	length from SP to front waist
SSW_B	–	length from SP to back waist
SSN_F	–	surface length from shoulder point to front neck point
SSN_B	–	surface length from shoulder point to back neck point
SW_B	–	back shoulder width
SW_F	–	front shoulder width
T	–	textile material
UAG	–	upper arm girth

VC	–	virtual clone
VR	–	virtual reality
VT	–	virtual twin
VT_C	–	virtual twin transformed from virtual clone
VT_D	–	default virtual twin with typical morphology
VT_I	–	individualized virtual twin
VT_P	–	parametric virtual twin
WG	–	waist girth
WG_F	–	front waist girth
WG_B	–	back waist girth
WP	–	wrist point
WRG	–	wrist girth
Z	–	standard normal variate

LIST OF TABLES

1.1 – Differences between three types of clothing producing
1.2 – Variation of integral body morphologies based on different criteria
1.3 – Determination of body morphological features based on the basic BM
1.4 – Essential coordinates for locating the feature points on front bodice
1.5 – Evaluation items for different clothing parts in Kim's research
2.1 – Sample size of three types of bodies calculated by BM in this research
2.2 – Elementary measurements of the subjects
2.3 – BM and proportions of torso segments of three VC
2.4 – BM of neck segments of three VC, cm
2.5 – List of BM_N and BM_E
2.6 – Absolute errors of predicted front and back profile neck projections
3.1 – Mechanical properties of five textile materials
3.2 – Misfit gradation of neckline and collar
3.3 – Responsible BM and constructive reasons for the misfit
3.4 – Criteria of neckline and collar fit (when the neckline and collar are too large)
4.1 – BM of seven 170/92Y subjects
4.2 – Constant and variant eases for constructing an e-bespoke shirt
4.3 – Pattern indexes for the e-bespoke shirt
4.4 – BM_N and PM, E_P of RtW, MtM and e-bespoke patterns of subject S_{72}
4.5 – Principles for predicting fit or misfit with E_P
5.1 – Primary new body measurements of VT_C and VT_I
5.2 – Subjective evaluation of seven e-bespoke shirts in body-fit style
5.3 – Mean scores of subjective evaluations of RtW, MtM, and e-bespoke shirts in body-fit style
A.A – Styles and measurements of men's shirts
A.B – Ease allowances of body-fit shirts
A.C – Ease allowances of slim-fit shirts
A.D – Ease allowances of regular-fit shirts
A.E – Ease allowances of loose-fit shirts
B.A – Torso measurements of Y-type subjects
B.B – Neck, shoulder and arm measurements of Y-type subjects
B.C – Torso measurements of A-type subjects
B.D – Neck, shoulder and arm measurements of A-type subjects
B.E – Torso measurements of B-type subjects
B.F – Neck, shoulder and arm measurements of B-type subjects
C.A – Consumers' opinion towards men's shirts
D.A – Fit criteria of neckline and collar
D.B – Fit Criteria of shoulder seam

D.C – Fit criteria of sleeve
D.D – Fit criteria of bodice

LIST OF FIGURES

1.1 – Required BM and morphological information for MtM men's shirt of different level of quality:
a - low level from Uniqlo, *b* - medium level from iTailor ,
c - high level from MatchU
1.2 – Frames of RtW, MtM and e-bespoke process
1.3 – 3D virtual men's shirt and virtual clone from e-bespoke ateliers:
a - virtual shirt from Tailor-i, *b* - virtual clone from Meepl
1.4 – Body scanning in phone applications:
a – Size:Me, *b* – Meepl
1.5 – New methods of developing customization:
a - 3D-to-2D pattern flattening technique,
b - parametric pattern-making model for jeans
1.6 – Variations of proportional body segments:
a - neck, *b* - shoulder, *c*- front chest, *d* - belly, *e* - back, *f* - seat
1.7 – Torso morphology defined by Miyoshi:
a - thicknesses of torso, *b* - angles of different areas,
c – angles of neck, *d* – angles of lower back
1.8 – Torso morphology analyzed by new body curve angle:
a - body curve angles on sagittal cross-sections,
b - examples of specific torso morphology shapes
1.9 – Nine fundamental landmarks and three levels for measuring male body
1.10 – BM_E for men's upper garments
1.11 – Three main types of 3D body scanner:
a - 3D scan booth from VITRONIC, *b* - 3D scan rotating platformfrom FIT3D, *c* - portable scanner from TechMed3D
1.12 – Automatic and manual body measurement with 3D scanned bodies from SizeStream
1.13 – Utilization of virtual clone:
a - virtual clone in front and profile views, *b* - air gap,
c - indicators CEV for system "female – body dress",
d - distance ease distribution of female pants
1.14 – Process of 3D-to-2D pattern flattening in Hong's research:
a - locate the feature points, *b* - connect the feature points, *c* - generate the 3D meshed clothing surface, *d* - generate the 2D unfolded pattern
1.15 – Different styles of shirt:
a - body-fit, *b* - slim-fit, *c* - regular-fit, *d* - loose-fit
1.16 – Proportional method of upper menswear prototypes drafting:
a - Japanese Bunka-style, *b* - Chinese methods from Liu,
c-Donghua University (unit: cm, B represents CG here)
1.17 – A men's shirt by short measure method in Joseph-Armstrong's book:
a - body measurements, *b* - shirt bodice pattern (unit: inch)
1.18 – Feature points and Cartesian coordinate systems of front and back bodice patterns

1.19 – Adapted patterns for the untypical bodies with different morphology: *a* - slightly protruding chest, *b* - hump back, *c* - and square shoulder (solid lines: adapted patterns; dotted lines: standard patterns), where A, B, C are the difference between the BM (FL, BL, AW_F, AW_B) of individual and typical bodies
1.20 – Pattern adaption with shoulder shape anthropometer:
a - shoulder anthropometer,
b - pattern adaption for a forward-thrust square shoulder
1.21 – Placement of eases on a shirt bodice
1.22 – Superposed pictures of the mannequin and the female dress made of different fabrics:
a - D_1, *b* - D_2, *c* - D_3, *d* - D_4
1.23 – Jacket segments for local fit evaluation:
a - thirteen parts in front, *b* - six parts in side, *c* - twelve parts in back
1.24 – Fit evaluation scale for a jacket:
a - front bodice, *b* - upper back, *c* - center back, *d* - shoulder slope,
e - shoulder width, *f* - sleeve position, *g* - collar at front, *h* - lapel
1.25 – Movements for comfort evaluation of men's jackets
in SAYĞILI's research:
a - extending the arm sideward by 90°, *b* - flexion - bringing the arm to front by 145° (holding the tie), *c* - flexion and extension, *d* - flexion - extending the arm from the shoulder to the front by 90°
1.26 – Wearer acceptability scale in Huck's research
1.27 – Measurements of numerical fit indicators:
a - clothing pressure in real environment,
b - distance ease in virtual environment (in Modaris 3D Fit)
1.28 – Fit criteria for a men's shirt
1.29 – Criteria of eases for different clothing stylefrom the previous literatures:
a - bust, *b* - waist, *c* - hip
1.30 – Separation of front, side and back:
a - of the body on hip cross-section,
b- of corresponding pattern indexes concerning hipline
1.31 – Three modules in 2D CAD software:
a - pattern construction (PAD System),
b - pattern grading (TUKACAD), c - marker making (TUKACAD)
1.32 – User interface of CLO 3D
1.33 – Process of virtual clothing making and fit evaluation
1.34 – Generation of avatar in CLO 3D:
a - default avatar in the library, *b* - parametric avatar adapted to thepersonal BM, *c* - DT converted from the VC, *d* - individualized avatar generated from VC
1.35 – Module of virtual fabric in CLO 3D:
a - a default fabric (cotton canvas) in the library,

b - CLO fabric emulator andthe instruments of CLO Fabric Kit,
c - list of digital properties
1.36 – Virtual evaluation of clothing fit in CLO 3D:
a - exterior appearance of a clothing, *b* - transparent mode of aclothing,
c - measuring of distortion rate and the strain map
1.37 – Framework of development of real and virtuale-bespoke men's shirt
2.1 – Acquisition of VC of male body:
a - raw scan mesh model, *b* - the reconstructed VC
2.2 – Methods of obtaining BM in Rhinoceros:
a - perpendicular-based, *b* - slice-based,
c - outline-based, *d* - divisional coronal plane
2.3 – Horizontal and vertical proportions of main torso reflected by front and back girths and surface lengths
2.4 – Three VC of 170/92Y types with different proportionsof torso segment
2.5 – New morphological features of neckline spatial shape
2.6 – Front, profile and top views of the half necklinesextracted from three VC
2.7 – Spatial location of shoulder lines:
a - front view, *b* - profile view, *c* - back view
2.8 – Front, profile and top views of the left shoulder lines extracted from three VC
2.9 – Scheme of measuring of BM_N and BM_E
2.10 – Geometric model of neckline and its application to pattern:
a - neckline configuration and its projection of the VC in a 3D Cartesian coordinate system, *b* - neckline construction
2.11 – Geometric model of shoulder line and its application to pattern:
a - shoulder area of the VC, *b* - shoulder line construction
2.12 – Geometric model of main torso, arm and its application to pattern:
a - main torso segment of the VC, *b* - bodice pattern, *c* - sleeve pattern
3.1 – KES-FB1, FB2, FB3 instruments
3.2 – Men's shirt try-on photos shot from the view of:
a – front, *b* – profile, *c* – back
3.3 – Five textile materials:
a – T_1, *b* – T_2, *c* – T_3, *d* – T_4, *e* – T_5
3.4 – Configuration and measurement of bodice pattern:
a - scheme of variant bodices, *b* - shoulder sloping index SS
3.5 – Fit indicators:
a - bottom height differences, *b* - angle of front contours
4.1 – Distribution of body types of the 150 subjects
4.2 – Seven 170/92Y virtual clones
4.3 – Illustration of the men's shirt used in the research
4.4 – Scheme of customizing an e-bespoke shirt pattern
4.5 – Overlapped patterns:
a - RtW, e-bespoke patterns for 170/92Y subjects,

b - RTW, MtM, e-bespoke patterns for subject S_{72}
4.6 – E-bespoke shirt patterns in different styles for subject S_{72}
4.7 – PM and corresponding BM:
a - PM_{SSNF}, *b* - SSN_F
5.1 – Acquisition of VT_C of male body
a - locating of joints in Mixamo,
b - VT_C with virtual joints and skeletons
5.2 – Cross-sections of VT_C (solid lines) and VT_I (dashed lines):
a - torsos in horizontal view, *b* – torsos in coronal view,
c – torsos in sagittal view, *d* - contours of necklines
5.3 – Processes of virtual shirt making in CLO 3D:
a - defining of body segments on VT_C, *b* – craftsmanship, arrangement of 3D pieces and seams, *c* - design of buttons, *d* - arrangement of lining in collar piece
5.4 – Front, profile, back holistic views and details of neck and shoulder of virtual e-bespoke shirts in body-fit style for the 170/92Y subjects:
a - S_3, *b* - S_8, *c* - S_{34}, *d* - S_{37}, *e* - S_{56}, *f* - S_{72}, *g* - S_{87}
5.5 – Front, profile, back holistic views and details of neck and shoulder of virtual shirts in body-fit style for subject S_{72}:
a- RtW, *b* - MtM, *c* - e-bespoke
5.6 – Strain maps of RtW, MtM and e-bespoke shirts in body-fit styleon subject S_{72}:
a - stain maps, *b* - segments for measuring the distortion rates
5.7 – Variation of distortion rates of RtW, MtM and e-bespoke shirts in body-fit style of:
a - subject S_7, *b* - of mean values of seven 170/92Y subjects
5.8 – Try-on effects of e-bespoke shirts for subject S_{72}in different styles:
a - slim-fit, *b* - regular fit, *c* - loose fit
5.9 – Try-on effects of e-bespoke shirts for subject S_{72}made from different DT_M:
a - DT_{M1}, *b* - DT_{M4}, *c* - DT_{M5}
5.10 – Profile views of the eight virtual clones of individual male consumers from Texel company
5.11 – Procedures of the practical production testing for Sergey K.:
a- mark landmarks and body measurements on the virtual clones,
b- customized shirt bodice patterns in different styles,
c- finished virtual slim-fit shirt, *d*- sewed real slim-fit shirt sample

FULL INTRODUCTION

Actuality. Digitalization of the modeling process of clothing construction, which has become the reality in sewing industry, allows us to review the content of many traditional processes. The so-called targeted design or MtM (made-to-measure) is implemented for the manufacture of clothing on bodies with atypical morphologies in industrial production; in terms of the content, this technology is an intermediate link between RtW (ready-to-wear) and individualized (bespoke) clothing. The characteristic of individualized design is the different composition of the anthropometric database of the consumer’s body, including the additional body measurements. Depending on the accomplishment of such a base, manufactured clothing will possess different indicators of proportionality and balance.

Owing to the advent of body scanning technology and the advantages of contemporary CAD systems, the volume of anthropometric information about the morphology of bodies has increased significantly, which allows you to make quantitative and qualitative changes in the processes of customized design and move it to the virtual environment.

Depth of topic development. Currently, such a direction is being developed in many countries or regions (China, USA, Europe, Japan, etc.) with a high level of digitalization in everyday life. The main advantage of digital customization is the ability to design and demonstrate a clothing with a high level of fit for a specific consumer, which opens up the possibility of saving resources, working on the principle of remote access, and increasing the consumer segments.

However, the successful development of this direction requires the formalization of professional knowledge in terms of anthropometry, clothing design, textile material science, and the evaluation of virtual objects. Scientific research in the field of formalization of professional design knowledge is carried out by scientists and practitioners **S.-E. Jang** (Korea), **K. Liu, B. Gu** (China), **K.**

Kim (Japan), **Nadia Magnenat Thalmann** (Singapore), **Pascal Bruinex**(France), **E.G. Andreeva**, **I.Y. Petrosova** (Russian State University named after A.N. Kosygin),**A.Y. Moskvin**, **M.V. Moskvina (**Saint-Petersburg State University of Industrial Technologies and Design), Department of Sewing Products Design IVGPU. The obtained results are available to other researchers through regular publications in the journals **Textile Research Journal**, **International Journal of Clothing Science and Technology**, **The Journal of the Textile Institute**, which are included in the international analytical database of WoS, allowing to argue about the emerging scientific direction in the field of digitalization of customized clothing design. The practical implementation of scientific results conducting with software products for customized design CLO 3D, Marvelous Designer (Korea), Assyst Vidya (Germany), Lectra (France), Browzwear (Singapore), EFI Optitex (USA), TUKA 3D (Japan), and the scope of Internet platforms BrooksBrothers, ProperCloth, Indochino, Woodies (USA), Budd (UK), bivolino (Belgium), Uniqlo (Japan), Spire & Mackay (Canada), Apposta (Italy), TailorStore (Sweden), MatchU, RedCollar (China) demonstrates the increasing of clothes sold.

The results obtained are usually based on the personal experience of researchers, features of national design and sizing systems, separated technical and software products, which does not yet allow to investigate the establishment of a universal hardware and software composed with a scientifically based database of all elements and the principles of their generation in virtual system “body - clothing”. Therefore, the development of this scientific direction for the development of a new technology for individualized design in the digital environment (e-bespoke) is relevant with the perspective of further digitalization of all areas of production and consumption.

The research has been done in 2017-2020 at the Department of garment design, IVGPU, in the framework of the scientific direction **“Analysis and synthesis of real and virtual systems ‘body-clothing’”, state grant “Development of software for virtual design of static and dynamic systems**

'body-clothing' and virtual fitting of clothing Fashionnet" (No. 2.2425.2017/ПЧ) and the grant of the Ministry of Science and High Education of Russian Federation **"Development of digital twins of historical costume with the help of technology reverse engineering"** in the form of grants under the Federal target program "Research and development on priority directions of development of scientific-technological complex of Russia for 2014-2020" (05.616.21.0113).

The research has been done in accordance with the scientific specialty 05.19.04 – Technology of sewing garments (engineering sciences): 1 «Development of theoretical bases and establishing of common relations of clothes design for standard and specific human bodies», 3 «Development of mathematical and information supports for CAD», 5 «Development of quality evaluation and designing of clothes with predictable consumer preferences and production efficiency». p

Aim of this research is to develop the e-bespoke technology of men's shirt design in a virtual environment.

To achieve this aim, it is necessary to complete the **following tasks:**

1. conduct anthropometric studies of male bodies to establish a new set of body measurements which is sufficient to describe the morphological features of the torso.

2. Develop typical models of sections of the torso of male body to coordinate their morphological features with the deployment of the planes responsible for the fit.

3. Improve the method of designing men's shirts.

4. Develop a system of criteria for evaluating the fit of men's shirts.

5. Study the influence of fabric properties on the features of shirt outline shaping with different styles.

6. Develop an algorithm for designing men's shirts in a virtual environment.

7. Conduct production testing of the results obtained.

Object of research – male bodies, shirts with different spatial shapes, and the design process.

Subject of research – the body measurements of the torso of male bodies, indicators of fabric properties, and parameters of pattern construction.

Research field – the process of designing men's shirts.

Methods and tools of research. To study separate elements and the integrated system "men's body – shirt", we used a non-contact method of measuring men's bodies, methods of generating virtual objects, and a method of sensory analysis for fixing eye movements in the modes of neuro eye-tracking technologies.

To conduct experimental research, a system of hardware and software was established that provides generation and transmission of digital information received at each stage of research, which included six components:

(1) VITUS Smart XXL laser non-contact 3D body scanner for obtaining scanned male body according to ISO 20685-2010 (E);

(2) Anthroscan program (Human Solutions, Germany) for processing anthropometric information;

(3) ET CAD (BUYI Technology, China) for digitalized construction;

(4) KES-F (Kawabata Evaluation System for Fabrics) or FAST (Fabric Assurance by Simple Testing) measuring systems for testing textile fabrics;

(5) Computer program CLO 3D, version 5.0.156.38765, (CLO Virtual Fashion, Republic of Korea) for generating static and dynamic virtual objects;

(6) Measuring kit including Tobii Pro Nano and Tobii Pro Glasses 2 Wireless instruments (Sweden) for fixing eye movement;

(7) Tobii ProLab software (Sweden) for studying visual response;

Statistical processing of measurement results was performed using the SPSS program (IBM, USA).

Scientific novelty of the research consists in the establishment of a new set of body measurements that are necessary and sufficient to generate detailed flat pattern blocks in accordance with the predicted spatial position of the shirt and the morphology of the upper torso of the male body.

Provisions for defense:

1. A new anthropometric database obtained after measuring the vertical and horizontal cross-sections of the male torsos.

2. The algorithm for generating flat sewing pattern blocks of male torsos.

3. The structure of hardware and software systems for design and generation of system “body - shirt” virtual twins.

4. Criteria for men shirt fit evaluation.

Practical significance of the research is to create a technology of e-bespoke (customized) virtual design of men's shirts with predicted sewing pattern indicators on bodies of different morphological types. The developed anthropometric database can be used to develop new clothing labels in online stores and improve methods of planar and volumetric design. The results were implemented at Texel LLC (Moscow) which develops software for virtual clothing design.

Scientific significance consists in creating theoretical and experimental foundations for the virtual design of men's shirts. Some of the theoretical results were introduced into international scientific circulation and included in the monograph "Anthropometry, Apparel Sizing and Design (Second Edition)", Edited by Norsaadah Zakaria and Deepti Gupta. - The Textile Institute Book Series. -Duxford, United Kingdom, Cambridge, United States, Kidlington, United Kingdom, Woodhead Publishing, 2020,415 p. - Chapter 9. Evaluation of pattern block for fit testing (quality control of pattern blocks for fit evaluating), p. 217-251,https://doi.org/10.1016/B978-0-08-102604-5.00009-3.

Reliability degree of the results of the thesis is provided by the consistency of the results of experimental studies of the source elements of male bodies, designs of shirts, textile fabrics, ensurance of obtaining men's shirts with a predictable fit, the correct shaping of teaching sample of scanned bodies, and the positive results of production testing.

Approbation of the results. The main results of the work were reported at

11 conferences: the 16th AUTEX world textile conference, June 2016, 8-10 June 2016 **(Ljubljana, Slovenia)**; the 7th international conference “3D body scanning Technologies”, November 30th - December 1st. 2016 **(Lugano, Switzerland)**; XXIII and XXIV international scientific and technical conferences "University Information environment", November 23th – 25th, 2016, November 22th – 23th, 2017 **(Ivanovo)**; all-Russian scientific student conference “Innovative development of light and textile industry INTEX 2016”, April 5th – 6th, 2016 **(Moscow)**; scientific and technical interuniversity conference of postgraduates and students (with international participation) “Young scientists - development of textile and industrial cluster” (SEARCH), 2016, 2019, 2020 **(Ivanovo)**; 17th World Textile Conference AUTEX 2017 “Textile – Shaping the Future”, June 2017 **(Corfu, Greece)**; 18th World Textile Conference AUTEX 2018, June 21th – 23th 2018 **(Istanbul, Turkey)**; Aegean International Textile and Advanced Engineering Conference AITAE 2018, September 5th – 7th, 2018 **(Mytilene, Greece)**;International Conference on Techniques, Technologies and Education ICTTE 2020, November 5th – 6th, 2020 (**Yambol, Bulgaria**); in the educational curriculum "Digital looks: artistic and industrial design of 3D clothing in virtual reality" of national project "Education" 2020 **(Ivanovo, IVGPU**).

Publications. Based on the results of the dissertation research, 13 publications were published, 6 of them in publications indexed in the international citation and analytical databases Web of Science and Scopus, and 7 in the proceedings of conferences at various levels.

Structure and volume of the dissertation. The dissertation consists of an introduction, five chapters, conclusion, list of references and appendixes. The content is set out on 223 pages of typewritten text, including 72 figures and 39 tables. The list of references used includes 171 titles.

BRIEF INTRODUCTION

The MtM (made-to-measure), an intermediate link between RtW (ready-to-wear) and bespoke, is the clothing customized for atypical bodies in industrial production. The MtM clothing is produced based on the different composition of the anthropometric database of the consumers' bodies, including the additional body measurements. Depending on the accomplishment of such a base, the finished clothing will possess different indicators of proportionality and balance.

Owing to the advance of technologies, the latest 3D body scanner and 3D CAD for clothing design enables the significant increase of volume of anthropometric information of the body morphology, which allows the quantitative and qualitative changes in the customization process and move it to the virtual environment.

Currently, such a direction is being developed in many countries or regions (China, USA, Europe, Japan, etc.) with a high level of digitalization in everyday life. The main advantage of digital customization is the ability to design and demonstrate a clothing with a high level of fit for a specific consumer, which opens up the possibility of saving resources, working on the principle of remote access, and increasing the consumer segments.

The successful development of this direction requires the formalization of professional knowledge in terms of anthropometry, clothing design, textile science, and the evaluation of virtual objects. Scientific research in this field of formalization is carried out by some scientists (e.g., Bingfei Gu (China), Pascal Bruinex (France)). The obtained results are available through the publication of journals (e.g., Textile Research Journal) indexes in WoS, Scopus, etc.. The practical implementation of scientific results conducting with 3D CAD software (e.g., CLO 3D) and the internet customization ateliers (e.g., BrooksBrothers) demonstrates the increasing of clothing sold.

However, the previous results are usually based on the personal experience, features of national sizing systems, separated technical and software products, etc. which does not yet allow to investigate the establishment of a universal hardware and software composed with a scientific database of all elements and the principles of their generation in virtual system "body - clothing". Therefore, the development of this scientific direction for the development of a new technology for individualized design in the digital environment (e-bespoke) is relevant with the perspective of further digitalization of all areas of production and consumption.

The aim of this research is to develop the e-bespoke technology for custom design of men's shirt in a virtual environment through establishment of the anthropometric database of new body measurements, development of new method of men's shirt pattern drafting and the criteria of its fit evaluation and the algorithm for designing virtual e-bespoke men's shirt.

CHAPTER 1. CURRENT SITUATION OF REAL AND VIRTUAL DESIGN OF CUSTOMIZED CLOTHING

The results obtained in this chapter are published in one work [159].

With the increasing demands on exclusive fit, aesthetic and individuality, customized clothing, which is usually tailored as MtM or bespoke, becomes the dominating trend in fashion industry in recent years. MtM always involves some standardizations in pattern and manufacturing, while the bespoke is entirely conducted on the basis of a consumer’s specification and tailor' craftsmanship with far more attention on minuting fit details and using multiple fitting during sewing process[1-3]. The fit and exterior appearance of these garments are better than mass-produced RtW garments, especially, bespoke is exclusively fitted.

Conventionally, the customization procedure is executed manually by experienced pattern maker or tailor, which is proven to be time-consuming and sometimes unsatisfactory. With the popularization of advanced technologies, the whole procedure has been drastically optimized. The precise 3D model with real body measurements can be obtained instantly through 3D body scanner [4]. The virtual try-on simulation can be exhibited instantaneously before the sewing process through CAD in 3D virtual environment[5]. Other technologies like AI, IoT have also brought up the online fast customization since the past several years.

Nevertheless, the contemporary customized garments cannot befit each consumer especially those who are featured with untypical morphological features, causing by the insufficient cognition of relation between body morphology, pattern block construction, clothing fit, etc. First and foremost, the applied body measurements and block construction are incapable to characterize the important morphologies such as anteroposterior proportions. Moreover, although customization is shifting more attention into the virtual platform, the existing virtual customization still cannot reflect the real clothing fit and appearance. Therefore, the new databases and methods should be investigated to develop the existing customized clothing.

This chapter is aimed to study the existing literatures and services to find the current scientific and practical situation and problems of real and virtual design of customized garment for enlightening the new method of e-bespoke men’s shirt.

1.1. Customization as the primary trend in clothing industry

With the improvements of industry and upgrade of consumers’ perception towards clothing, the customization that can provides more exclusive fit and experience than mass production, has been the primary trend. Meanwhile, the novel online and virtual customization were born at this proper time and conditions involving with the new technologies and retailing modes.

In this section, the similarities and differences between RtW, MtM and bespoke clothing, the reasons of customization’s popularity, the contemporary methods of clothing customization as well as their merits and demerits were investigated.

1.1.1.Difference between RtW, MtM, and bespoke tailoring

There are three categories of contemporary clothing: RTW, MtM (also known as mass customization), and bespoke.

RtW clothing has emerged since the invention of weaving and sewing machines after the Industrial Revolution in the middle of the XIX century. It is manufactured on the basis of patterns designed for typical bodies from the standard sizes derived from anthropometric database [6, 7], which is supposed to satisfy the majority of the consumers [8]. Although RtW is the most economical and convenient choice for the consumers, many of them reported about negative experience of fit and monotony [9, 10].

On the contrary, MtM and bespoke clothing is customized for the individual consumers who pursue higher quality, individuality, and fitting products. MtM garment is produced in accordance with the individual body measurements by modifying RtW pattern [11]. It can satisfy higher needs of fit and aesthetics with relatively lower expense and cost of producing than bespoke garment. However, MtM cannot also guarantee the good fit on account of the traditional body measurements and pattern construction it applied.

Bespoke clothing is the individual-exclusive tailoring made for premium quality and fit, which has been famous as Haute Couture in France from the XIX century. The pattern and design completely made for the highest level of personalized fit and aesthetics often require the highest expense and most complex procedure [1, 2].

According to the Gill's summarization of three types of garments producing, the main differences between RtW, MtM and bespoke clothing in three aspects are shown in Table 1.1 [1].

Table 1.1 - Differences between three types of clothing producing

Garment type	Producing process		
	Body measuring	Block construction	Fit evaluation
RtW	Basic measurements from sizing system	Normalized prototypes based on typical sizes	On the dummy
MtM	Manual basic measurements from individual body	Customized pattern adjusted from the prototype	On the individual body
Bespoke	Extended manual measurements from individual body	Exclusively customized pattern	

As shown in Table 1.1, RtW production is based on the standardized size, block and dummy. Bespoke is executed in an exclusive manner. And MtM is the compromise between RtW and bespoke with both standard and individual information involved.

1.1.2. Trend of customization

Customization is reviving as the dominating trend in fashion industry on account of two primary reasons [12].

For one thing, the consumers are shifting more attention to personality and quality with the upgrade of consumption and aesthetics [13]. The previous research shown that 41% consumers are interested in personalized garment, 53% of whom aged from 16 to 39 years old [14, 15]. The market of men's customized garment is showing the great potential with increasing consumption growth by young men. In China, there are about 60% men from the first-tier and second-tier cities expect customized garment, the most categories are shirt, suit, trousers, etc [16, 17].

For another thing, the reports and the national strategies illuminate that the transmission to industry 4.0 which is featured as digitalized, intelligent, automatic, data-driven production perfectly serve the new possibility of customization [18 - 24]. The clothing customization production is also evolving to the next stage with advanced technologies such as 3D body scanning, VR and AR, IoT, AI, etc. introduced [25 - 27]. Moreover, the new C2M retailing mode arises in response to the new mass-customization with efficiency and productivity improved [28].

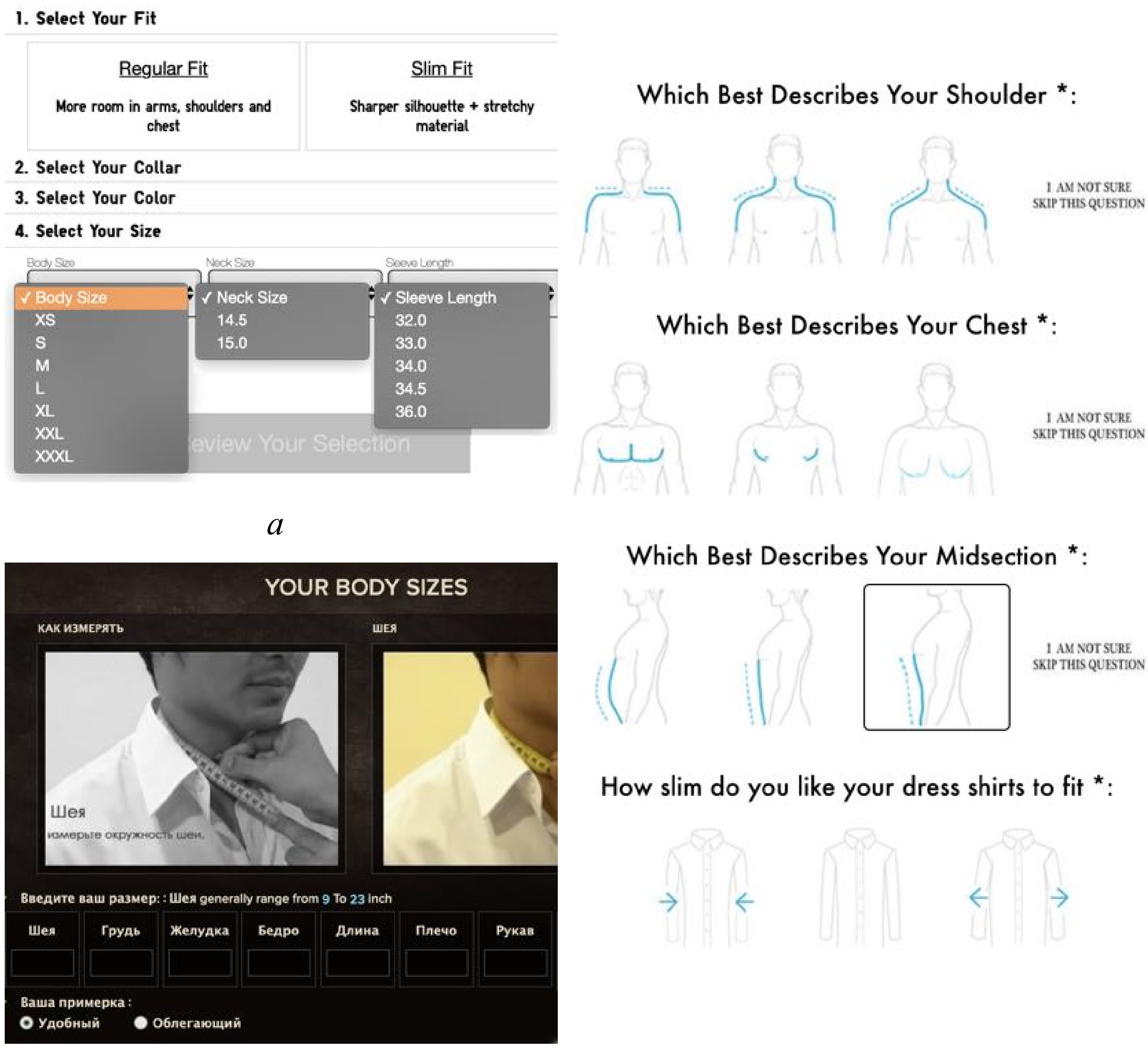
1.1.3. Contemporary methods of clothing customization

In contemporary time, the conventional MtM ateliers and companies (Bivolino, Brooks Brothers, Budd Shirtmakers, Indochino, iTailor, MatchU Tailor, Proper Cloth, Spier & Mackay, Tailor Store Sweden, Uniqlo, etc.) usually offer several alternative individualization options, including textile fabrics, garment styles, details (e.g., collar, pocket, cuff, trim, monogram) [29-38]. However, various requirements of body morphological information from the ateliers lead to different levels and complexity of block customization, which accordingly determines the fit state of finished clothing. The conventional MtM can be divided into three levels considering the required BM and morphological information, and the block construction (Fig. 1.1):

a. The same size as that in the sizing system with only a few customizable dimensions (height, weight, neck girth (NG), arm length (AL)). The block is similar as the existing RtW block with only collar and sleeve length modified [29-31];

b. More BM are required: chest girth (CG), waist girth (WG), hip girth (HG), shoulder length (SL), wrist girth (WRG), etc. The block is drafted by adapting the RtW block to the individual measurements [32-34].

c. More information about morphological attributes is required, such as the shoulder sloping (normal, up, down), and the abdomen shape (flat, abdominous, concave). The block is further modified to the individual morphology. [35-38]



b *c*

Figure 1.1 - Required BM and morphological information for MtM men's shirt of different level of quality:
a - low level from Uniqlo, *b* - medium level from iTailor ,
c - high level from MatchU [32,35, 37]

Fig. 1.1 shows the screenshots of three levels of MtM men's shirt captured in the online ateliers Uniqlo, iTailor, and MatchU. From the lowest to highest levels, more information is required for drafting more adapted block and providing better fit.

However, all of these approaches are still based on limited number of basic BM, traditional landmarks such as shoulder point (SP), side neck point (SNP) etc. and existing RtW block construction, which together are inadequate to represent the essential morphological features. For example, in the highest-level MtM, SL and sloping are applied to characterize the shoulder shape, the shoulder direction information (straight, forward thrust, back thrust) is neglected. The good clothing fit cannot be guaranteed by conventional MtM, especially for the untypical bodies.

With the advance of technologies and computer software, the neoteric customization – e-bespoke (or e-MtM) [39-41] that brings the process to digital and virtual platforms – is developed. The one-to-one virtual clone and new body measurements can be instantly generated by 3D body scanner, the realistic virtual try-on model can be exhibited through VR technology, and some of the customization procedures can even be processed in the AI-based applications in a smartphone [42, 43]. Different from the conventional RtW and MtM process, the e-bespoke process runs digitally as Fig. 1.2.

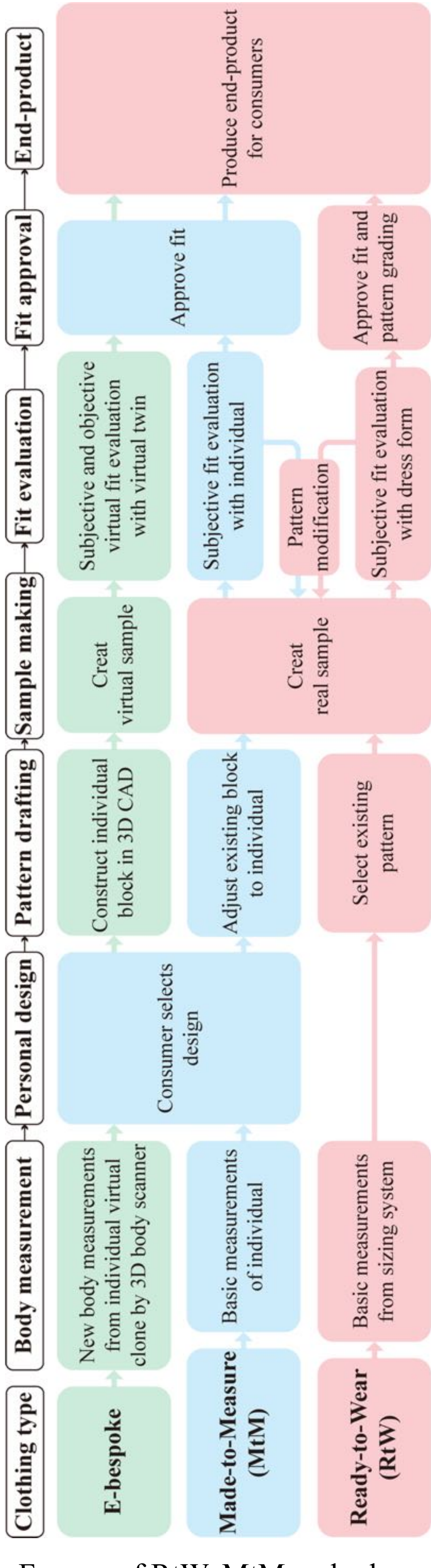


Figure 1.2 - Frames of RtW, MtM and e-bespoke process

As shown in Fig. 1.2, the e-bespoke process is different in three essential aspects:

a. The adequate new BM are generated from the VC without manual measuring;

b. The pattern is originally customized in a 3D CAD instead of adapting the RtW prototype;

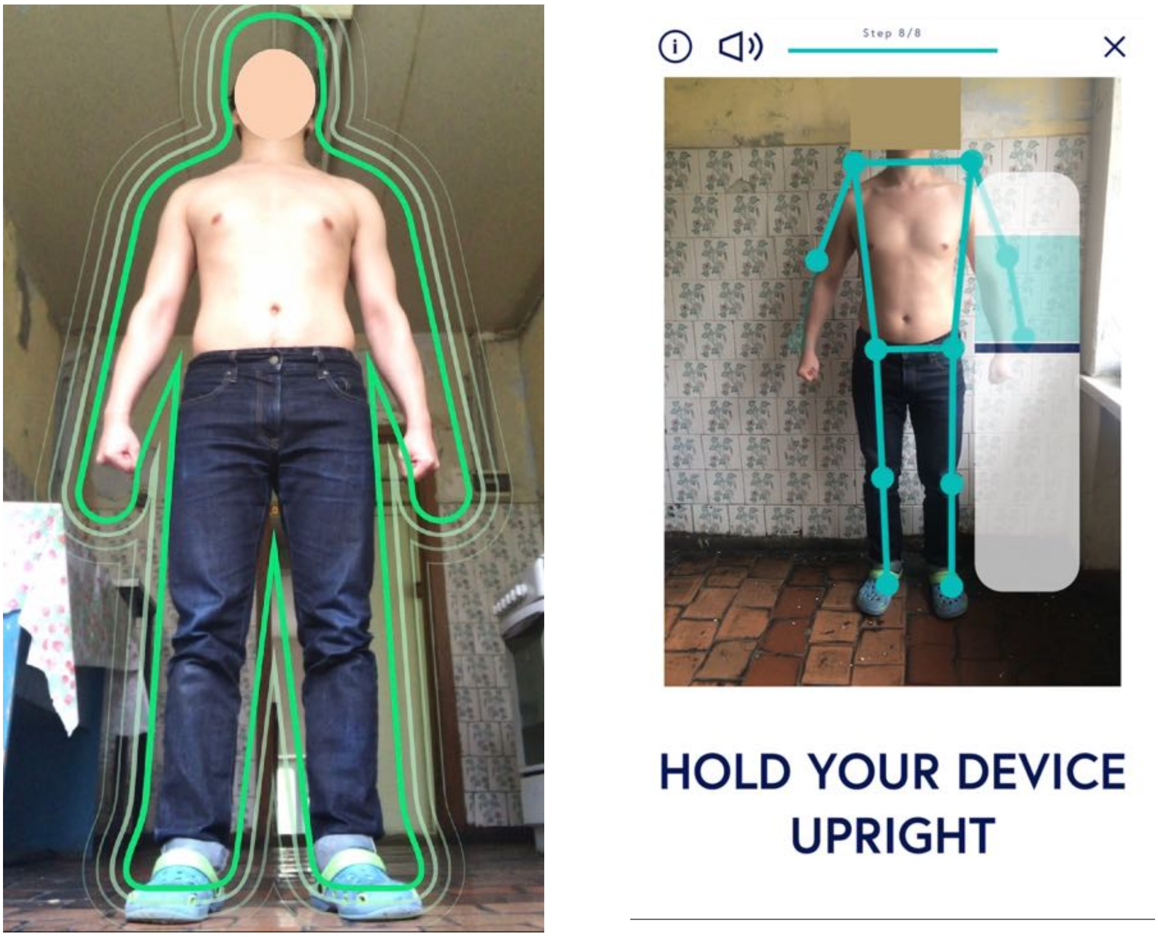
c. The sample sewing and fit evaluation are conducted based on the virtual simulation in a 3D CAD instead of repeated and time-consuming real sample trials.

Contemporarily, the e-bespoke ateliers provide two main services for consumers. First, the real-time 3D self-customized finished clothing can be visualized online after customer choosing individual design and inputting own basic BM [44] (Fig, 1.3, *a*).

a *b*

Figure 1.3 - 3D virtual men's shirt and virtual clone from e-bespoke ateliers:
a - virtual shirt from Tailor-i, *b* - virtual clone from Meepl [44, 45]

Second, the 3D customized VC, estimated BM can be generated online after camera-scanning or photo-shooting by a smartphone (Fig. 1.3, *b*). As shown in Fig. 1.4, the phone applications Size:Me and Meepl could generate the individual BM or VC after camera-scanning by particular algorithms [37, 45].

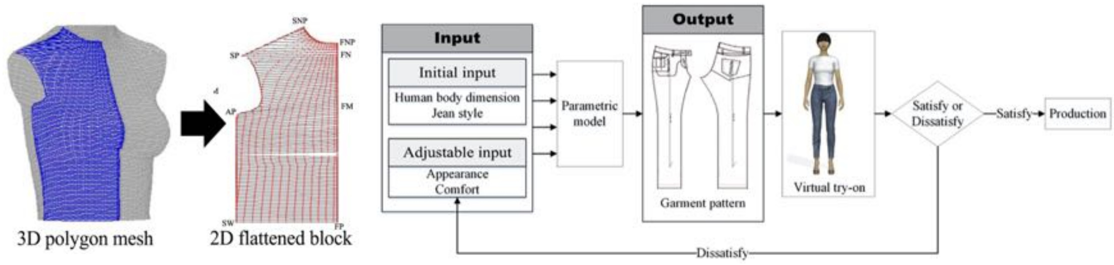


a *b*

Figure 1.4 - Body scanning in phone applications:
a- Size:Me, *b*- Meepl [37, 45]

As shown in Fig. 1.3, the virtual image exhibited the realistic effects of the end-product shirt, and the VC exhibited the morphology as real body. However, the both services cannot evaluate the quality and fit of a clothing on the consumer's body, which sometime is specious rather than useful.

Some recent scholars proposed new methods of developing customization to eliminate the existing problems. First, through the 3D-to-2D flattening technique, the 2D pattern can be created after transformation from 3D polygon mesh which is made by connecting feature points on the surface of VC (Fig. 1.5, *a*)[46, 47]. Although the pattern can be directly obtained without body measuring, it is only advantageous for simple-styled formfitting garments.



a *b*

Figure 1.5 - New methods of developing customization:
a - 3D-to-2D pattern flattening technique,
b - parametric pattern-making model for jeans [46, 49]

Second, the parametric pattern-making models were proposed to automatically generate patterns of different styles by inputting particular body measurements which were still derived from the existing basic BM and landmarks (Fig. 1.5, *b*) [48, 49]. Some scholars established the estimation models that output a huge number of pattern-oriented BM with inputting a few basic measurements by regression equations or AI[50, 51]. However, it was of high inaccuracy when estimating the dimensions of untypical bodies. Both models cannot entirely characterize the individual morphology.

Third, some scholars proposed the method of pattern adjustment to eliminate local misfit such as shoulder area after observation of the untypical morphology[52]. However, the customized pattern cannot be directly sketched once, and there is no systematic adjustive method for improving the holistic clothing fit.

In general, the conventional MtM is processed with manual body measuring, construction modified from existing RtW block, fit evaluation with real samples and final producing. Through 3D body scanning and VR technologies, the current e-bespoke moves the process to the digital platform with realistic visualization of VC or virtual simulated clothing. The latest researches also improved the customization through 3D-to-2D flattening technique, parametric pattern model, body dimension estimation model, pattern adjustment method, etc. Nevertheless, these methods are still defective to make the customized garment of assured good fit and aesthetics for a variety of inadequacies: BM, limited pattern construction, virtual fit evaluation, etc.

1.2. Morphology and anthropometry of male bodies

Morphology is a branch of biology dealing with the study of the form and structure of organisms and their specific structural features [53]. In the exploration of clothing outline shape and ergonomics, the body morphology usually signifies the external appearance (or eidonomy) of a human body, including shape, structure, size, etc.

In clothing production, the anthropometric measurements (or BM) is the elementary factor for sewing a clothing that well fits the body morphology. Anthropometry is the science of obtaining systematic measurements of the human body [54], which usually involves the measuring of size (e.g., height), and structure (e.g., shoulder width, arm length, and neck girth) of humans.

The conventional anthropometry requires complex and time-consuming manual measuring by special meters (e.g., the Martin anthropometers). Whereupon, the emergence of 3D body scanning technology which can capture the precise body morphological data in a short duration reforms the process of body measuring and brings about the new possibilities for further anthropometric researches.

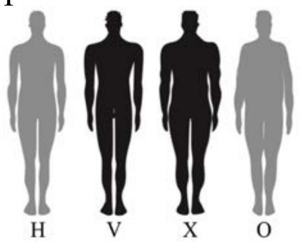
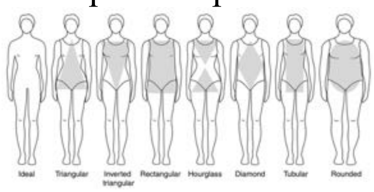
In this section, the essential male body morphology for clothing ergonomics, the existing BM utilized in clothing production, and the new anthropometric researches by 3D body scanning technology were surveyed.

1.2.1. Essential morphological features of male bodies

To achieve the good fit for each kinds of clothing, the principal element that should be considered is the body morphology [55]. Due to the different characteristics of skeletons, tissues including muscles, fat, etc., the morphology of human body are kaleidoscopic. For this reason, it is tough to exhaust every morphological features of each body. Thus, the scholars have surveyed the census samples representing the specific population and discovered the limited essential morphological features by clustering methods based on different criteria. In our research, only the upper body morphology above perineum level (including torso, neck, arm) was discussed, which is helpful for the production of upper wear.

The most common approach is to characterize the integral body morphology through the contour or silhouette of the front or the profile. Bellemare et al. described the bodies as alphabetical shapes – H, V, X, O, etc. [56, 57]. Simmons et al. used the graphic shapes to describe the body morphologies, for instance by triangular, inverted triangular, rectangular, hourglass, etc. [58-60]. Table 1.2 shows the variation of integral body morphologies based on different criteria.

Table 1.2 - Variation of integral body morphologies based on different criteria

Approach	Researcher	Torso variation	Criteria
Alphabetical letter based 	Bellemare et al. [56]	H, V, X, O	Weight and complete body measurement data
	August et al. [57]	A, X, H, V, W, Y, T, b, d, i, r	Front view width, side view width, and front view length
Graphic shape based 	Simmons [58]	Hourglass, bottom hourglass, top hourglass, spoon, rectangle, diamond, oval, triangle, inverted triangle	Girths of bust, waist, stomach, and abdomen
	Connell et al. [59]	Hourglass, pear, rectangle, inverted triangle	Front body shape: shoulder point to shoulder point, the front waistline, and the widest point between the waist and crotch line
	Rasband et al. [60]	Ideal, triangular, inverted triangular, rectangular, hourglass, diamond, tubular, rounded	Girths of bust and hip

As shown in Table 1.2, the both of two approaches characterize the bodies as specific pictographic shapes through the criteria based on basic BM (only Bellemare et al. did not mention the concrete measurements in their article). The pictographic shapes demonstrate the particular features of each body type. For example, in the approach of Bellemare et al., H-shaped body represents a slimmer, ectomorphic man; V-shaped body tends to have proportionally smaller buttocks, bigger chests and wider shoulders; X-shaped body is characterized by prominent buttocks and shoulders, naturally muscular arms and thighs, but with a slimmer waist; O-shaped body generally deposits a fat around waist, abdomen, and ~~the~~ stomach region is generally wider than hip region.

In addition, the male body morphologies can be identified by the BM (height, drop values between bust and waist, etc.) from different groups according to sizing system of China, Japan, Russia, etc. [61 - 63]. For example, Chinese sizing system classified the male bodies according to height (150 … 190cm, interval 5cm), chest girth (72 … 116cm, interval 4cm) and drop (Y type – more than 17cm, A type – 12 … 16cm, B type – 7 … 11 cm, C type – smaller than 6cm) [64]. The US sizing system further identifies the male bodies into three main types (young men, mature men and mature big men) with three levels of height (short, regular, and tall)[65-67]. The RtW or elementary MtM clothing can be produced by locating the group body belongs to and acquire the relevant anthropometric data (heights, girths, lengths).

However, the both of pictographic shape-based method and the grouping in sizing system classify the male body morphology into several typical groups. For one thing, these groups are based on the basic BM which cannot reveal some detailed morphological features such as shoulder shape. For another, many bodies don’t belong to these typical shapes such as extra skinny or obese.

To resolve this dilemma, some researches concentrate to discover the detailed morphological features of different body segments. In Bellemare’s research [56], the proportional body segments of neck, shoulder, front chest, belly, back, seat (hip) etc. are further discussed as Fig.1.6.

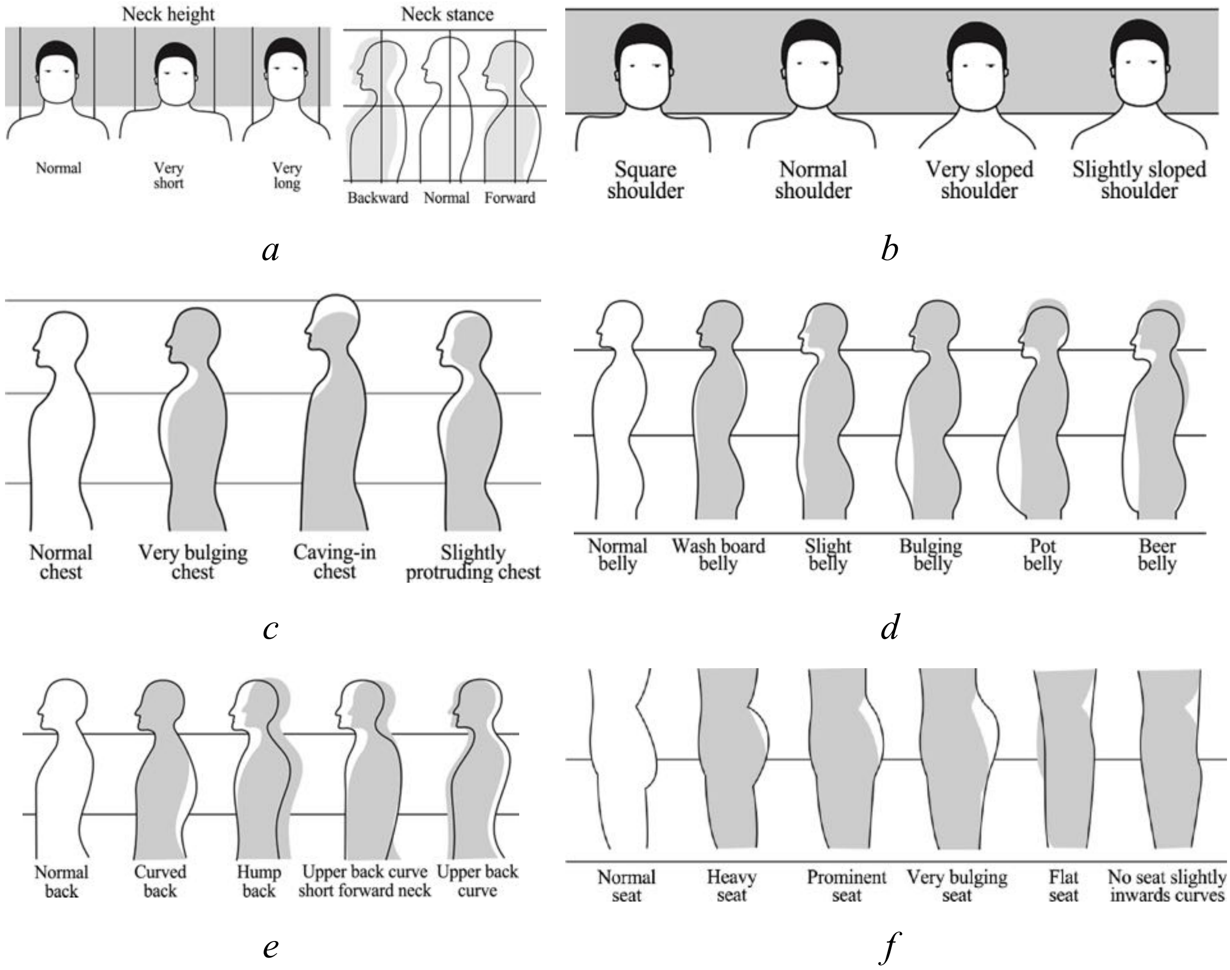


Figure 1.6 - Variations of proportional body segments:
a - neck, *b* - shoulder, *c*- front chest, *d* - belly, *e*- back, *f* - seat [56]

As shown in Fig. 1.6, seven proportional body segments can be classified into various essential shapes. For example, the neck morphologies can be defined with height and stance with respective three groups: normal, short, long; normal, backwards, forwards. Considering the upper body proportions, the shapes of neck and shoulder segments have a direct impact on the clothing draping on the body. The front chest, belly, back, etc. are also necessary for defining contours and proportional curves, as they are important for determining body equilibrium.

Yang further analyze the main torso and shoulder by combining observation of the exterior contours and basic body measurements [68]. Table 1.3 shows the determination of body morphological features based on the basic BM.

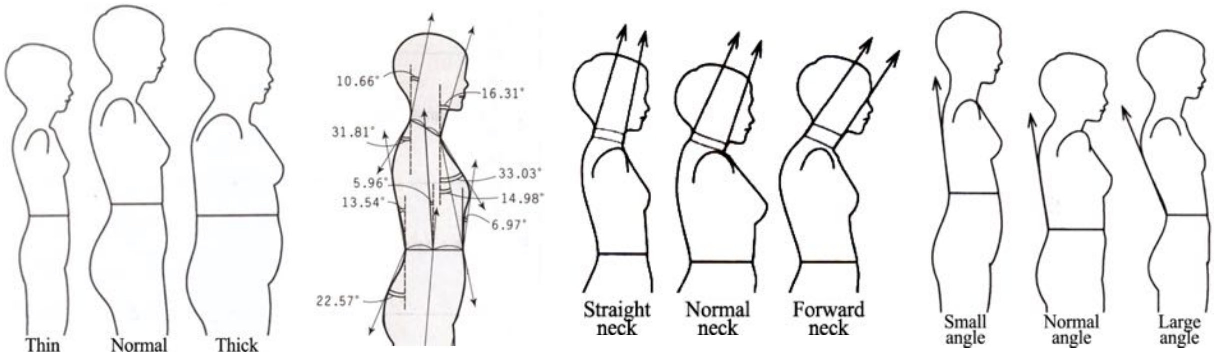
Table 1.3 - Determination of body morphological features based on the basic BM

Body segment	Morphological features	BM
chest and back	normal	FL, BL, AW_F, AW_B
	slightly protruding chest	$FL_1 = FL + A_1$ (2 … 4 cm), $BL_1 = BL - B_1$ (1 … 2 cm), $AW_{F1} = AW_F + C_1$ (1 … 2 cm)
	very bulging chest	$FL_2 = FL + A_2$ (2 … 4 cm), $AW_{F2} = AW_F + C_2$ (2 … 4 cm)
	hump back	$FL_3 = FL - A_3$ (1 … 2 cm), $BL_3 = BL + B_3$ (2 … 4 cm), $AW_{B3} = AW_B + C_3$ (1 … 2 cm)
belly	normal	D (12 … 16)
	slight belly	D_1 (7 … 12)
	bulging belly	D_2 (2 … 6)
	pot belly	$D3 \leq 0$
shoulder	normal	SLA (19 … 22°)
	square	$SLA_1 \leq 19°$
	sloped	$SLA_2 \geq 19°$

Where: FL is the front length, BL is the back length, AW_F is the across front width, AW_B is the across back width, D is the drop between chest girth and waist girth, SLA is the shoulder sloping angle (See Fig. 1.10 in Section 1.2.2). A, B, C are the measurement differences between the untypical bodies and normal bodies. The subscript represents each indicator correspond the body morphology belongs to.

As shown in Table 1.3, the morphologies of chest and back, belly and shoulder can be recognized by simple calculations. For example, the chest and back can be determined by comparing the measurements (FL, BL, AW_F, AW_B) of individual and typical bodies.

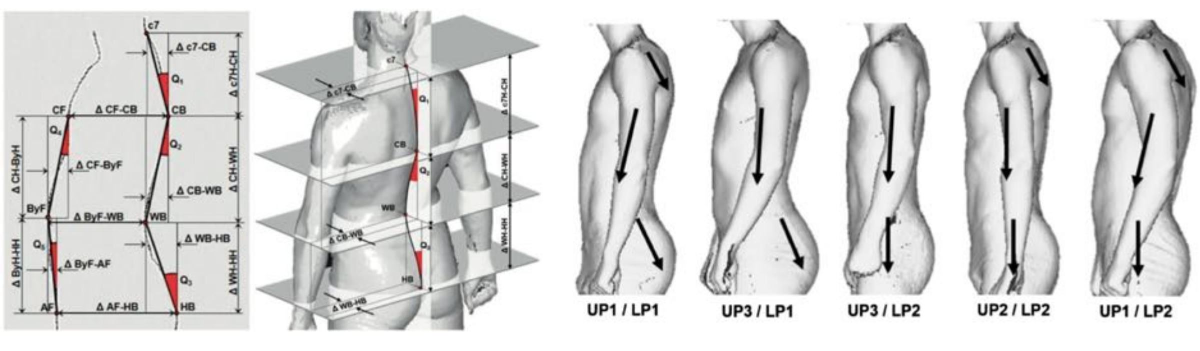
Miyoshi defined the torso morphology by analyzing the thickness and angles of body surface in the profile view after analyzing the photos of 150 Japanese female students [69]. As shown in Fig.1.7, *a*, the thicknesses of torso are classified into three types: thin, average and thick. As shown in Fig. 1.7, *b* - *d*, the angles of different areas can be also defined with several characteristic groups.



a *b* *c* *d*

Figure 1.7 - Torso morphology defined by Miyoshi:
a - thicknesses of torso, *b* - angles of different areas,
c – angles of neck, *d* – angles of lower back [69]

In the similar way, Maja et al. discovered the torso morphology by analyzing the new body curve angles on the sagittal cross-sections of VC [70]as Fig. 1.8, *a*. The angles of upper, lower torso can be primarily defined as three (UP1, UP2, UP3), three types (LP1, LP2, LP3), respectively. The final results show that there are nine shapes with combination of upper and lower torso morphology, six specific torso shapes are shown in Fig, 1.8, *b*.



a *b*

Figure 1.8 - Torso morphology analyzed by new body curve angle:
a - body curve angles on sagittal cross-sections,
b - examples of specific torso morphology shapes [70]

From the previous literatures, a preliminary cognition about male torso morphology and its extension in clothing design could be reached: the male torso is various in the shapes, proportions, angles, etc. of some essential segments – chest, waist, hip, neck, shoulder, back, etc. The morphological features to produce a well-fitted clothing, especially in customization, should be comprehensively considered.

1.2.2.Existing body measurements reflecting the male body morphology

Body measurements play an intermediary role between the body morphology and the clothing design. On the one hand, body measurements are the foremost tool to represent the morphological features, e.g., neck girth and neck shape. On the other hand, every pattern is drafted based on certain quantity of BM, e.g., bust girth as the most frequently used one. Thus, a good set of BM should not only primarily characterize the specified body segments, it should also be practicable in pattern drafting. If the both conditions were met simultaneously, the final clothing would show appropriate appearance and fit on the selected body.

Conventionally, the landmarks and levels of human body are the fiducial base for body measuring. According to the international standard ISO 7250-1 and ISO 8559-1 [71, 72], the fundamental landmarks and levels for measuring male body (includes torso, neck and arm) can be located as Fig. 1.9. As shown, three are in total four landmarks in shoulder and armscye areas (SP, APF, APB, AP), three landmarks (FNP, SNP, BNP) in neck area, two landmarks (EP, WP) area in arm area, and three levels (chest, waist, hip) in the torso area.

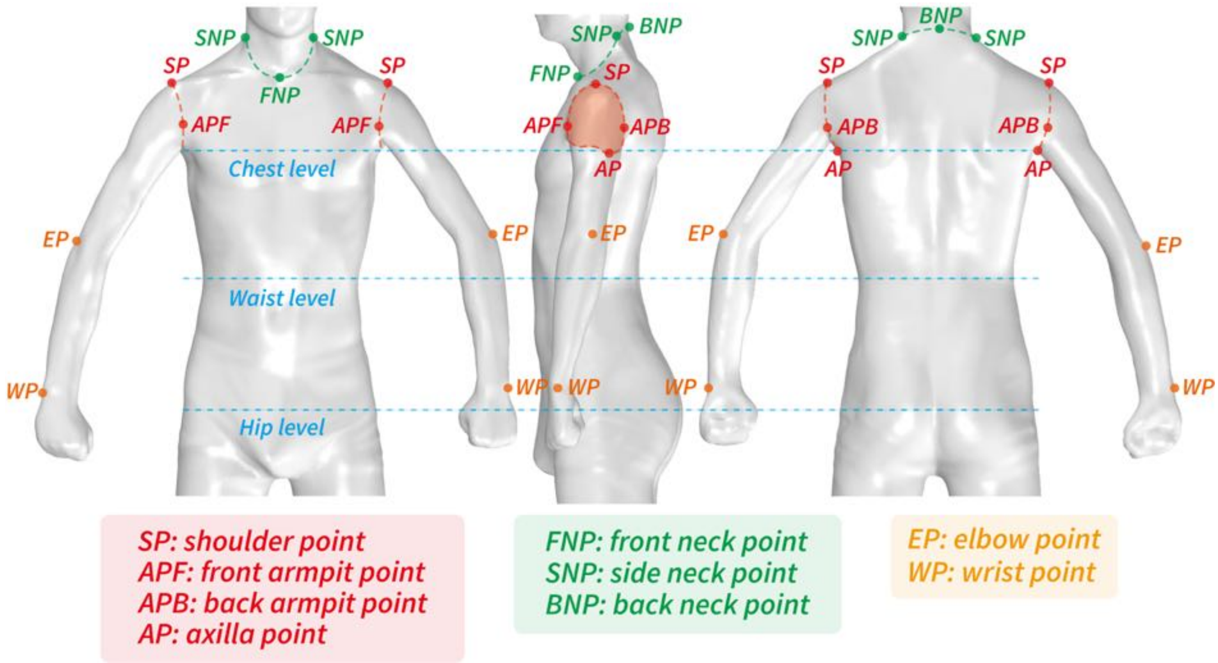


Figure 1.9 - Nine fundamental landmarks and three levels for measuring male body

On the basis of these landmarks and levels, the BM_E that reflect the male body morphology are diverse for different categories of clothing, types of production, level of exclusivity, etc.

Seven basic BM from the sizing systems are usually applied to represent the primary body morphology for drafting RtW patterns of a men's upper clothing: chest girth (CG), waist girth (WG), hip girth (HG), neck base girth (NG), back shoulder width (SW_B), back length (BL) and arm length (AL) [73].To achieve the higher requirements of fit, customized clothing involves more BM to reveal the morphology, e.g., wrist girth (WRG), upper arm girth (UAG), shoulder length (SL).

Some scholars also proposed more BM to characterize more features [74, 75], e.g., across front width (AW_F), across back width (AW_B), armscye girth (AG), surface length from SNP to front waist (SNW_F), surface length from SNP to back waist (SNW_B), vertical height of BNP, chest, waist and hip (H_{BNP}, H_C, H_W, H_H). BM_Ewere concluded for men's upper clothing usually used in clothing design and proposed by the previous researches as Fig. 1.10.

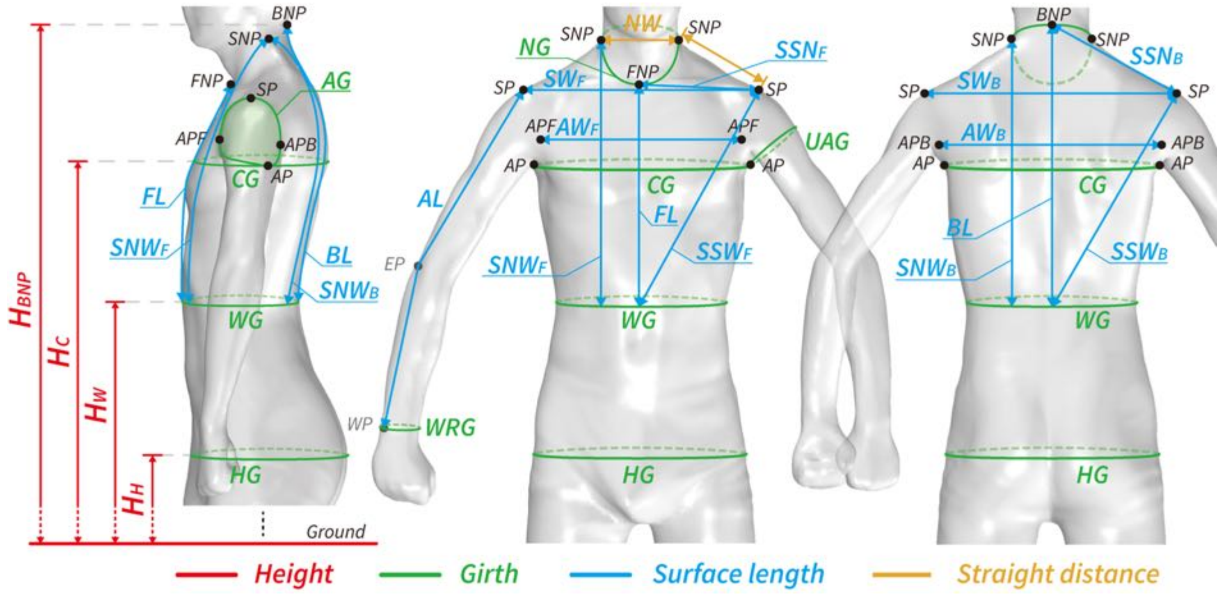


Figure 1.10 - BM_E for men's upper garments

As shown in Fig. 1.10, in total 25 BM_E of four kinds for men's upper clothing exist:

a. Height: the vertical distance from the selected level to the ground, including four BM_E - height of BNP (H_{BNP}), chest height (H_C), waist height (H_W), hip height (H_H);

b. Girth: the circumference measured at the selected level around the body, including seven BM_E - chest girth (CG), waist girth (WG), hip girth (HG), neck girth (NG), armscye girth (AG), upper arm girth (UAG), wrist girth (WRG);

c. Surface length: the shortest distance measured close to the surface of body between landmarks or levels, including 12 BM_E – across front width (AW_F), across back width (AW_B), length from SNP to front waist (SNW_F), length from SNP to front waist (SNW_B), length from SP to FNP (SSN_F), length from SP to BNP (SSN_B), length from SP to front waist (SSW_F), length from SP to back waist (SSW_B), front length (FL), back length (BL), front shoulder width (SW_F), back shoulder width (SW_B);

d. Straight distance: the shortest distance between landmarks or levels, including two BM_E - shoulder length (SL), arm length (AL).

According to these BM_E, the pattern blocks can be drafted for the morphological features of typical and untypical bodies. Despite the intermediate role BM_E plays, BM_E still often bring about the problem of misfit or imbalance of clothing especially for customized clothing as a result of inadequacy of characterizing the body morphology. For example, only NG is used to represent the neck, which is obviously impossible to depict the neck variations (see Fig. 1.6, *a* and Fig. 1.7, *c*) including the overall shape, vertical depth, neck width, anteroposterior proportions, etc.. And the similar problems exist in chest, waist, hip, shoulder as well. Thus, in order to construct the clothing which can well fit the various bodies, the complementary BM_N for more comprehensively characterize the detailed morphological features (e.g., spatial shape, proportion) should be discovered.

1.2.3. Application of 3D body scanning technology

In tradition, the main BM were manually measured with tape either pattern maker or consumers, but the accuracy highly depended on the experiences of the gaugers [55]. As the increasing requirements of anthropometric researches for clothing design, the specialized instruments and methods (e.g., Martin anthropometer, cross-section anthropometer, plaster method, Moiré interference fringes) were invented[69, 76].

The 3D body scanning technology which can instantly capture the accurate 3D image of human body with easy processes, has resolved the existing problems and raised numerous possibilities in anthropometric researches [77]. The current light-based (e.g., TELMAT, $[TC]^2$, SizeStream) and laser-based (e.g., Human solutions, VITRONIC) 3D body scanners [78-83] are primarily composed by three modules: the structure-light projectors or laser projectors that project lights or laser stripes onto the body, the CCD (charge-coupled device) cameras or sensors that capture the optical data, and the compatible software that operate data processing. Fig. 1.11 shows three main types of 3D body scanners.

a *b* *c*

Figure 1.11 - Three main types of 3D body scanner:
a - 3D scan booth from VITRONIC, *b* - 3D scan rotating platform from FIT3D,
c - portable scanner from TechMed3D [78, 80, 81]

3D body scanners can benefit the anthropometric research and clothing industry for many reasons [28]:

1. Basically, body scanners and the compatible software can automatically obtain an unlimited number of linear or non-linear BM in a matter of second. Fig. 1.12 shows the example of automatic and manual body measurement with VC from SizeStream [82]. As shown, in the measuring process, the landmarks, joints and levels are automatically located, and abundant default measurements and personalized BM can be measured automatically and manually, respectively.

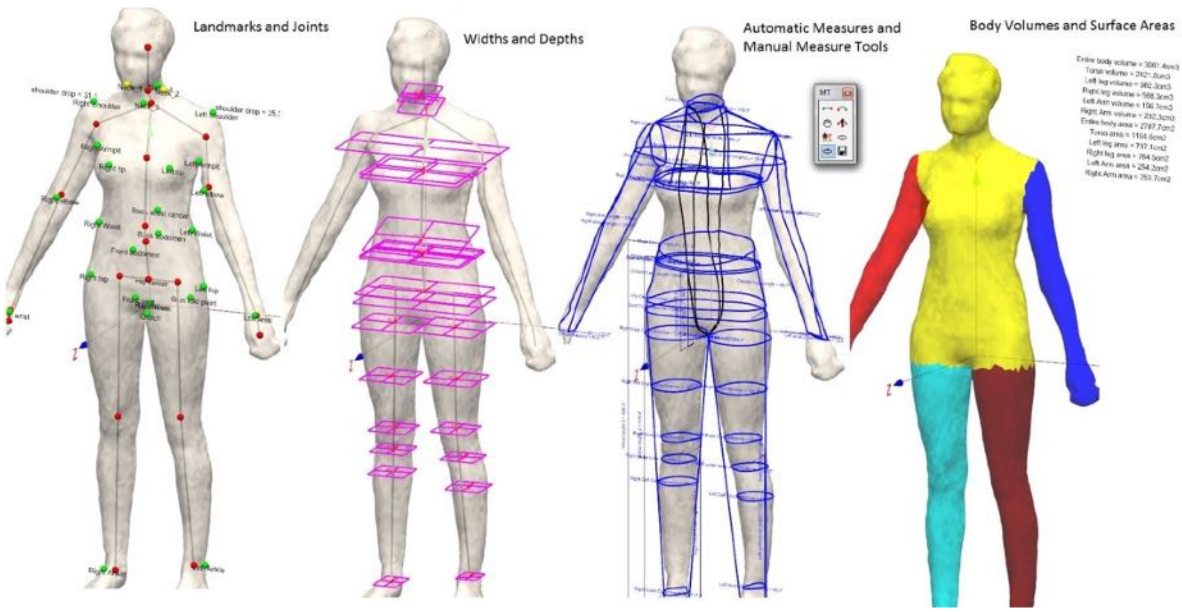


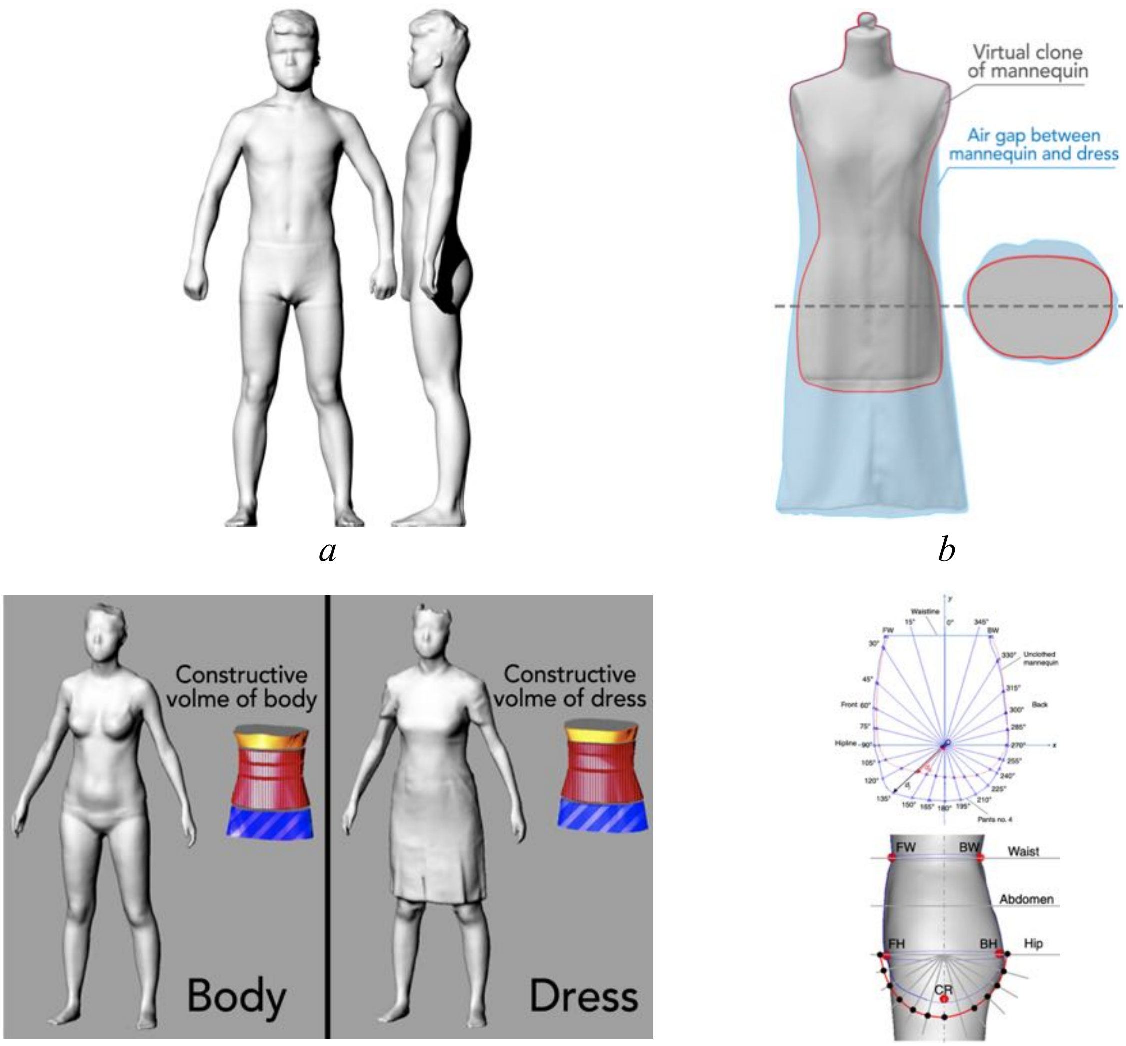
Figure 1.12 - Automatic and manual body measurement with 3D scanned bodies from SizeStream[82]

For one thing, the anthropometric census like national sizing survey projects (e.g., SizeUSA, SizeKorea) [84, 85] have been executed in many countries by collecting the BM of huge number of scanned bodies. The results of surveys were used to establish the new anthropometric database of the population, develop the national sizing systems, improve the industrial products, etc. Some scholars also investigated the body morphological features with new body measurements from 3D scan for further understanding the human body morphology and improving the sizing systems [86, 87].

For another, the BM from VC are also widely used to develop clothing design. Scott et al. proved the potential and viability of scan-to-pattern theory, from which the well-fitted pattern was obtained directly from the updated measurement extraction software to access underutilized body scan data [88]. Cheng et al. developed the method of men’s underwear construction based on new body measurements and classification of male lower torso [89]. Wang et al. leveraged 11 BM from VC to develop a 3D neck model for improving the ergonomic fit of the collar part [90]. Some other researches also developed the new methods for designing other clothing with the measurements from 3D scan [48].

2. The 3D scanned body, also called VC model [91] that is created by forming 3D surface data from a body scanned point cloud, has the same size and morphology as the real body (Fig. 1.13, *a*). By taking advantage of this feature, the researchers can also reduplicate body model instead of previous plaster method, and investigate the shape of clothing after its scanning.

Vuruskan et al. obtained the VC in active cycling positions by means of 3D body scanner and made the specialized real dress forms. The dress forms were easy to made by 3D printing technique instead of previous plaster method, and they were of high value for evaluating the fit of bicycle shorts [92].



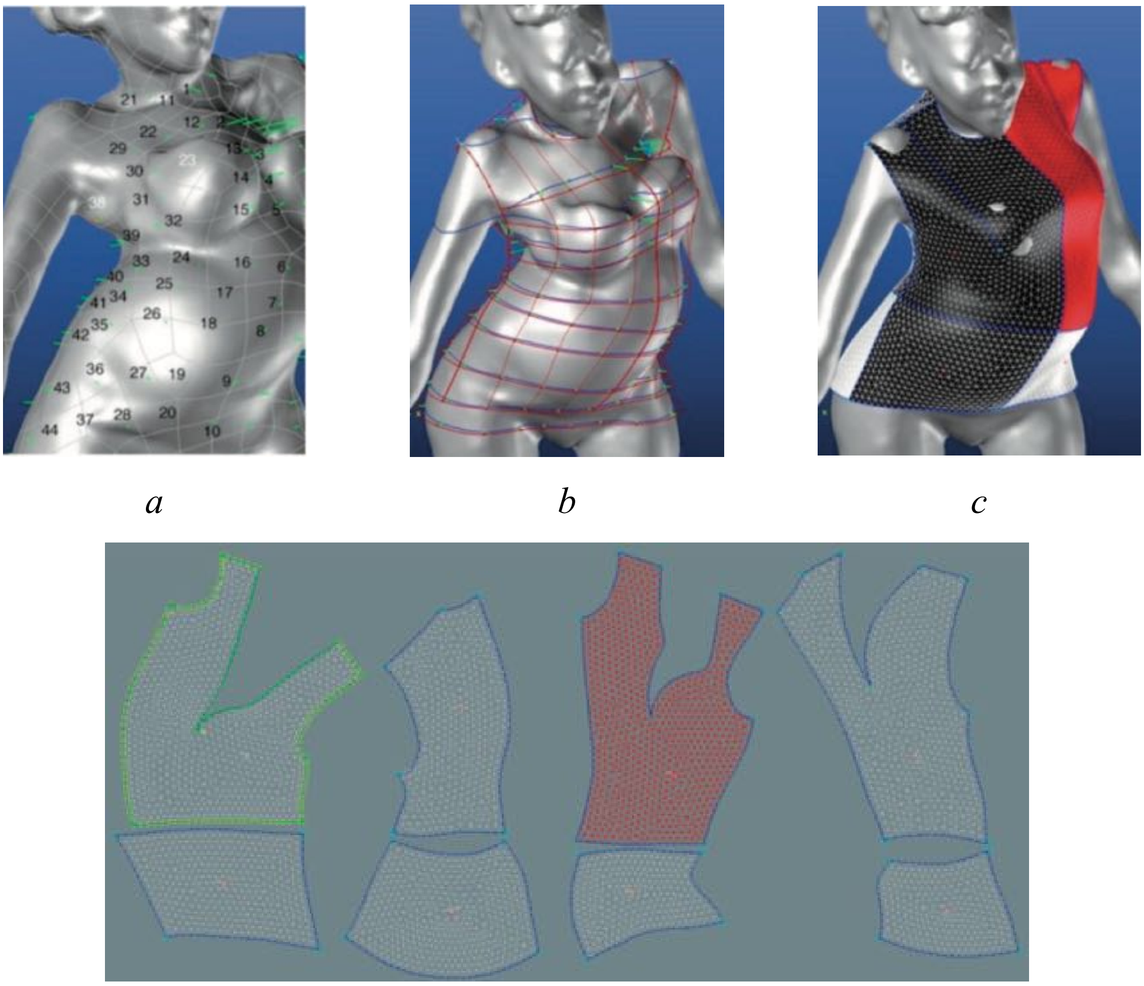
a *b* *c* *d*

Figure 1.13 - Utilization of virtual clone:
a - virtual clone in front and profile views, *b* - air gap,
c - indicators CEV for system “female – body dress”,
d - distance ease distribution of female pants [91, 93 - 95]

The air gap which was previously a conundrum for manual measurements has been clarified as the 3D exterior clothing scan model subtract the 3D interior body virtual clone. As shown in Fig. 1.13, *b*, the air gap between clothing and body are constructive for improving pattern construction and real and virtual clothing design [93]. Guo et al. proposed the indicators CEV "constructive ease volumes" of system "female body – dress" by subtract the volumes of segments of dress and body at different levels to establish the algorithm for dress shaping (Fig. 1.13, *c*) [94]. In the same manner, the divisional air gaps were utilized to establish the database concerning multiple factors (e.g., textile materials, patterns, clothing styles, sewing techniques) to improve the real and virtual design of dress and skirt [93]. Moreover, Gu et al. used the new indicator "distance ease distribution" of pants by analyzing the sagittal images of crotches form VC and pants (Fig. 1.13, *d*) [95].

3. Moreover, the VC can enable the new 3D clothing for special body, and the virtual fit evaluation before the actual production, which will especially facilitate the customization in clothing industry.

First, the pattern of the close-fitted bodice or pants that clings to body surface was previously obtained by unfolding the 3D plaster or gel layers into the 2D flat pieces [76]. The 3D-to-2D pattern flattening technique with VC has been devised to replace this method in 3D CAD (Fig. 1.5, *a*). Instead, the 2D pattern is obtained by unfolding the 3D polygon mesh which is made by connecting feature points on the surface of virtual clone. Hong et al. used this technique to design the real and virtual clothing for the scoliosis body, which was difficult by using traditional methods [96, 97]. Fig. 1.14 shows the process of 3D-to-2D pattern flattening in Hong's research. In the similar way, Lee et al. developed the 3D and 2D pattern for functional outdoor pants [98]. In spite of the advantages, this technique is only useful for the simple-styled close-fitted clothing.



a *b* *c*

d

Figure 1.14 - Process of 3D-to-2D pattern flattening in Hong’s research: *a* - locate the feature points, *b* - connect the feature points, *c* - generate the 3D meshed clothing surface, *d* - generate the 2D unfolded pattern [97]

Second, a DT is the digital representation of a unique asset, that alters its properties, condition and behavior by means of models, information and data [99]. The VC can be transformed into DT as the counterpart of the real body and be imported into 3D CAD for virtual fit analysis before a garment is actually made, which is particularly helpful for customized clothing production.

In conclusion, the 3D body scanning technology are much more capable in body measuring, clothing development and virtual design compared to the traditional methods. It brings about many new possibilities in anthropometric work and clothing engineering, especially for the individual body and customized clothing.

1.3. Men’s shirt and its pattern construction

In the contemporary daily life, shirt is regarded as one of the most frequently worn menswear. Coffin proposed the integral definition of shirt in his book: Any garment that hangs from the shoulders and has a neckline; has a mostly single-layer, if at all, primarily by the shoulder and side seams; has no internal structure, padding, or interfacing except possibly in a collar or cuffs; and has sleeves that project from the body at an angle, rather than fall parallel to it, counts as a shirt [100].

Since the first emergence in ancient Egypt [101], the shirt has gone through great evolutions during the thousands of years. The modern men’s shirt is composed by some specific components (e.g., front and back piece, yoke, collar, sleeve) and usually categorized to several groups according to the style that characterizes the silhouette, shape and air volume of the shirt.

In the modern clothing industry, three traditional methods of pattern drafting are usually utilized for shirt sewing: proportional method that use several body measurements (BM) to calculates all the pattern indexes through linear regression equations, short measure method that directly use a set BM to draw the pattern, and the third method combining with proportional and short measure methods. Based on the three methods, some of the new parametric models have been also proposed for automatically sewing the pattern.

For MtM clothing, the patterns should be further adapted to the individual body morphology mainly in two way: make adjustments according to the untypical morphological features and utilize more individua BM instead of the standard BM.

1.3.1.Men’s shirt and its styles

The men’s shirt is typically composed by a number of components: front piece, back piece, tail (hem), collar and collar stand, front placket, sleeve, cuff, yoke, and the other details. The changes of these components create the numerous variations of shirt designs. However, the most elementary factor for describing the integral shirt design is the style, referred to as fit that indicates the specific silhouette and shape of shirt around the body[3, 29]. Normally, the clothing companies or ateliers categorize the shirt styles in to three to five groups according to the volumes of shirt body and sleeve.

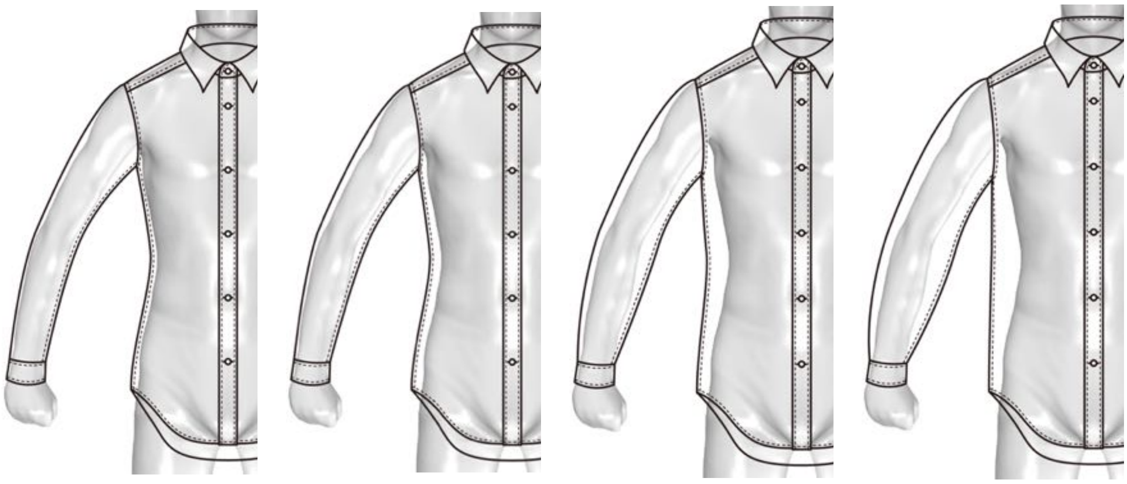
The styles of 62 shirts from 15 famous brands (Beanpole, C&A, Funday, GAP, GJ, Hugo Boss, H&M, Jack&Jones, K-Boxing, Oodji, O’Stin, Santa Barbara Polo&Racquet Club, Scofield, Urban Revivo) were surveyed in the physical and online stores (the detail information was in Table A.A, Appendix A). The four typical shirt styles were concluded as Fig. 1.15 shows:

- body-fit (or extra slim-fit, tight-fit): slimmest shirt with the cloth closed to the body surface, which apparently exhibits the waist curve and the contour of the torso;

- slim fit: as one of the most usual style, this shirt with small volume around chest, waist, hip, and arm;

- regular fit (or classic-fit): as one of the most usual style, this shirt provides adequate air volume around chest, waist, hip and arm for daily movement with the square bodice contour;

- loose-fit (or relaxed-fit): the biggest, sometime oversized, shirt with excessive air volume around the torso and arm, deep armhole, and sometimes natural draping folds on the bodice.



a *b* *c* *d*

Figure 1.15 - Different styles of shirt:
a - body-fit, *b* - slim-fit, *c* - regular-fit, *d* - loose-fit

As shown in Fig. 1.15, shirts in four types of styles are different in the contours and air volumes around the torso and arm. Referred to these four styles, the subsequent real and virtual experiments of men's shirts will be conducted.

1.3.2. Contemporary methods of pattern drafting

The traditional pattern drafting can be categorized into three primary methods: proportional, short measure, and combined.

Derived from the census of abundant sample population, the proportional method constructs the integral pattern with the regression calculation equations that calculate the necessary pattern indexes of other segments based on only several BM (e.g., CG, BL), which is widely used for the RtW clothing in Japan and China [102, 103]. The advantages and disadvantages of this methods is obvious. On the one hand, it requires very limited body measuring, which saves much time and labor. On the other hand, the correlations between CG and other dimensions (e.g., neck drop, neck width) are unexplainable by current results; and the method requires certain experience for pattern maker. These disadvantages will lead to the misfit of the end-product.

Fig. 1.16 shows the upper prototypes of Japanese Bunka-style and

Chinese methods from Liu and Donghua University (Shanghai, China) [69, 102, 104]. The two prototypes are generally constructed in the similar ways with the different details. The similarities are: the same BM used (CG and BL), the overall logic process of construction, the calculation of some pattern parameters (e.g., waist line length, back length, front width). The differences are: some parameters with the same coefficients but different suffixal constant (e.g., back width, neck width) due to the different populations and techniques, the detailed configuration of armhole line, shoulder line and neck line.

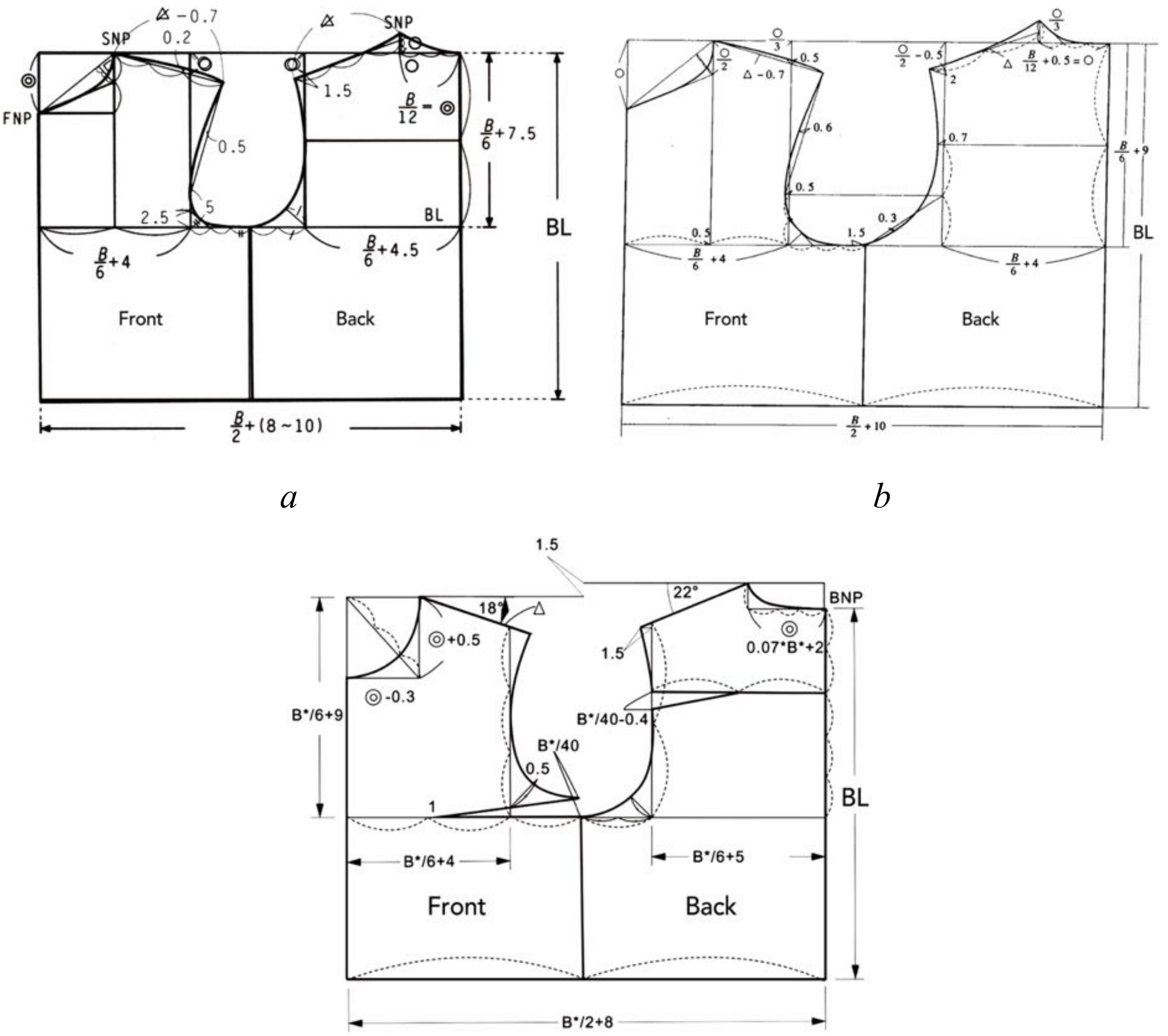


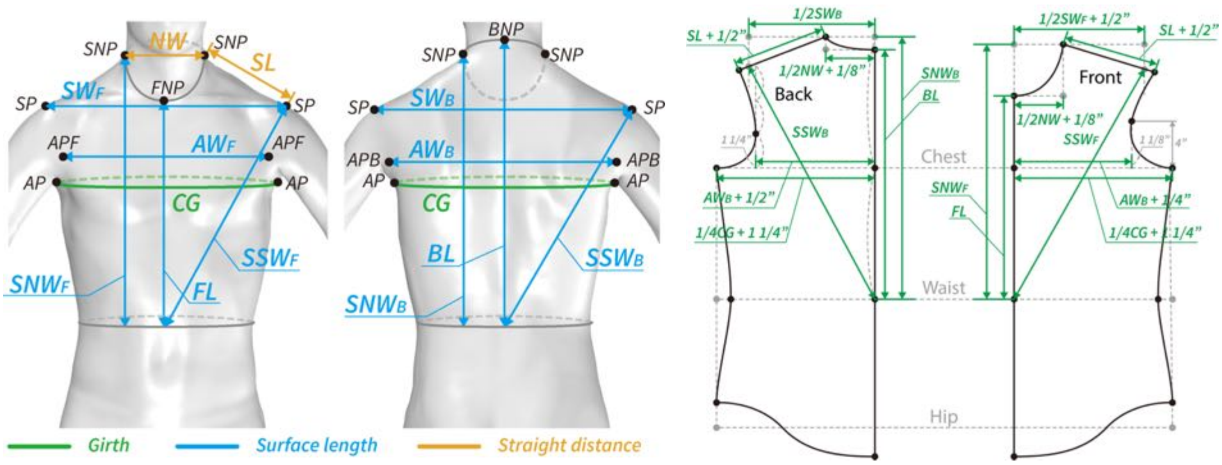
Figure 1.16 - Proportional method of upper menswear prototypes drafting:
a - Japanese Bunka-style, *b* - Chinese methods from Liu,
c-Donghua University (unit: cm, B represents CG here) [69, 102, 104]

The short measure method directly uses the pattern indexes from BM of the standard sizes or the individual body without equations, which can be used for both RtW and MtM clothing, respectively. These parameters are usually calculated by raw body measurements plus certain adjustive constants as Equation (1.1):

$$I_P = BM + E, \quad (1.1)$$

where: I_P are the indexes of pattern block, E are the pre-defined ease allowance.

This method is also double-edged. It involves time-consuming and complex body measuring process and requires high accuracy of the BM. However, once the BM is alright measured, the pattern will achieve good clothing fit. Fig. 1.17 shows the BM and corresponding men's shirt bodice prototype by short measure method in Joseph-Armstrong's book[105].



a *b*

Figure 1.17 - A men's shirt by short measure method in Joseph-Armstrong's book:
a - body measurements, *b* - shirt bodice pattern (unit: inch) [105]

As shown in Fig. 1.17, the bodice construction contour can be drafted stepwise by directly using the 14 BM concerning chest, shoulder and neck and adjustive constant as Equation (1.1).

In the similar way, Kershaw proposed the basic upper prototype with 6 BM: CG, AD (armsyce depth = $H_{BNP} - H_C$), BL, Depth from waist to hip ($H_W - H_H$), AW_B, NG (neck girth) [106]. The Metric shirt bodice from Aldrich is based on five BM: CG, AD, BL, AW_B, NG [107]. These patterns can better fit the body than the proportional pattern. However, the misfit problems are not completely resolved.

The combined method, as its name indicates, involves the both methods - proportional and short measure - by using both regression equations and a few more complementary BM together. In Miyoshi's book, the prototype is constructed by using the raw body measurements AWB and BL, and the regression equations calculated by CG and NG [69].

On the basis of the three methods, many scholars proposed new parametric models for sewing customized men's shirt pattern [108-110]. The establishment of the parametric models usually includes several steps: the determination of BM, the determination of feature points and Cartesian coordinate system of the pattern, the pattern drafting by regression-equation-based coordinates. For instance by Hong's research, the linear relations and equations were first developed by the statistical analysis about the 26 comprehensive BM and the representative BM. Once the four BM (CG, NG, BL, SW_B) of the selected body were surveyed, the feature points and the coordinate systems for front and back segments were determined (Fig. 1.18). The final pattern can be drafted by the coordinates calculated from the BM (Table 1.4) [108].

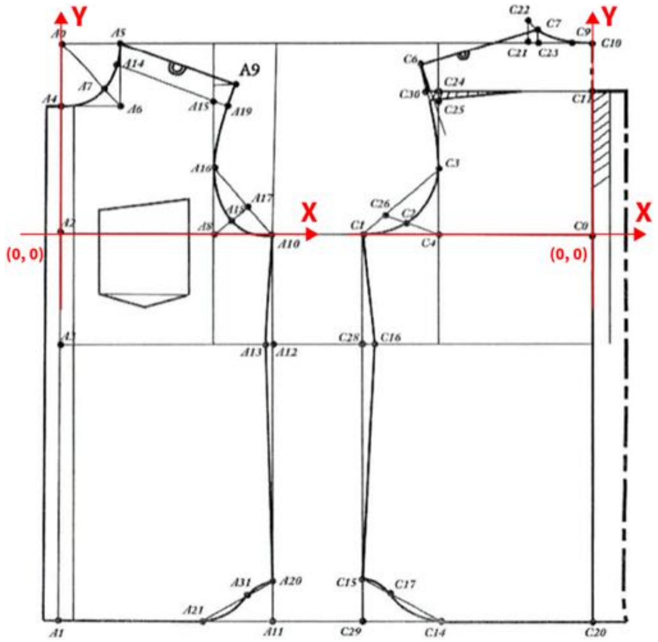


Figure 1.18 - Feature points and Cartesian coordinate systems of front and back bodice patterns

Table 1.4 - The essential coordinates for locating the feature pointson frontbodice

Point	Coordinate	Point	Coordinate
A1	(0 , -2BL + CG/6 + 27/2)	A13	(CG/4 +3 , -BL + CG/6 + 19/2)
A4	(0 , CG/6 – NG/5 + 42/5)	A16	(CG/6 +4 , 33CG/800 + 19NG/500 +13661/4000)
A5	(NG/5 + 1/10 , CG/6 + 19/2)	A20	(CG/4 , -2BL + CG/6 +37/2)
A7	(2NG/15 + 1/15 , CG/6 – 2NG/15 + 263/30)	A21	(CG/6 +8/3 , -2BL + CG/6 +27/2)
A9	(CG/6 + 13/2 , 31CG/300 + 19NG/250 + 1767/250)	A31	(2CG/9 +32/9 , -2BL + CG /6 + 101/6)
A10	(CG/4 +4, 0)		

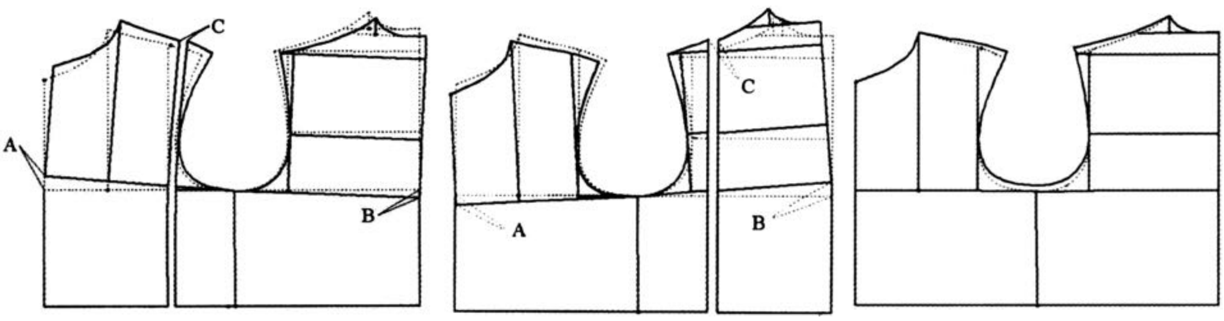
With the parametric model as Fig. 1.18 and Table 1.4, the individual pattern can be automatically drafted by inputting specific BM. Qi et al. proposed the similar parametric models for men’s shirt by inputting different sets of basic BM [111].

1.3.3. Methods of adapting pattern to body morphology

Due to various body morphological features, the before-mentioned contemporary pattern drafting methods often cannot obtain the clothing that fits everyone. For MtM clothing, this situation will lead to serious fit problem and failure of customization. Thus, two methods of adapting the pattern to individual body were proposed.

For one thing, the adaption to the standard pattern can be made according to the untypical morphological features [68]. This method requires abundant experience in pattern sewing and several try-on trials to determine the design. Moreover, the pattern adaptions will be difficult to determine when the different segments (e.g. chest, belly, hip, back, shoulder, neck) are of untypical morphologies at the same time.

Based on the morphologies of chest, back, belly, shoulder and the corresponding basic BM (see Table 1.3 in Section 1.2.1), Yang proposed the schemes of concrete adapted patterns (Fig. 1.19).

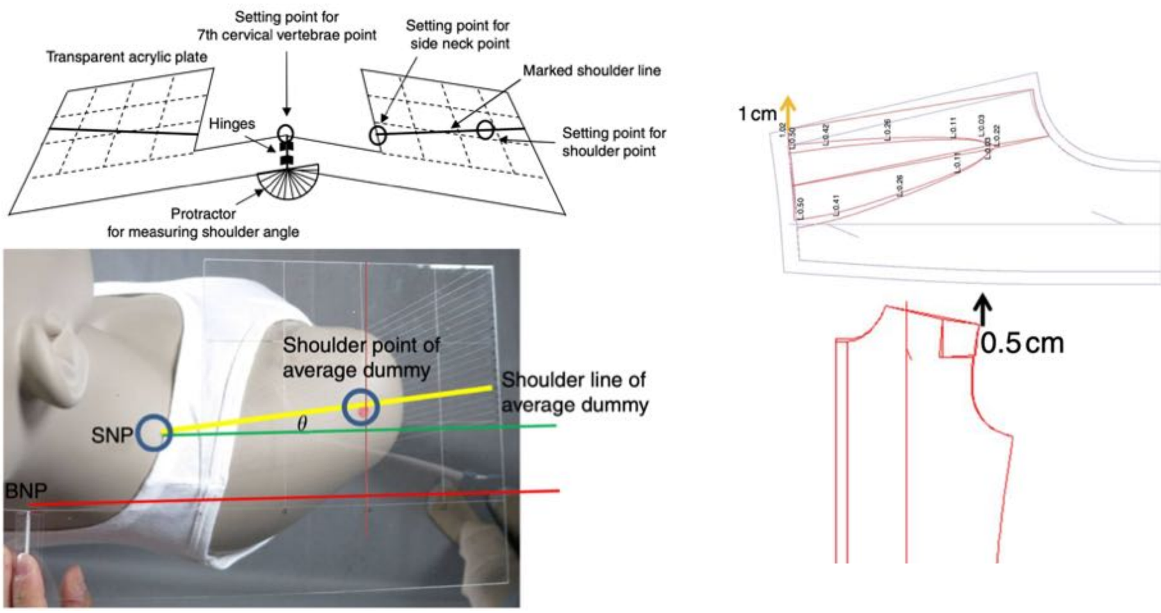


a *b* *c*

Figure 1.19 - Adapted patterns for the untypical bodies with different morphology:
a - slightly protruding chest, *b* - hump back, *c* - and square shoulder (solid lines: adapted patterns; dotted lines: standard patterns), where A, B, C are the difference between the BM (FL, BL, AW_F, AW_B) of individual and typical bodies [68]

As shown in Fig. 1.19, for the slightly protruding chest, the pattern was adapted by lengthening FL, widening AW_F, moving backwards the front neckline and shoulder line, and shortening BL. For the hump back, the pattern was adapted by shortening FL, moving forwards the front neckline and shoulder line, lengthening BL, and widening AW_B. For the square shoulder, the pattern was adapted by decreasing the front and back shoulder slopes and armhole depth.

Kim et al. devised the shoulder shape anthropometer that were capable of simultaneously measuring shoulder slope angle, shoulder length, shoulder direction [52]. Through comparisons between the shoulder measurements of individual body and standard dummy with the anthropometer, the comprehensive shoulder shape was easily determined and the necessary adaptions were made to the patterns of front bodice and yoke. Fig. 1.20 shows the shoulder shape anthropometer and the pattern adaption for a forward-thrust square shoulder. In the similar way, the adaptions can be executed to the pattern according to the other morphological features [112, 113].



a *b*

Figure 1.20 - Pattern adaption with shoulder shape anthropometer:
a - shoulder anthropometer,
b - pattern adaption for a forward-thrust square shoulder [52]

For another, the pattern can be adapted by increasing the scheme of BM and substituting the individual BM for standard ones, which is based on the short measure method. It is vitally important that individual BM are taken accurately and in the correct place on the body.

Aldrich proposed in her book 12 BM for the individual upper menswear [107]. Chan et al. utilized the 34 BM (some are measured in both left and right segments, e.g. left and right shoulder angles) from 3D body scans to establish parametric models for predicting the pattern indexes by both linear regression equations and ANN [48]. However, both of their methods are still operated based on the BM_E (see Fig. 1.10) the standard prototypes. As discussed before, BM_E cannot comprehensively characterize the main body morphology such as the proportions, and some of the non-basic BM cannot directly applied in standard patterns.

Thus, to accomplish the well-fitted pattern by the second method, it is inevitable to discover the BM_N as complements that can comprehensively characterize the body morphology, and to devise the corresponding new pattern that can be adapted to BM_N.

1.4. Methods of achieving and evaluating clothing fit

A clothing fit which has long been regarded as the single most important element to customers in clothing is the indicator to judge the two final results – design and tailoring [114]. A well-fitted clothing should be comfortable and not impede the movement of the wearer [115].

When determining the fit state of a clothing, observation and measurement to the “body - clothing” interactive system were always conducted. The former is concerning the criteria and evaluation of the clothing fit, and the latter is concerning the fundamental factors that influence on the clothing fit. There are usually three main influential factors: body morphology, pattern block construction and textile material. And the evaluation of clothing fit can be conducted subjectively and objectively based on concrete criteria concerning the exterior appearance, the wearing comfort, pattern, textile material, etc.

1.4.1. Factors that influence on the clothing fit

The system of "body - clothing" renders the integral clothing fit state with the synthesis of a specific sewed clothing and a wearer, which is influenced by three factors: body morphology, pattern block of certain ease allowance and style, and properties of textile material.

The main reason why the clothing itself and the body are regarded as a system is that the final clothing fit usually varies obviously from one wearer to anther owing to the diversity of body morphologies. As mentioned in Section 1.2.1, the morphologies of different wearers are various in different body segments (e.g., chest, waist, hip, shoulder, neck, arm). With regard to the same clothing, the final fit state will be distinguishing when worn by different wearers due to the variant compatibility between pattern and bodies. Monobe et al. proved the great influence of body morphology on the clothing fit by comparing the effects of one women jacket worn on the dress forms with different bust sizes [116].

An ease allowance (or ease) defined as the difference in space between the clothing and body, can be divided into three types [55]:

a. dynamic ease (DE) provides sufficient spaces for body shape and their movement;

b. fabric ease (FE) takes into account the influence of fabric;

c. style ease (SE) provides the additional spaces for the particular clothing style (e.g., loose fit, oversize).

Thus, the integral ease (E) usually used in pattern sewing should satisfy:

$$E = DE + FE + SE, \quad (1.2)$$

According to Equation (1.2), a pattern with suitable ease should provide an good fit and physical comfort, permit the body movement, conform to the textile material, and construct the desired clothing style and shape. Fig. 1.21 shows the placements of eases on a shirt bodice [117].

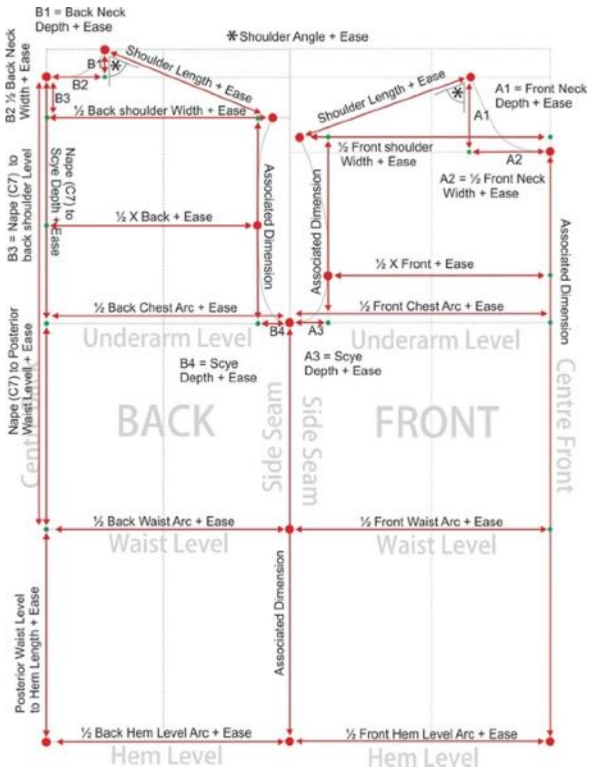


Figure 1.21 - Placement of eases on a shirt bodice [118]

Chen et al. investigated personalized eases related to key body positions and wearer's movements, permitting to further improve the wearer's fitting perception [118]. Gu et. initiated the new indicator distance ease at crotch curves and discovered the corresponding prediction algorithms for desired crotch design (see Fig. 1.13, *d*) [95].

The clothing made of different fabrics shows disparate appearance and fit state. For one thing, FE should be varied with the thicknesses of fabrics, which is especially important for the heavy clothing. For another, the mechanical properties (e.g., tensile, bending, shearing) of fabric also influence on the appearance and fit. Lage et al. investigated distance ease distribution in respect to fabrics mechanical properties in virtual try-on software, and make recommendations for good clothing fit (e.g., using fabrics with tensile strain lower than 10% and ease allowance more than 2cm, the wrinkles in dress waist and hip areas could eliminated) [119].

In previous experiment, the dresses (D_1, D_2, D_3, D_4) made with diverse fabrics (thin calico, thin polyester, elastic denim, thick elastic polyester) of different mechanical properties and the same pattern shows entirely different appearance and fit as Fig. 1.22.

a *b* *c* *d*

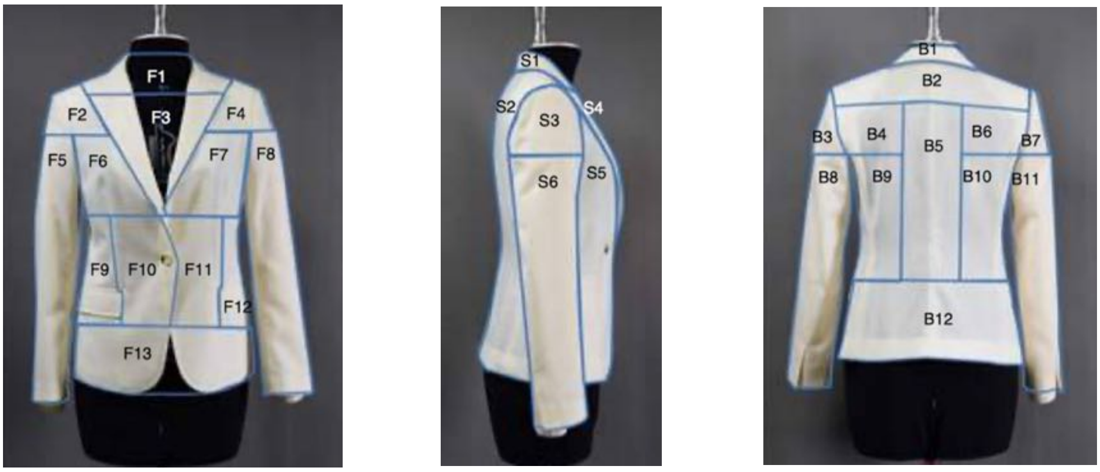
Figure 1.22 - Superposed pictures of the mannequin and the female dress made of different fabrics:
a - D_1, *b* - D_2, *c* - D_3, *d* - D_4

Obviously, the hem contours of four dress are of big difference. Moreover, D_2 and D_4 shows narrower contours while D_1 and D_3 shows loose contours. D_2 and D_3 have the smaller shoulder angles as the mannequin's, while D_1 and D_4 have much bigger obvious angles as the misfit on shoulder area. These differences of fit and appearance depends on the drapability and formability of the fabrics which are determined by the mechanical properties.

1.4.2 Evaluation and criteria of the clothing fit

The clothing fit is often evaluated based on specific criteria from the perspectives of both subjectivity and objectivity. For one thing, the subjective evaluation is conducted by surveying the perception of clothing contributing to the try-on, observation or analysis from respondents[120-122]. For another, the numerical indicators can be measured for objectively describing or explaining the clothing fit and appearance [123].

The subjective evaluations are usually conducted in two aspects: the aesthetics, and the wearing comfort. The former is characterized as the exterior appearance of a clothing which is evaluated visually, including the overall beauty, the silhouette of different sections, the positions of structure lines and sewing lines, the distribution of wrinkles, bulges and creases, etc.. Monobe et al. segmented the jacket of three views into 31 and mark the fit (fitting, not fitting, neither) and beauty (beautiful, not beautiful, neither) by evaluating the shape, silhouettes, wrinkles and smoothness of different parts (Fig. 1.23) [116].



a *b* *c*

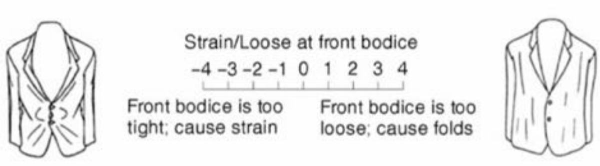
Figure 1.23 - Jacket segments for local fit evaluation:
a - thirteen parts in front, *b* - six parts in side,
c - twelve parts in back[116]

In the same way, Kim et al. proposed the evaluation items in seven different aspects for different parts as Table 1.5 [124].

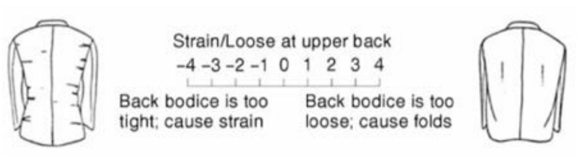
Table 1.5 - Evaluation items for different clothing parts in Kim's research [124]

Evaluation item	Part	
	Front	Side
Many wrinkles – Few wrinkles	Shoulder, bust, waist, entire Waist line	bust, waist, entire Front line
Fitting – unfitting		
Attractive – not attractive		
Looks young – looks old		
Looks slim – looks fat		
Beautiful – not beautiful		
Beautiful silhouette – not beautiful silhouette		

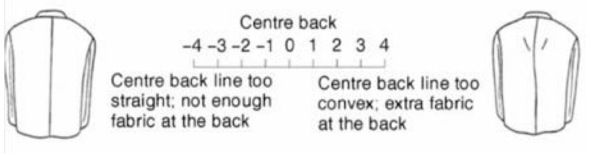
Yu et al. proposed the further fit scales for exactly evaluating each part of a jacket as Fig. 1.24 [125]. As shown, the nine-point scale comprehensively covered the misfit and fit state appeared in different parts of a jacket.



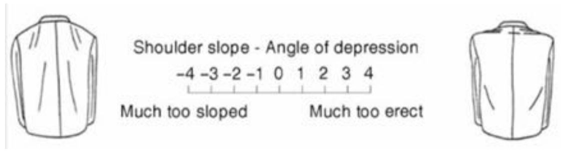
a



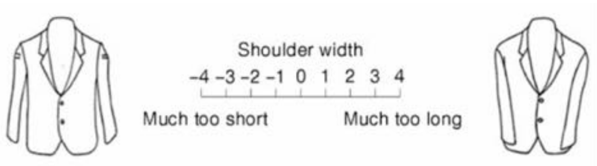
b



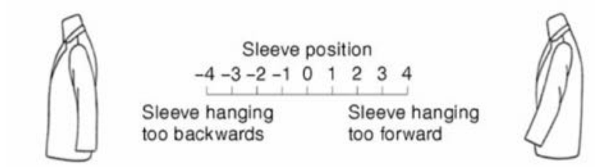
c



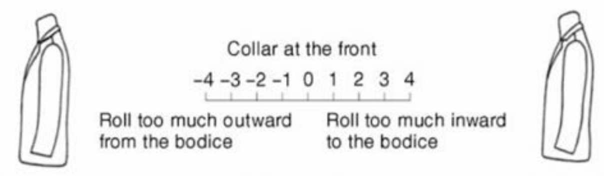
d



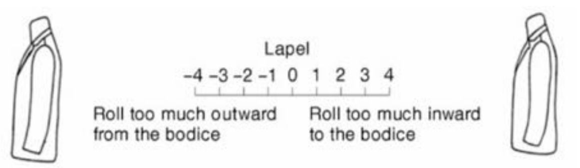
e



f



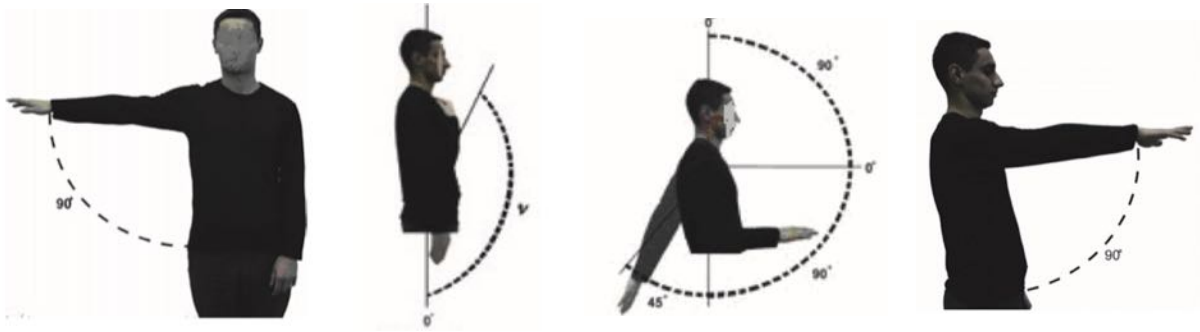
g



h

Figure 1.24 - Fit evaluation scale for a jacket:
a - front bodice, *b* - upper back, *c* - center back, *d* - shoulder slope,
e - shoulder width, *f* - sleeve position, *g* - collar at front, *h* - lapel [125]

Wearing comfort, the final aspect of subjective evaluation, concerns the sensorial comfort (the elicitation of various neural sensations when a textile comes into contact with skin) and the body movement comfort (ability of a textile to allow freedom of movement, reduced burden, and body shaping, as required) [3]. Different body postures and movements are usually involved to survey the comfort of a clothing in daily activities. Gu et al. enrolled five respondent wearers to try-on the jackets and evaluate the comfort with a five-point scale in five different body postures: arms down, arms apart in 45°, arms apart in 90°, contracted arms on shoulder and bending [50]. SAYĞILI et al. conducted the comfort evaluation of men's jackets with four different movements as Fig. 1.25 [126].



a *b* *c* *d*

Figure 1.25 - Movements for comfort evaluation of men's jackets in SAYĞILI's research:
a - extending the arm sideward by 90°, *b* - flexion - bringing the arm to front by 145° (holding the tie), *c* - flexion and extension, *d* - flexion - extending the arm from the shoulder to the front by 90°[126]

Huck et al. proposed the more detailed wearer acceptability scale for the wearers determining their personal wearing comfort evaluation in a nine-point scale as Fig. 1.26 [127].

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 1.26 - Wearer acceptability scale in Huck's research [127]

In the scope of objective evaluation, the numerical indicators are measured by instruments of software: clothing pressure, angles, distances, etc.. In the real environment, the clothing pressure (the most frequently-used index to reveal the interactive force of a clothing applied to the human body) is usually measured to determine the distribution of misfit and fit areas [128], the numeric measurements such as angles are also used. In the virtual environment, except for the above mentioned indicators, more indicators which are hard to measure physically were measured, for instance by the distance ease between avatar and clothing, the distortion rate, etc. (Section 1.5) [119, 129]. Fig. 1.27 shows the measurements of numerical fit indicators in real and virtual environments.

a *b*

Figure 1.27 - Measurements of numerical fit indicators:
a - clothing pressure in real environment,
b - distance ease in virtual environment (in Modaris 3D Fit) [119, 128]

Based on these existing means of clothing fit evaluation, some scholars conclude the criteria of clothing assessment to determine whether a garment is well-fitted or not. One of the benchmarks providing clear criteria to assess the fit of garments in product development are those outlined by Erwin et al. [26, 55]. They proposed five fundamental factors as the universal subjective evaluation criteria related to three different areas:

1. One factor relates to textile fabrics: the grain direction which influences fabric draping;

2. One factor relates to the pattern block: the ease allowances which show the difference between clothing and BM and produce an air gap between them in the ready ‘‘body - clothing’’ system;

3. Three factors relate to the ‘‘body - clothing’’ system: the contour lines which reflect the relationship between silhouette, clothing construction, and human body; the set which is as an indicator of smoothness, location of stress folds, or unnecessary creases; the balance which shows the symmetry of clothing around and over the body in front, profile, and back views.

These principles are expected to meet different criteria or be designed examples of good or poor fit characteristics in regard to the definition of clothing fit. The friendly fit criteria of different type of garments were recommended for consumers to evaluate a clothing on account of the appearance and wearing comfort. For a men’s dress shirt, the fit criteria differ in different sections (as Fig. 1.28) [130]:

1. The collar should graze the neck without constriction when buttoned;

2.The shoulder seam should be right where the shoulder starts (SNP) sloping down to the arm (SP);

3.The armholes should be comfortable in motion, namely being not so tight that they cut into the underarm and not so loose that excess fabrics accumulated around armpit;

4.The sleeves should not be too tight or too loose. The natural motions should be allowed;

5. The body of the shirt should fit closely around the torso, no matter what the shape and size of the body are;

6. If the shirt is untucked, its bottom should end around mid-crotch area. If the shirt is tucked in, its bottom usually ends at the bottom or past the crotch.

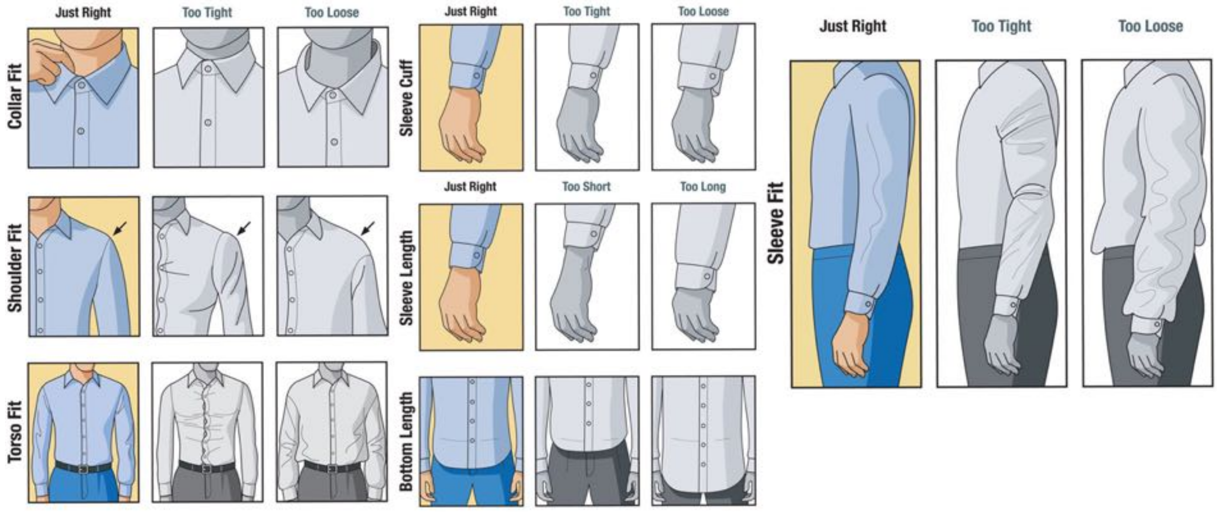


Figure 1.28 - Fit criteria for a men's shirt [130]

With these simple but feasible principles, even the untrained consumer can assess the fit situation of a shirt and make a decision. Similarly, the fundamental fit criteria of Erwin et al. should be evolved into detailed principles for comprehensive types and styles of garments. The main items for the criteria should contain the exterior appearance (silhouette, structure lines, balance, etc.), comfort and ease for movement. In addition, for special categories of garments such as the tights and activewear, more items should be involved to meet the higher requirements of their functionality and aesthetics.

For the pattern maker or tailor, the more effective way to predict the clothing fit is to check the pattern itself with particular criteria of pattern block before production. The most fundamental criterion is the consistency of adjacent points and lines (e.g., front side seam = back side seam, the smoothness of assembled front and back armhole or neckline). The next criteria are the indicators of ease, proportionality, pattern index, etc.

As mentioned before, eases are designed in consideration of the body morphology, dynamic movement and fabric properties. The criteria of good clothing fit concerning the eases are formulated with types and styles of clothing, because the eases vary drastically with them, such as the knitted tight fitting garments with minus ease values and oversize garments with enormous ease values. As shown in Fig. 1.29, Gillhas concluded the eases recommendation classified by style of clothing from literatures[1].

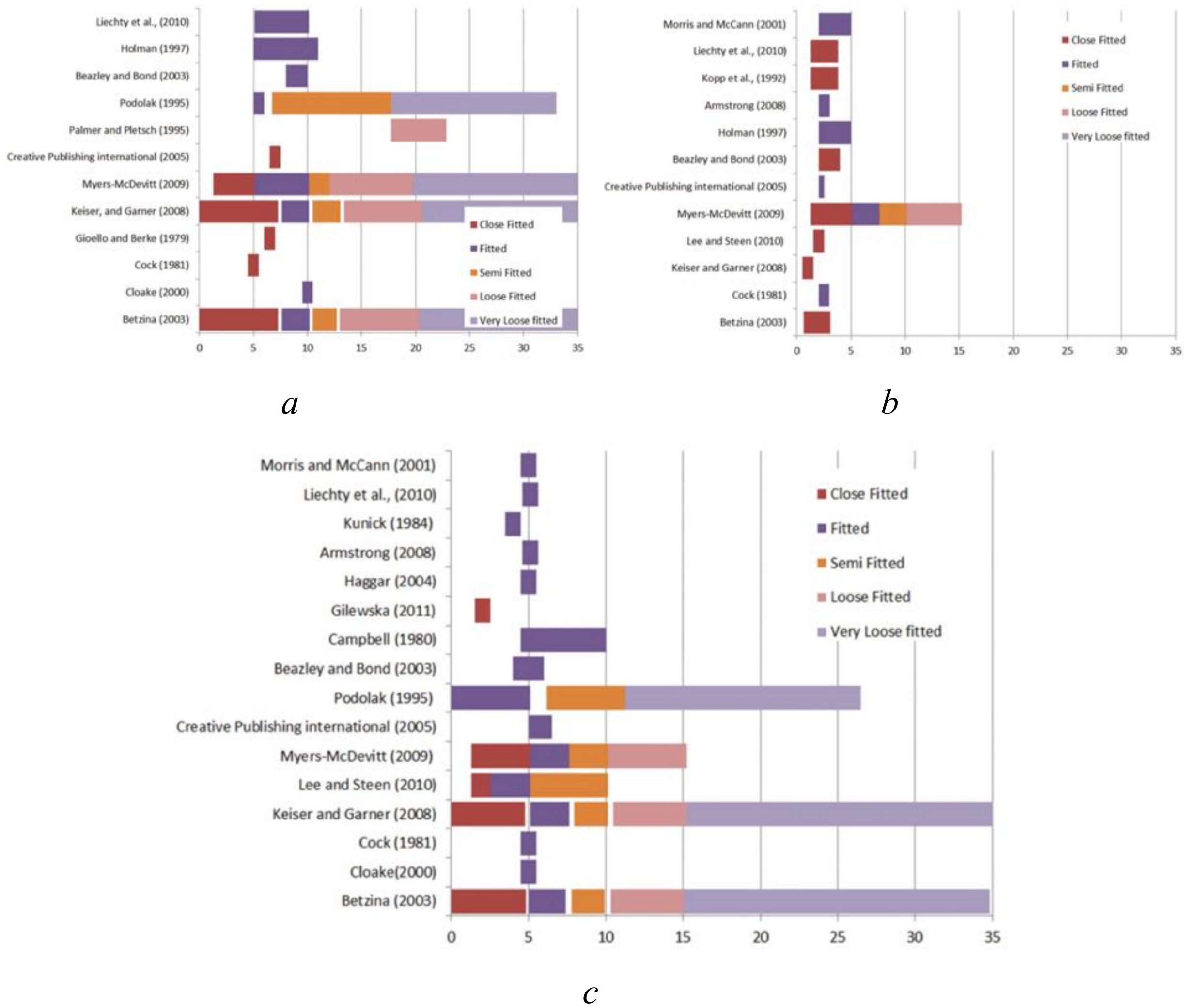


Figure 1.29 - Criteria of eases for different clothing stylefrom the previous literatures:
a - bust, *b* - waist, *c* - hip [1]

Although their criteria are diverse, the intervals of each eases for different styles are similar. The recommended ease values (EBG: ease to bust girth, EWG: ease to waist girth, EHG: ease to hip girth) gradually increased from close fitted clothing to very loose fitted clothing. Moreover, the variance of clothing style is more sensitive to EBG and EHG, and the acceptable ease interval of loose fitted and very loose fitted clothing are wider than the other styles.

Concretely, Qi proposed ECG (ease to chest girth) for pattern construction of different styles of men's shirt (body-fit: 0 … 12 cm, slim-fit:

12 … 18 cm; regular-fit: 18 … 25 cm; loose-fit: ≥ 25 cm) [111]. Surikova et al. proposed the criteria to validate the applicability of different combination of clothing types, styles, ECG and CG [114].

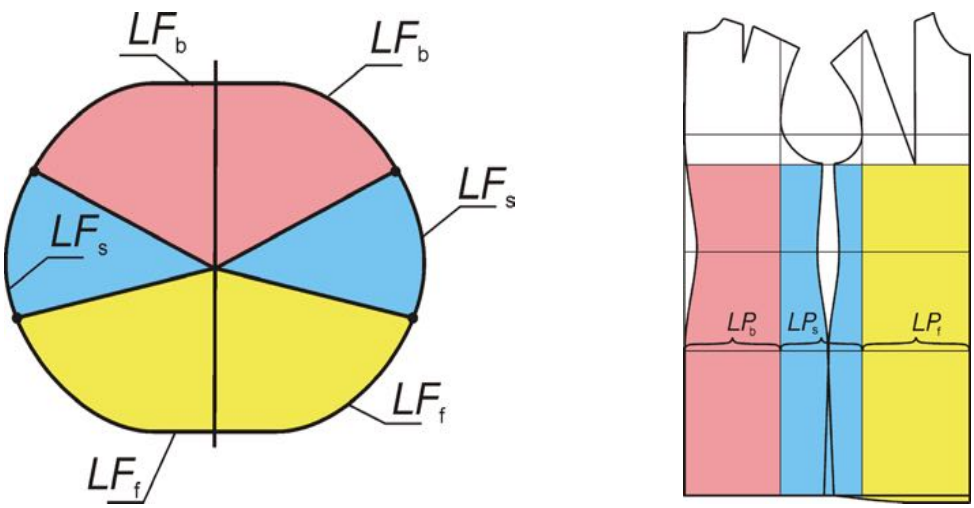
The proportionality, or balance, is the proper ratio between clothing sizes and the body sizes, reveals the allocations of different block pieces on a body. From the latitudinal aspect, the pattern and body are usually distributed into front, lateral and back sections. If the ratio between clothing and body of a certain section are too big or too small, wrinkle will appear caused by the shearing force due to the unbalanced proportionality. As shown in Fig. 1.30, *a*, Surikova et al. proposed the criteria to calculate the front, side and back width of hip girth (HG) for typical bodies:

$$LF_f = 0.205\ HG, \quad (1.3)$$

$$LF_s = 0.12\ HG, \quad (1.4)$$

$$LF_b = 0.175\ HG, \quad (1.5)$$

where: LF_f, LF_s and LF_b are the widths of the body site across hip on the front, side and back, respectively.



a *b*

Figure 1.30 - Separation of front, side and back:
a - of the body on hip cross-section,
b- of corresponding pattern indexes concerning hipline [114]

Moreover, Surikova et al. measured the permissible lack of the clothing site width of different fabrics by original device, which simulated the allowable fabric transverse shear. Fig. 1.30, *b* shows the pattern indexes concerning hipline that correspond to the partition of the body. The site on the pattern block will be sufficient to cover the corresponding body site if its size is equal or less than the body site by permissible lack of width d:

$$LP_i \geq LF_i - d, \qquad (1.6)$$

where: LP_i is the width of the pattern block site across hipline, cm. LF_i is the width of the body site across hipline, cm. d is the permissible lack of the clothing site width across hipline of different fabrics.

A patter maker should also estimate the influence of properties of fabrics on clothing appearance by manipulate fabric ease (FE) to achieve the desired fit, shape and style of a clothing. Zvereva et al. proposed the index of wrinkle coefficients of pants calculated by mechanical indexes from KES, which allowed to estimate the increasing of the fabric surface length comparing to the body surface on different longitudinal levels [131]. Surikova et al. explored the criteria of allowable transverse shear value to keep smooth appearance in clothes made of fabrics with different formability indicators. The value should be considered in pattern making process according to the fabric properties to get the good fitting clothes [114]. Xue et al. plotted the data chart for pattern designers to predict the formability of a fabric from its mechanical properties for producing a suit of satisfactory silhouette [120].

In summary, the subjective and objective evaluation of clothing fit can be conducted based on the specific criteria concerning the exterior appearance, proportionality, pattern, style, textile material, etc. in both real and virtual environments. To make a fit-assured clothing, the fit criteria should be established first and be applied the whole process from BM measuring to the final production.

1.5. CAD for clothing design

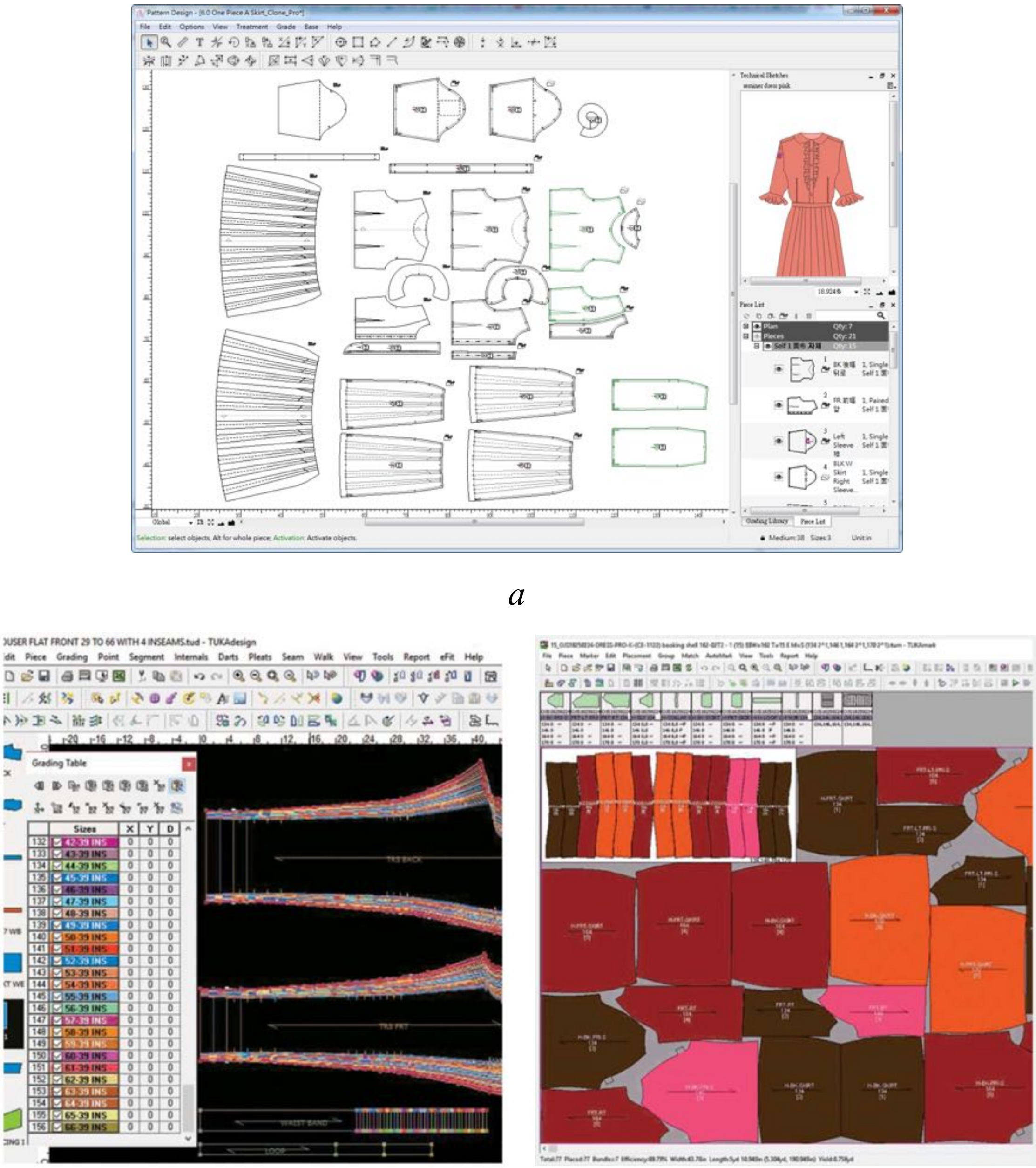
CAD is the use of computers to aid in the creation, modification, analysis, or optimization of a design. CAD software is used to increase the productivity of the designer, improve the quality of design, improve communications through documentation, and to create a database for manufacturing[132].

The traditional 2D CAD for clothing design which has been developed since 1970s is used to design and deploy the electronic flat pattern. The current 3D CAD composed by 3D virtual avatar, 3D fashion design, 3D pattern drafting, 3D sewing and 3D virtual try-on, etc. has been risen for decades. Compared to the manual design and 2D CAD, 3D CAD software move the whole physical design into electronic virtual environment with much higher productivity and unlimited possibilities.

1.5.1.2D CAD

The derivation of CAD can be traced to 1969 when it was first utilized in the machinery field with the popularization of PC (personal computer). In the 1970s, Ron Martell et. al developed the first 2D CAD system Camsco which specialized in clothing construction, and Levi Strauss & Co. was the first customer. As the expand of 2D CAD in clothing industry, many companies have participated in developing the new and feasible functions for actual production [133].

The popular existing 2D CAD software includes AccuMark (Geber Technology LLC, USA), CAD.Assyst (Assyst GmbH, Germany), ET SYSTEM (BUYI Technology, China), GRAFIS CAD Clothing (GRAFIS, Germany), Modaris (Lectra, France), PAD System (Pad System International Limited, Canada), Richpeace (RICHPEACE AI CO. China), TUKAcad (Tukatech, USA), etc. [134 - 141]. As shown in Fig. 1.31, three main modules are usually included in these software: pattern construction, grading and marker making.



a

b *c*

Figure 1.31 - Three modules in 2D CAD software:
a - pattern construction (PAD System), *b* - pattern grading (TUKACAD),
c - marker making (TUKACAD)[139, 141]

As shown in Fig. 1.31, the pattern drafting module enable the comprehensive construction of the flat pattern with diverse tools (e.g., point, curve, dart, seam). The grading module can automatically grade the pieces to the user's predefined sizes. The marker making module enable manual or automatic marker making of the pattern pieces for the subsequent cutting process. The outcomes from three modules can be exported to the corresponding machines for actual production.The 2D CAD has changed the obsolete way of clothing production by moving the manual work in to the electronic platform with higher productivity and efficiency in mass production.

1.5.2.3D CAD

With the overwhelming deployment of 4.0 industry, every industry or field have spared no effort to develop the hardware or software featuring at the prospective intelligent and automatic production. One of the most essential requirements is to build the DT that can simulate the actual physical counterpart (e.g., products, production process) enhanced by the technologies of VR, software analytics, etc. [142]. The contemporary VR-based 3D CAD for clothing design has been risen in response to this proper times and conditions.

Some 2D CAD have evolved into the new 3D CAD: AccuMark 3D (Geber Technology LLC, USA), ASSOL (Russia), CLO 3D and Marvelous Designer (CLO Virtual Fashion Inc., Korea), Modaris 3D Fit (Lectra, France), PDS (Optitex, USA), Vstitcher (Browzwear Solutions Pte Ltd., Singapore), 3D Vidya (Assyst GmbH, Germany), TUKA 3D (Tukatech Inc., USA) etc. [134,135, 137, 138, 141, 143 - 147]. These software are featured at realizing the 3D virtual avatar, 3D fashion design, 3D pattern drafting, 3D sewing and 3D virtual try-on, etc. and composed by the similar modules:

a. 2D patter drafting and grading module as the traditional 2D CAD for flat pattern construction;

b. 3D virtual avatar module that can generate the default built-in avatars and the individualized avatar adapted to the personal BM;

c. 3D fabric module including editable virtual materials of different digital properties, which will exhibit the various draping effects;

d. 3D sewing module that can sew the flat pieces into the 3D shape with editable crafting works (e.g., interlining, pleat, zip, button);

e. 3D real-time virtual simulation module that can objectively and subjectively evaluate the 3D try-on effects of a clothing on a certain avatar;

f. other modules such as modular design library, picture and video rendering, 3D runway, etc.

Fig. 1.32 shows the main user interface of software CLO 3D including libraries (e.g., fabric, avatar), 3D sewing and simulation module, 2D pattern drafting and grading module, etc.

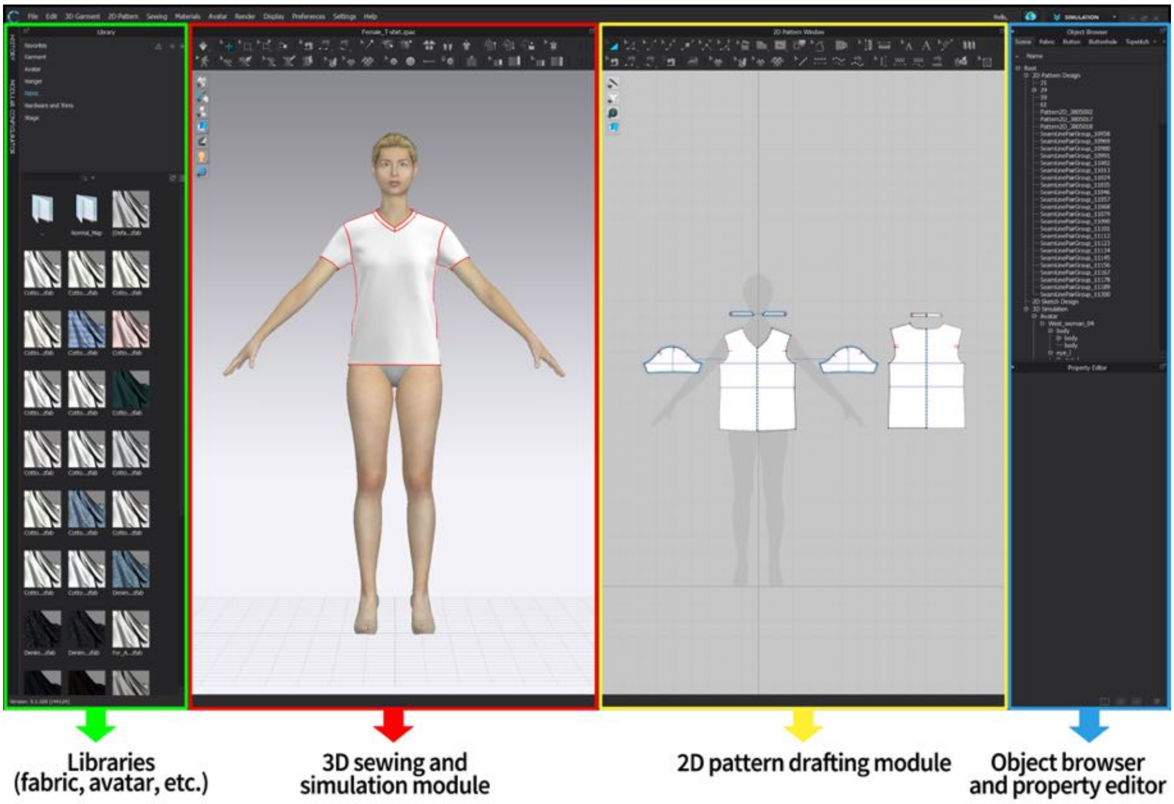


Figure 1.32 - User interface of CLO 3D

Based on the integral system of the existing modules, the virtual clothing and its fit evaluation can be accomplished following the common process shown in Fig. 1.32.

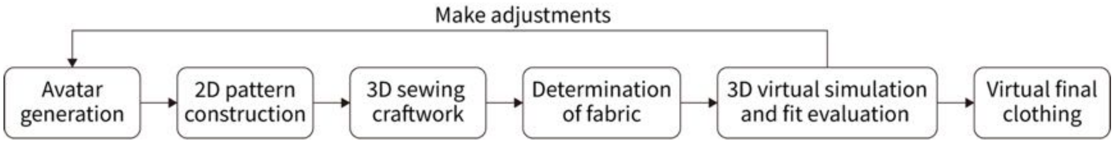


Figure 1.33 - Process of virtual clothing making and fit evaluation

Fist, the default avatar or the individualized one should be selected or generated. The avatar is the VT, the morphed virtual human body that is applied BM acquired through manual or automatic measurements. It usually has the exterior morphology and interior virtual bones and joints as the real human [91]. In CLO 3D, the avatars can be generated in four ways:

1. the default avatars with typical morphology of different genders and ethnics (Fig. 1.34, *a*) can be directly selected from the library;

2. the parametric avatar (Fig. 1.34, *b*) can be generated by inputting basic BM (e.g., heights, girths, widths) measured from a real body. However, because of the BM can only reflect the limited aspects of morphology, this avatar is usually different with the real body;

3. the VT with inserted skeletons and joints (Fig. 1.34, *c*) converted from the virtual clone can be imported in CLO 3D. It has the same morphology as real body and the posture is adjustable;

4. the individualized avatar (Fig. 1.34, *d*) can be generated automatically by inputting the virtual clone. It has the similar morphology as the real body.

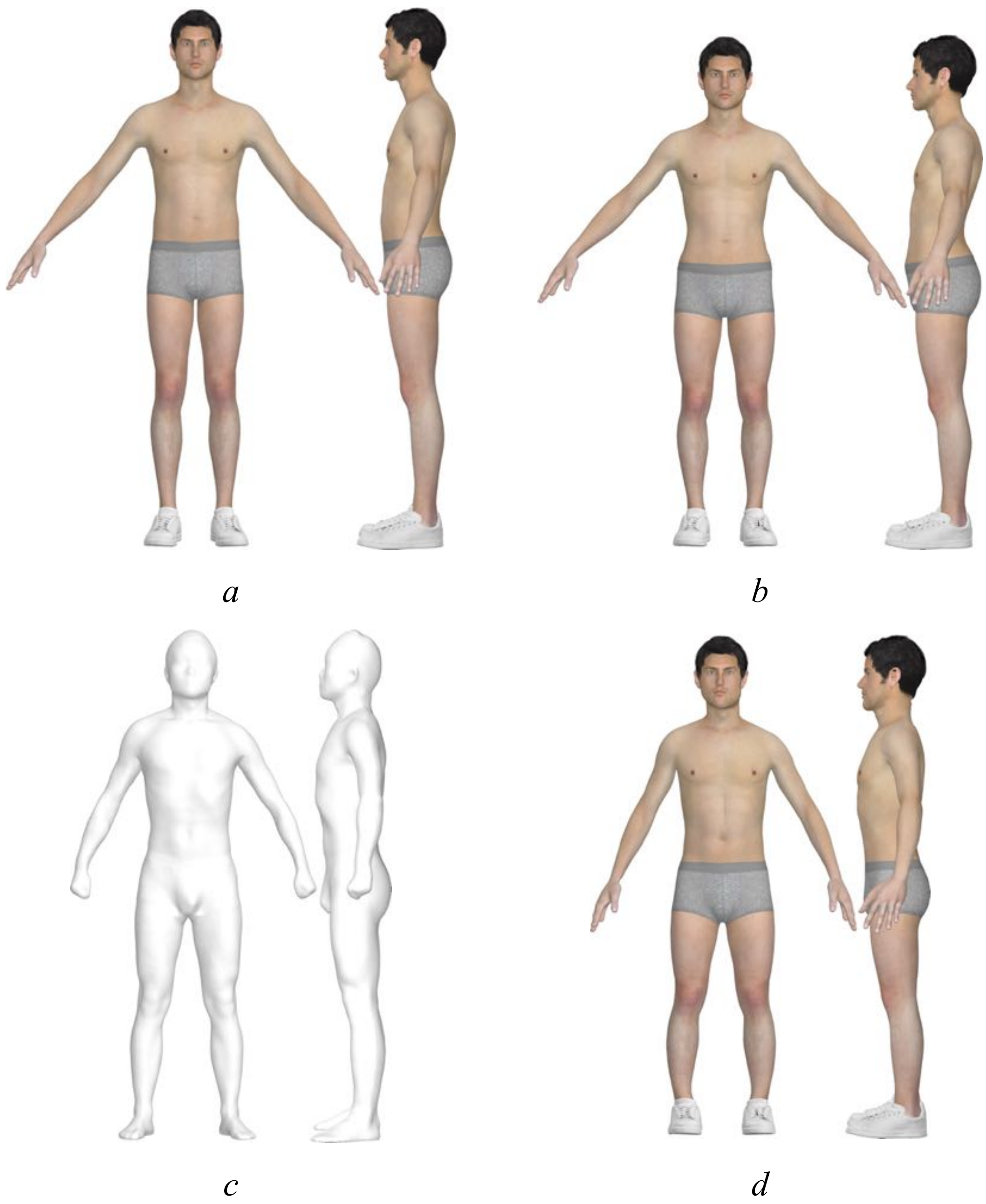


Figure 1.34 - Generation of avatar in CLO 3D:
a - default avatar in the library, *b* - parametric avatar adapted to thepersonal BM, *c* - DT converted from the VC,
d - individualized avatar generated from VC

In consideration of the requirements, different avatar should be adopted. The default and parametric avatar is adequate for RtW clothing, but the DT and individualized avatar is required for customized clothing.

Second, the 2D pattern should be drafted in the 2D pattern drafting module as the operations in 2D CAD.

Third, the 3D sewing craftwork should be arranged. Above all, the 3D pieces should be well positioned around the corresponding body segments, and the seams between adjacent pieces should be defined. Additionally, the detailed craftworks (e.g., button and button hole, lining) should be edited according to personal design.

Forth, the virtual fabrics of each pieces should be selected or generated in three ways:

1. 65 kinds of built-in fabrics with different texture and properties can be selected from the fabric library. Fig. 1.35, *a* shows the cotton canvas in fabric library;

2. the virtual fabrics can be generated by CLO fabric emulator and CLO Fabric Kit (Fig. 1.35, *b*). CLO fabric emulator is the software module that can generate the virtual fabric by inputting the test data which is from the simple tests with CLO Fabric Kit instruments [148];

3. the virtual fabrics can be generated from properties of real fabrics through special algorithms [149].

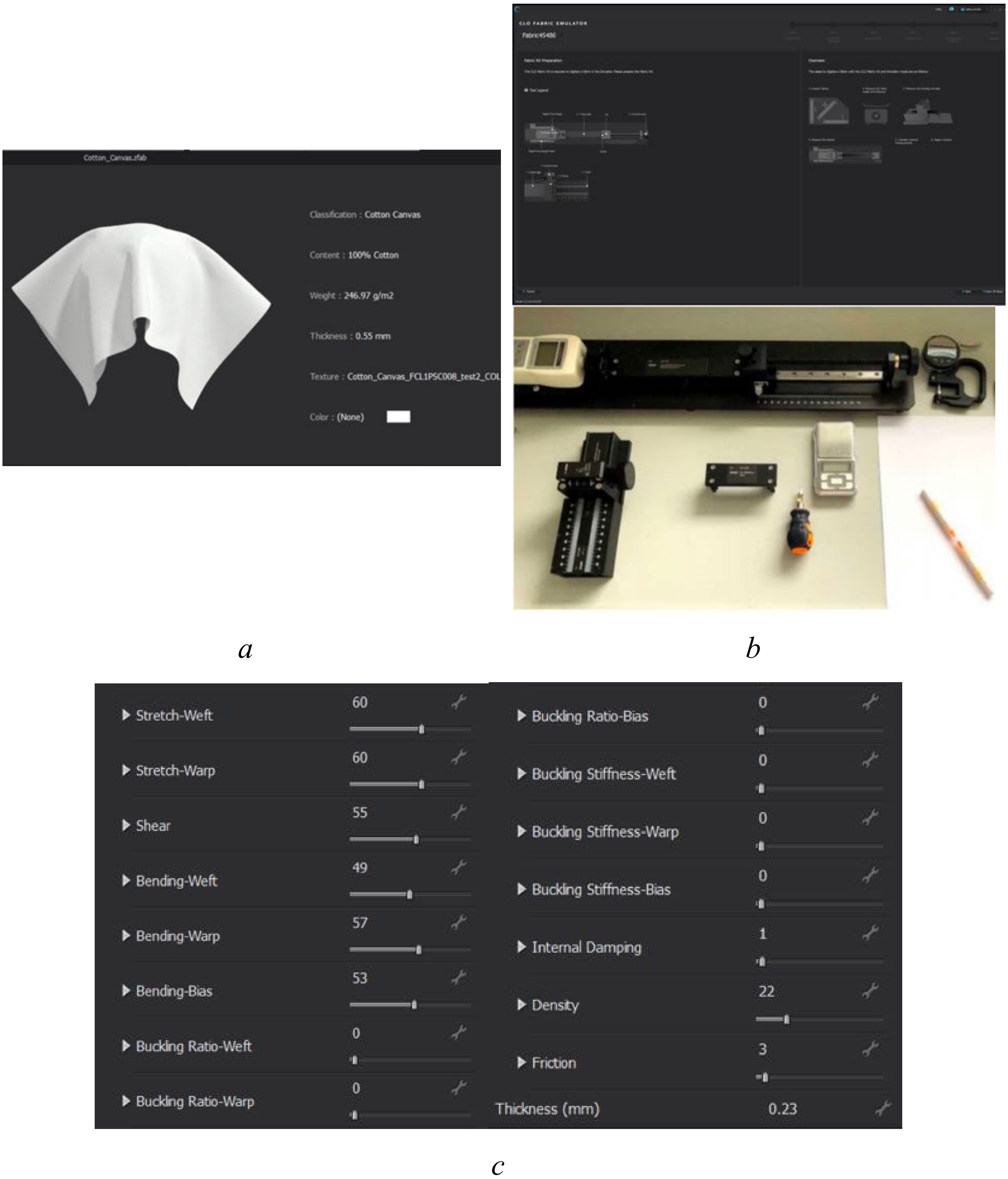


Figure 1.35 - Module of virtual fabric in CLO 3D:
a - a default fabric (cotton canvas) in the library, *b* - CLO fabric emulator andthe instruments of CLO Fabric Kit [148], *c* - list of digital properties

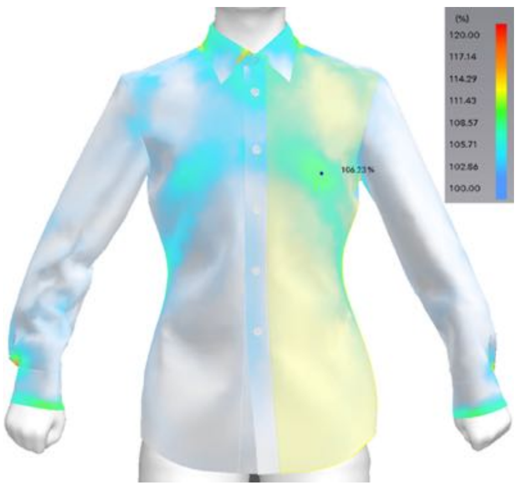
Fifth, the virtual try-on simulation and fit evaluation should be conducted with the 3D virtual simulation module. The try-on simulation can be achieved instantly after the determination of avatar, pattern block, craftworks and fabric. The virtual clothing fit can be evaluated subjectively and objectively.

For one thing, the exterior appearance of the try-on model from unlimited views can be visualize after sewing (Fig. 1.36, *a*). The air gap between clothing and avatar can also visualized in the transparency mode (Fig. 1.36, *b*).

For another, the numerical fit indicators can be measured at any point on the clothing surface with visualization of its distribution. Appearing in the range of color, the strain map (Fig. 1.36, *c*) indicates the clothing's distortion rate due to external stress appears in percentage. Moreover, the 3D model of the "clothing – avatar" system can be exported to 3D modeling software (e.g., Rhinoceros) for further evaluation with explicit processing such as dimension measuring, cross-section generating, etc.

a

b



c

Figure 1.36 - Virtual evaluation of clothing fit in CLO 3D:
a - exterior appearance of a clothing, *b* - transparent mode of a clothing,
c - measuring of distortion rate and the strain map

The adjustment can be made by iterate the circulation from first to fifth steps and the final clothing can be determined when the clothing fit and design are satisfactory. With the above virtual clothing making and fit evaluation, the difficult investigations in real environment are accessible now in virtual environment.

Liu et al. validated the fit of pants pattern block with pattern-oriented BM generated by ANN prediction model in virtual environment. Moreover, they simulated the human activities and measured the numerical clothing pressure in 3D CAD [129]. Similarly, the stress-contact point map and the transparent clothing were employed for comparing the fit and appearance of classic-fit and slim-fit shirts in the study of Kim et al [150]. Kuzmichev et al. applied the 3D CAD to reconstruct the historical pattern block and obtained the virtual appearance in accordance with the prototypes [151, 152]. The new 3D – to – 2D flattening technique (see Fig. 1.5, *a*; Fig. 1.15) has been also risen for designing the special clothing (e.g., compression clothing, simple-styled clothing, clothing for the disabled) [97, 98].

In conclusion, the contemporary 3D CAD for clothing design provides much higher productivity and more possibilities owing to the versatile modules than the traditional 2D CAD. In the 3D CAD software, the realistic try-on effect with subjective and objective evaluation of fit can be exhibited instantly instead of real sample trials after simple arrangement of pattern, fabric and sewing.

1.6. Main aim and steps of research

In consideration of the contemporary research status, the existing real and virtual customized clothing still need to be improved owing to the synergetic deficiencies in the existing body measurements unable to comprehensively characterize the main human body morphology, the pattern construction unable to assure the fit state-of-the-final clothing and the few investigations in virtual shirt customization with concrete criteria of fit evaluation.

The aim of this research is to develop the e-bespoke technology for custom design of men's shirt in a virtual environment.

To achieve this aim, the necessary steps should be conducted following the framework of this research (Fig. 1.37):

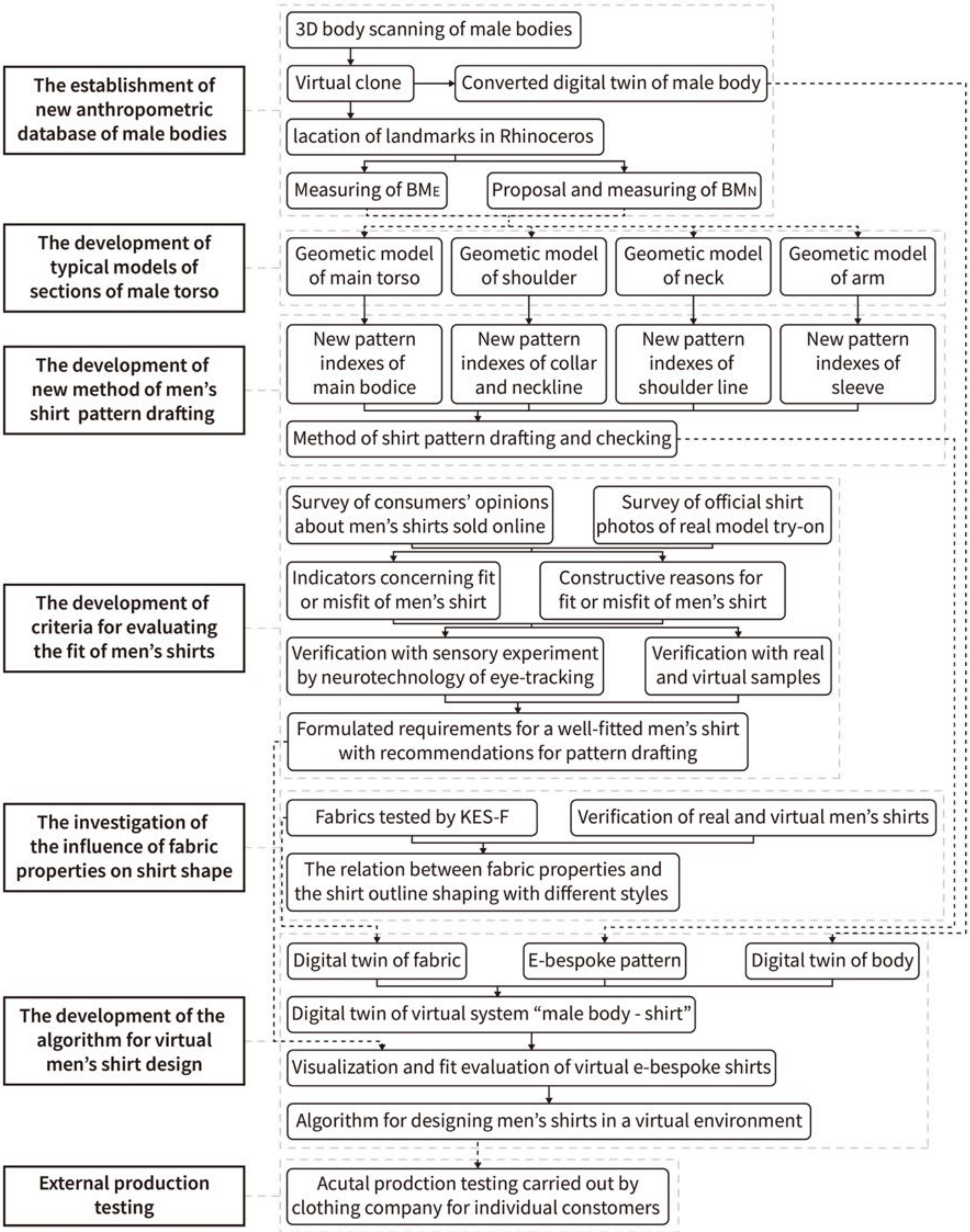


Figure 1.37 - Framework of development of real and virtual e-bespoke men's shirt

1. The new anthropometric database which can characterize the male body morphology with sufficient BM_N should be established.The adequate amount of young mal respondents should be first enrolled for the 3D body scanning and their VC will be saved. The VC will be transformed to the boned DT (see Fig. 1.15) for one thing, and will be marked with nine fundamental landmarks (see Fig. 1.8) in Rhinoceros for another. The BM_E (see Fig. 1.9) will be measured, and the complementary BM_N for representing the different body sections will be proposed and measured.

2. The geometric models of different body sections should be developed.With BM_E and BM_N, the typical geometric models of main torso, neck, shoulder and arm sections for coordinating their morphological features with the deployment of the planes responsible for the clothing fit.

3. The new method of men's shirt pattern drafting and checking should be developed.The new pattern indexes of different clothing segments (bodice, collar and neckline, shoulder line and sleeve) which corresponds to the body sections should be calculated by from the BM and ease allowances. An algorithm for adjusting the shirt pattern to individual body morphology will be developed.

4. The criteria for evaluating the fit of men's shirts should be established.Through the surveys of consumers' opinions and real shirt try-on photos from the internet clothing shops, the indicators concerning fit or misfit and the possible constructive reasons should be identified. The significance of each fit indicator will be verified with sensory experiments by using the neurotechnology of eye-tracking with experts. Moreover, the constructive reasons of misfit will be verified by real and virtual samples. Thus, the requirements for a well-fitted men's shirt will be formulated and the recommendations for constructing pattern will be defined.

5. The influence of fabric properties on shirt shape should be clarified.The fabrics for shirt making will be tested by KES-F system, and the real samples in four different styles (see Fig. 1.18) will be sewed with the fabrics.

The relation between fabric properties and the shirt outline shaping with different styles will be clarified.

6. The digital twin of virtual system “male body - shirt” should be developed.By integrating the results from previous steps of experiments, the digital twin of virtual system “male body - shirt” will be created by simultaneously developing the digital twin of fabric, the pattern of e-bespoke shirt and the digital twin of body in virtual environment. The algorithms for designing men’s shirts in a virtual environment will be developed.

7. The external production testing will be conducted.The results of this research will be tested in the external clothing company by producing the satisfactory well-fitted customized men’s shirt for individual consumers.

CHAPTER 2. ANTHROPOMETRIC DATABASEOF MALE TORSO

The previous literature investigated the variances of male body morphology and the BM_E for characterizing it. However, the existing knowledge about body variances failed to include some essential morphological features which cannot be reflected by the BM_E.

Achieving the good clothing fit requires first comprehensively understand the essential morphology and then discover the BM_N responsible for constructing a men's shirt. This chapter established the anthropometric database of male torso with essential morphology and BM_N by using 3D body scanner and the other software.

The results obtained in this chapter are published in three work [160 - 162].

2.1. Methods of research

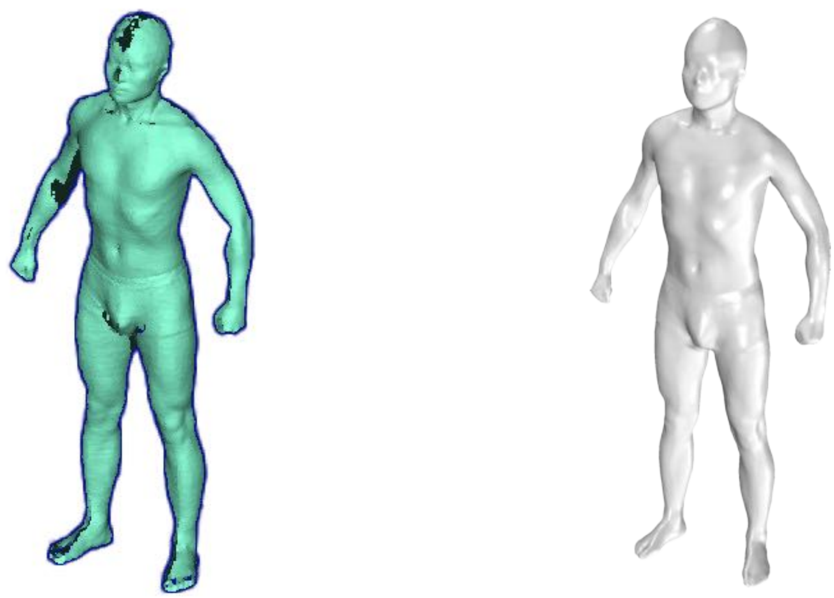
2.1.1. Instruments and software

To obtain and analyze the anthropometric data, the scanning process was conducted by VITUS Smart XXL non-contact 3D body scanner (Human solutions GmbH, Germany) at Ivanovo State Polytechnic University and Wuhan Textile University.

The scanner-compatible software Anthroscan (Human solutions GmbH, Germany) was utilized for manipulating the scanning process and to generate the VC. The online platform Mixamo (Adobe, USA) [153] was used to generate the boned DT which were applicable in subsequent virtual simulation. The VC were visualized and measured by versatile 3D computer graphic and CAD software Rhinoceros (Robert McNeel & Associates, USA). For statistical analysis, SPSS (IBM, USA) software was used.

2.1.2.Acquisition of virtual clones of male bodies

In accordance with ISO 20685-1:2018(E) [154], the respondents were required to wear only lower underwear in standard standing position: head in Frankfurt plane, parallel feet with 200 mm apart, upper arms forming a 20° angle with the side of torso, straight elbows, etc.. Each respondent was scanned for several times until the raw scan mesh model (Fig. 2.1, *a*) was applicable for subsequent measuring and try-on process.



a *b*

Figure 2.1 - Acquisition of VC of male body:
a - raw scan mesh model, *b* - the reconstructed VC

Due to the limitation of 3D body scanner, some minor areas (e.g., head top, crotch, axilla, sole) of the mesh surface were empty. The lacking mesh surfaces were patchedby “Reconstructed Surface” and “Refine TMecsh Adaptively” commands in Anthroscan. The reconstructed body model with complete smooth surface and realistic morphology was exported as the VC (Fig. 2.1, *b*) in .obj format, which was operable in Rhinoceros and the other software.

2.1.3. Method of obtaining body measurements in Rhinoceros

To measure BM_N, nine fundamental landmarks (SP, APF, APB, AP, FNP, SNP, BNP, EP, WP) and three levels (chest, waist, hip) in the torso area were first labeled according to ISO 8559-1:2017(E) (see Fig.1.9)[72]. Based on the landmarks, four groups of BM, namely heights, girths, surface lengths and straight distances, were obtained in Rhinoceros by three methods:

a. perpendicular-based: measuring from the landmarks to the ground, another landmark or a reference plane by "Line" tool. The first included the vertical height BM (e.g., H_W, see Fig. 2.9), the second included the distance between bilateral points (e.g., SL), the third included the horizontal distance (e.g., D_{BNP}, see Fig. 2.9), respectively. Fig. 2.2, *a* shows the BM measured by perpendicular-based method;

b. slice-based: measuring from the cross-sections which were generated by intersecting the mesh surface of DC with transverse and sagittal planes on different levels by "Mesh intersect" tool. The girths (e.g., WG_F, WG_B) and surface lengths (e.g., SNW_F, SNW_B) were measured by slice-based method as shown in Fig. 2.2, *b*;

c. outline-based: measuring from the outlines directly drawn on the mesh surface ofline on mesh" tool. For an exception, neck line and NG cannot be obtained by slice-based method because FNP, SNP and BNP were not coplanar, but should be obtained with drawing outlines by outline-based method as shown in Fig. 2.2, *c*.

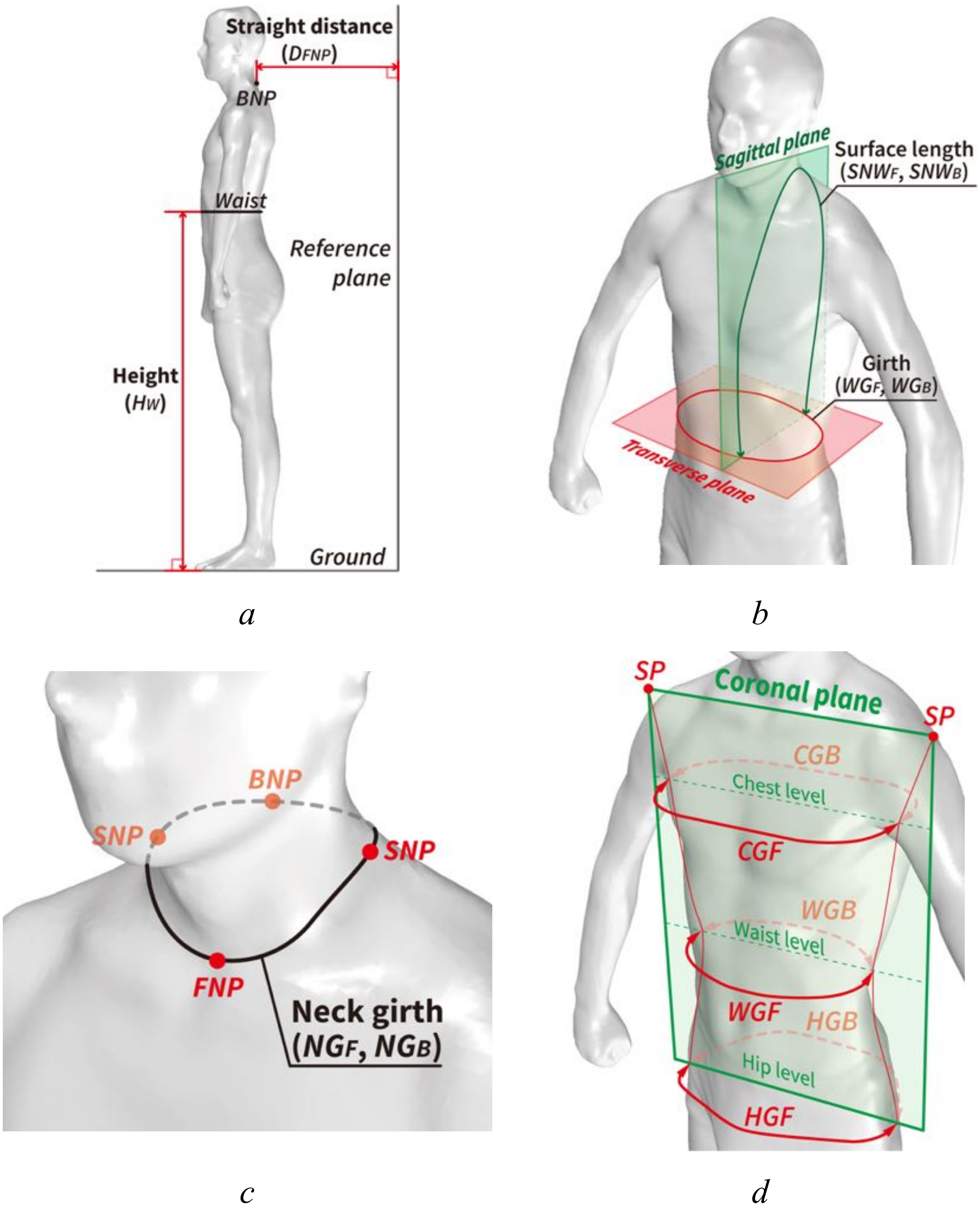


Figure 2.2 - Methods of obtaining BM in Rhinoceros:
a - perpendicular-based, *b* - slice-based,
c - outline-based, *d* - divisional coronal plane

Moreover, the divisional coronal plane divided the torso girths (chest, waist, hip) into front and back parts according to Fig. 2.2, *d*. This plane was made by connecting left and right SP and extending in the vertical direction with the ‘‘Rectangular plane: 3 points’’ tool. Hereby the girths were segmented into front and back parts by the divisional plane with the ‘‘Split’’ tool.

2.1.4. Statistic validation of the body measurements

In this research, a total of 156 young men subjects among whom 94 were from center China and 62 from west Russia aged from 18 to 30 year's old without morphological malformation (e.g., deformity in bone, joint and muscle) and physical disability were voluntarily enrolled. According to the Chinese standard [64], they were classified into three groups: 95 men of Y-type (drop bigger than 17 cm), 55 men of A-type (drop from 12 to 16 cm) and 6 men of B-type (drop from 7 to 11 cm).

For the sake of the validity of the subsequent experiments, the lease sample size was calculated as Equation (2.1) [155].

$$n = \frac{Z^2 + SD^2}{d^2}, \tag{2.1}$$

where: n is the estimated sample size, Z is the standard normal variate (in this study Z = 1.96 for 95% confidence interval), SD is the standard deviation of the variable, d is the margin of error (d was set as 5% of the mean value of the variable, which was adequate for the industrial production).

The BM which were used in the subsequent experiments were input as the variable to estimate the sample sizes for three types of bodies. The BM of three types of bodies were shown as Table B.A – B.F in Appendix B. Table 2.1 shows the sample sizes calculated by the BM (see Section 2.3) in this research.

Table 2.1 - Sample size of three types of bodies calculated by BM in this research

BM	Body type								
	Y			A			B		
	SD, cm	d, cm	n	SD, cm	d, cm	n	SD, cm	d, cm	n
H_C	7.65	6.56	6	6.24	6.36	4	8.16	6.44	7
H_W	6.69	5.59	6	5.22	5.39	4	6.16	5.48	5
H_H	6.22	4.50	8	5.09	4.34	6	5.74	4.45	7
SNW_F	2.62	2.30	6	1.97	2.23	4	2.74	2.25	6
SNW_B	2.65	2.24	6	1.99	2.19	4	2.79	2.22	7
AW_F	3.80	2.10	13	3.31	2.04	11	2.61	1.98	7
AW_B	3.28	1.96	11	3.05	1.86	11	2.06	1.87	5
CG_F	5.54	2.52	18	4.69	2.41	15	6.58	2.36	30
CG_B	4.77	2.45	15	4.77	2.31	17	1.43	2.33	2
WG_F	5.97	2.21	28	4.90	2.21	19	6.64	2.27	**33**
WG_B	5.48	1.63	**44**	6.20	1.68	**53**	3.55	1.79	16
HG_F	4.97	2.54	15	4.81	2.51	15	5.71	2.49	21
HG_B	5.10	2.25	20	6.01	2.24	28	5.03	2.30	19
H_{BNP}	8.22	7.63	5	6.30	7.39	3	7.94	7.50	5
NW	0.81	0.64	7	0.90	0.63	8	0.85	0.67	7
H_{FNP}	7.70	7.29	5	5.77	7.06	3	8.08	7.15	5
H_{SNP}	8.27	7.61	5	6.36	7.37	3	8.10	7.47	5
D_{FNP}	2.26	1.95	6	2.12	1.96	5	1.51	2.00	3
D_{SNP}	1.97	1.58	6	1.88	1.59	6	1.71	1.61	5
D_{BNP}	2.12	1.44	9	1.98	1.44	8	2.13	1.47	9
NG_F	3.39	1.36	24	2.07	1.34	10	2.34	1.39	11
NG_B	1.85	0.75	24	1.32	0.73	13	1.30	0.75	12
SL	1.13	0.72	10	1.04	0.69	9	0.40	0.67	2
SSN_F	1.45	1.07	8	1.19	1.03	6	0.93	1.03	4
SSN_B	1.34	1.07	7	1.26	1.02	6	0.79	1.02	3
UAG	3.73	1.53	23	3.04	1.46	17	3.29	1.49	19
AL	4.43	3.07	9	2.95	2.93	4	3.04	2.96	5
WRG	1.40	0.84	11	1.10	0.81	8	1.71	0.82	17

As shown in Table 2.1, the estimated least sample sizes are 44 for Y-type, 53 for A-type and 33 for B-type. Therefore, the 95 Y-type bodies and 55 A-type bodies which were selected before as the subjects were sufficient for the subsequent experiments. While B-type bodies were excluded due to the small size.

The further elementary measurements of the 150 subjects are shown in Table 2.2.

Table 2.2 - Elementary measurements of the subjects

Measurement	Height, cm	Weight, kg	BMI, kg/m^2	CG, cm	WG, cm	HG, cm
Interval	156.1 … 197.7	48.0 … 49.3	17.3 … 27.8	76.4 … 123.9	61.88 … 99.8	80.4 … 114.9
Mean	177.0	71.9	22.9	97.5	77.3	95.5
SD	8.2	8.1	2.0	7.9	7.2	5.7

As shown in Table 2.2, the measurements of the subjects distinctly varied in multiple dimensions. Most subjects were of normal stature ($18.5 < BMI < 25$ kg/m^2), and a few were skinny ($BMI < 18.5$ kg/m^2) or slightly obese ($25 < BMI < 30$ kg/m^2).

2.2. Morphological features of male torso

As discussed in Section 1.2.1, The variance of the morphological features of a section (e.g., shoulder) were usually classified into several groups (e.g., normal, slope, square). However, some of the male bodies belonged to none of these groups, and there was no BM for distinguish them and no method of adapting pattern. To resolve this dilemma, one principal method is to discover the BM_N which can universally characterize the morphological features for one thing, and be applicable in pattern construction for another. This section discusses the morphological features of male torso from the 150 respondents, enlightening the proposal pf the BM_N.

2.2.1. Proportions of anteroposterior main torso

The main torso is often recognized by the full girths (e.g., CG, WG, HG) and the other BM, which neglects many essential morphological features. Although some variances of torso morphology were proposed to emphasize the difference between the front and back parts of a specific segment (see Section 1.2.1), they still failed to characterize the integral torso morphology and the measurable BM were absentfor adapt the pattern to individual body. The untypical morphological features of torso usually exist on the different levels. To understand these features, a possible way is to recognize the anteroposterior proportions of these levels.

The proportions can be recognized in two directions. In horizontal direction, there are three significant levels concerning the morphological levels: chest level concerning the front chest and back scapula, waist level concerning the front and back waist, and hip level concerning the front belly and back hip (Fig.2.3). Because the front and back patterns are usually separated from SP to armhole line and side-seam line, SP were chosen as the divisional points to divide the front and back segments, and the divisional coronal plane was made from left and right SP (Fig.2.2, *d*). Therefore, the full girths at the three levels were divided to three front girths (CG_F, WG_F, HG_F, see Section 2.3) and three back girths (CG_B, WG_B, HG_B, see Section 2.3).

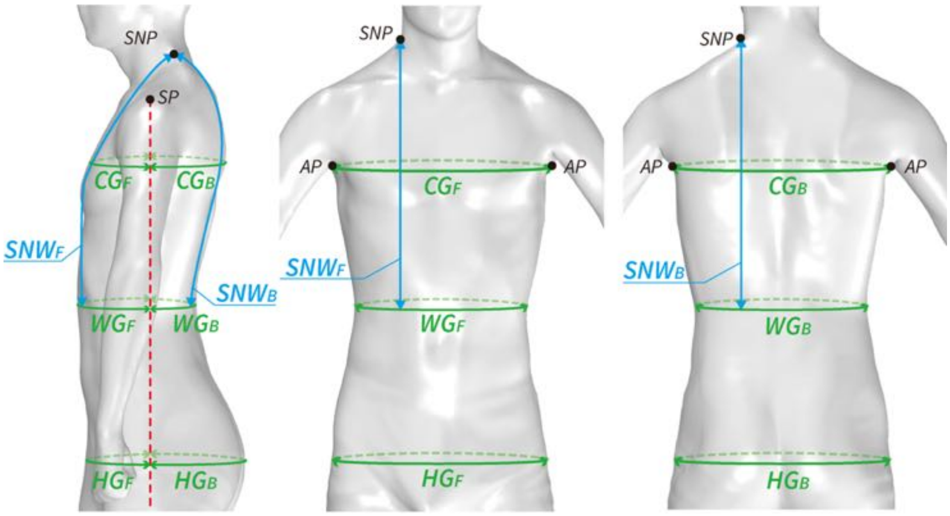


Figure 2.3 - Horizontal and vertical proportions of main torso reflected by front and back girths and surface lengths

In vertical direction, the front and back surface lengths (SNW_F, SNW_B, see Section 2.3) can also reflect the anteroposterior proportion (Fig. 2.3). SNP was chosen as the divisional point because it connected the front and back torso segment for one thing. For another, SNP was also the essential intersection of neck segment and shoulder area, which would help integrating the constructional lines of main bodice, neck and collar, and shoulder during the subsequent pattern drafting. Therefore, the horizontal and vertical proportions were reflected by front and back girths and surface lengths, respectively.

Fig. 2.4 and Table 2.3 shows the example of three VC of 170/92Y type with different proportions of torso segment.

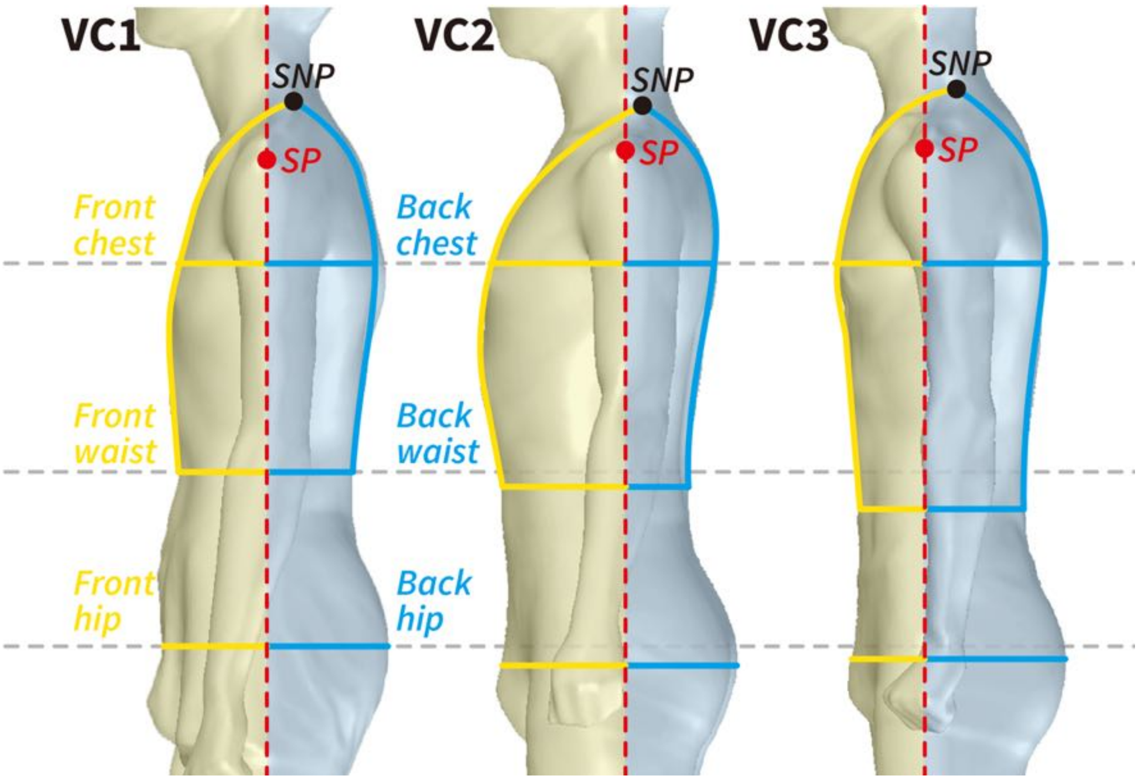


Figure 2.4 - Three VC of 170/92Y types with different proportions of torso segment

Table 2.3 - BM and proportions of torso segments of three VC

VC No.	BM, cm				anteroposterior proportion of			
	CG	WG	HG	$SNW_F + SNW_B$	CG_F/CG_B	WG_F/WG_B	HG_F/HG_B	SNW_F/SNW_B
1	91.9	72.0	93.9	84.7	0.454/0.546	0.497/0.503	0.496/0.504	0.498/0.502
2	92.9	71.6	92.0	84.4	0.553/0.447	0.612/0.388	0.542/0.458	0.514/0.486
3	91.8	70.4	89.1	86.2	0.426/0.574	0.438/0.562	0.434/0.566	0.499/0.501

As shown, CG and WG of three VG were approximate, HG and integral surface lengths (SNW_F+ SNW_B) differed a few. However, the proportions of each level were greatly different. VC1 possessed the relatively more typical morphology with four anteroposterior proportions closed to half-and-half. VC2 was featured as the very bulging chest and other front segments with considerably large front proportions in both horizontal and vertical directions. VC3 was featured as the huge back segment with largest back proportions of three horizontal levels. These proportions which have not been discovered undoubtedly were important for describing the body morphology and obtaining the balanced clothing with good fit state. Moreover, the depths between two adjacent levels (namely chest and waist levels, waist and hip levels) were different for each body, which should also be considered.

2.2.2.Spatialshape of neckline

The size of neckline is conventionally recognized by the single BM NG for both RtW and customized productions. However, the neckline is a complex spatial curve that varies in widths, anteroposterior proportions, etc. due to the diversity of neck spatial shapes. The spatial shape of neckline was determined by three primary aspects (Fig.2.5):

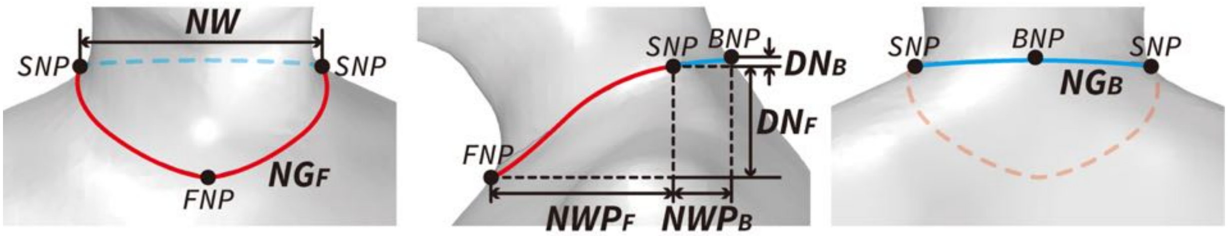


Figure 2.5 - New morphological features of neckline spatial shape

1.diameter or width (NW). In the front view, the widths of neck base by connecting both SNP are narrow, normal or wide for different bodies;

2. profile width, depth (height) and their proportions. In the profile view, the horizontal width and height of neck base from FNP to BNP depends on each body. Moreover, with SNP as the divisional point, the anteroposterior proportions of the profile widths (NWP_F, NWP_B) and depths (DN_F, DN_B) are various for different bodies;

3. NG and its proportion. NG depicts the overall size of the neck base. And its anteroposterior proportions should be depicted by NGF and NGB with SNP as the divisional point.

In consideration of the integral effects of the three aspects, the diverse spatial neck shapes were recognized. Fig. 2.6 and Table 2.4 shows three example necklines extracted from the VC who have the similar NG.

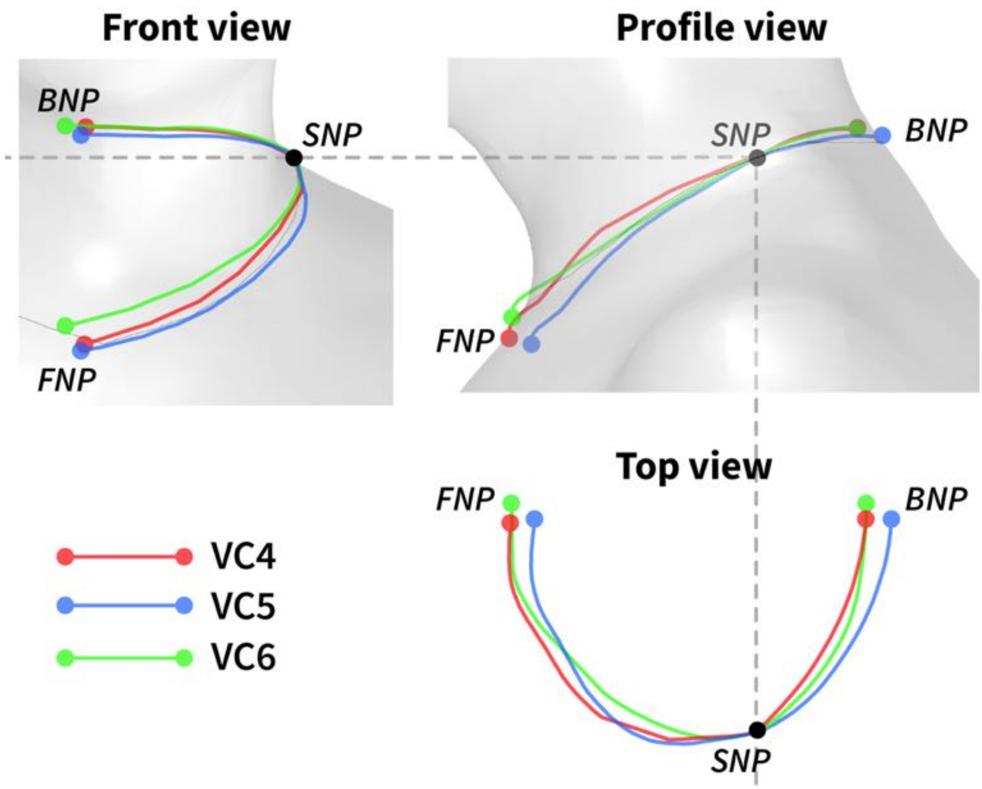


Figure 2.6 - Front, profile and top views of the half necklines extracted from three VC

Table 2.4 - BM of neck segments of three VC, cm

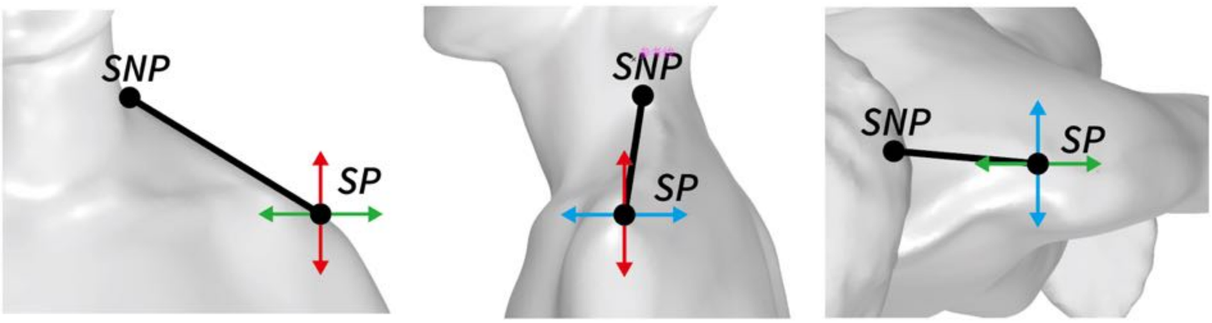
VC No.	NG	NG_F	NG_B	NW	NWP_F	NWP_B	DN_F	DN_B
4	39.1	24.6	14.5	12.1	7.2	3.0	5.3	0.8
5	39.1	24.3	14.8	12.2	6.4	3.7	5.4	0.6
6	39.2	23.2	16.0	13.2	7.0	3.0	4.7	0.9

Fig. 2.6 and Table 2.4 shows three necklines and their BM form VC4, VC5 and VC6 with their SNP intersected together. Although their NG were highly approximate, the morphology of each neckline differed a lot. The neckline of VC4 possessed the largest NG_F and smallest NG_B with narrowest front width and longest NWP_F. The neckline of VC5 was featured as the deepest FNP, flattest BNP, and shortest NWP_F. And the neckline of VC6 possessed the

largest NG_B and smallest NG_F with widest front width and flattest FNP. Due to the differences of these morphological features, the spatial neckline shapes of different VC were totally different, which would be useful for the constructing the neckline and collar patterns.

2.2.3. Spatial location of shoulder line

In clothing design, the shape of shoulder line can be simplified as a straight line pointed from SNP to SP. To reflect the location of this line on a pattern, SW and the shoulder sloping angle are conventionally utilized. However, these two BM are inadequate depict the location of a shoulder line in a 3D space. The spatial location of a shoulder line can be determined in different views as shown in Fig. 2.7.



a *b* *c*

Figure 2.7 - Spatial location of shoulder lines:
a - front view, *b* - profile view, *c* - back view

As shown in Fig. 2.7, the spatial location can be determined by fixing the SNP position and locating the SP position in the 3D space. For different bodies, the SP positions were varied in three dimensional directions (e.g., vertical – red, horizontal – green, coronal – blue), which would affect the length (SL), sloping and thrust direction (forward, normal, backwards) of shoulder line. Fig. 2.8 shows three example shoulder lines extracted from the VC who have the similar SL (14.1 … 14.3 cm).

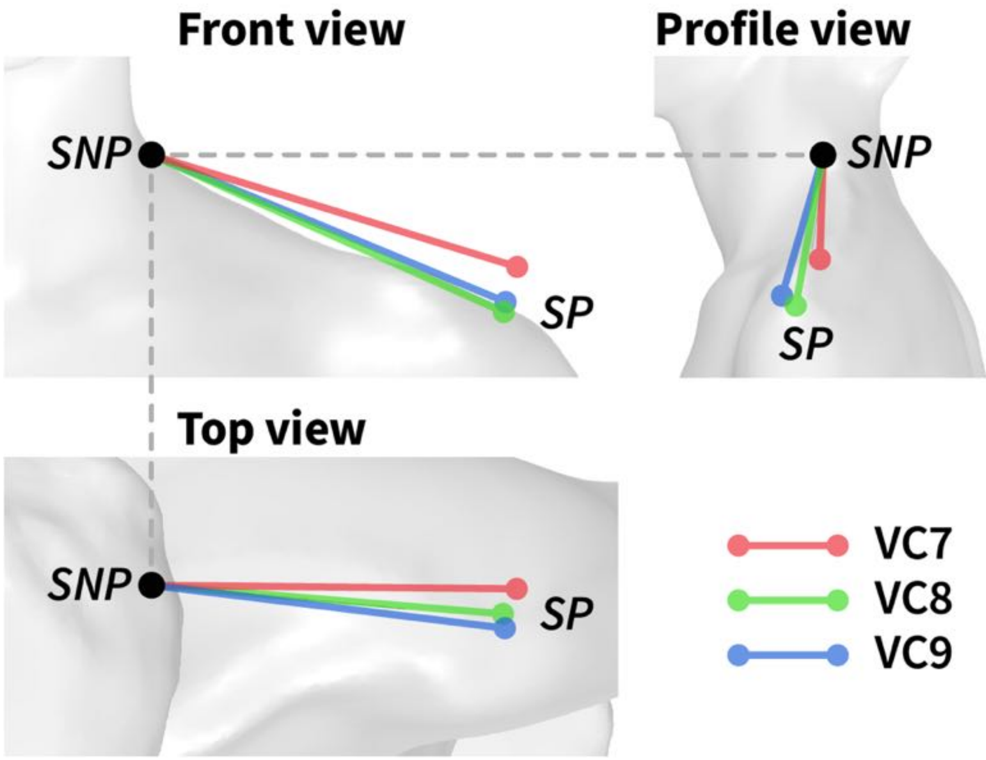


Figure 2.8 - Front, profile and top views of the left shoulder lines extracted from three VC

As shown in Fig. 2.8, three necklines from VC7, VC8, VC9 were compared by intersecting their SNP together. Although their SL were similar, the morphology of each shoulder line was different. From the front and profile view, it was obvious that three shoulder sloping angles were different, the red one was flattest and the green one was most sloped. The thrust directions were also varied: red one was a little backwards, green one was normal and blue one was forward. Due to the differences of these morphological features, the spatial shapes of different VC were totally different, which would be useful for the constructing the shoulder area on pattern.

2.2.4. Morphology of arm

The dissatisfaction about sleeve part of a men's shirt is perceived by the wearer primarily when the cuff size is too big or small, the sleeve length is too long or short and the sleeve is too loose or tight (Section 3.1.2). These misfit correspond to the morphology of arm segment which should be considered in three aspects.

First, the wrist size should be considered by measuring WG. Second, arm length should be considered by measuring AL. Third, the thickness and strongness of the arm should be considered by measuring UAG. Through understanding of these three features of arm and the corresponding BM, the main morphology of an arm segment can be depicted.

2.3. New body measurements

The BM_E often bring about the problem of misfit of clothing as a result of inadequacy of characterizing the diverse body morphological features. To simultaneously comprehensively characterize the body morphology and construct the clothing that can well fit the individual body, the complementary BM_N should be discovered. For this reason, the combined scheme of BM_N and BM_E was proposed, some of which were converted to pattern-oriented BM by specific algorithms.

2.3.1. Raw new body measurements

According to the morphological features discussed in Section 2.2, the systematic scheme of the combination of BMN and BME were proposed for characterizing main torso, neck line, shoulder line and arm at the same time by the four methods of obtaining BM with VC in Rhinoceros (Section 2.1.3). Fig. 2.9 and Table 2.5 shows the scheme and list of BM_N and BM_E in this research.

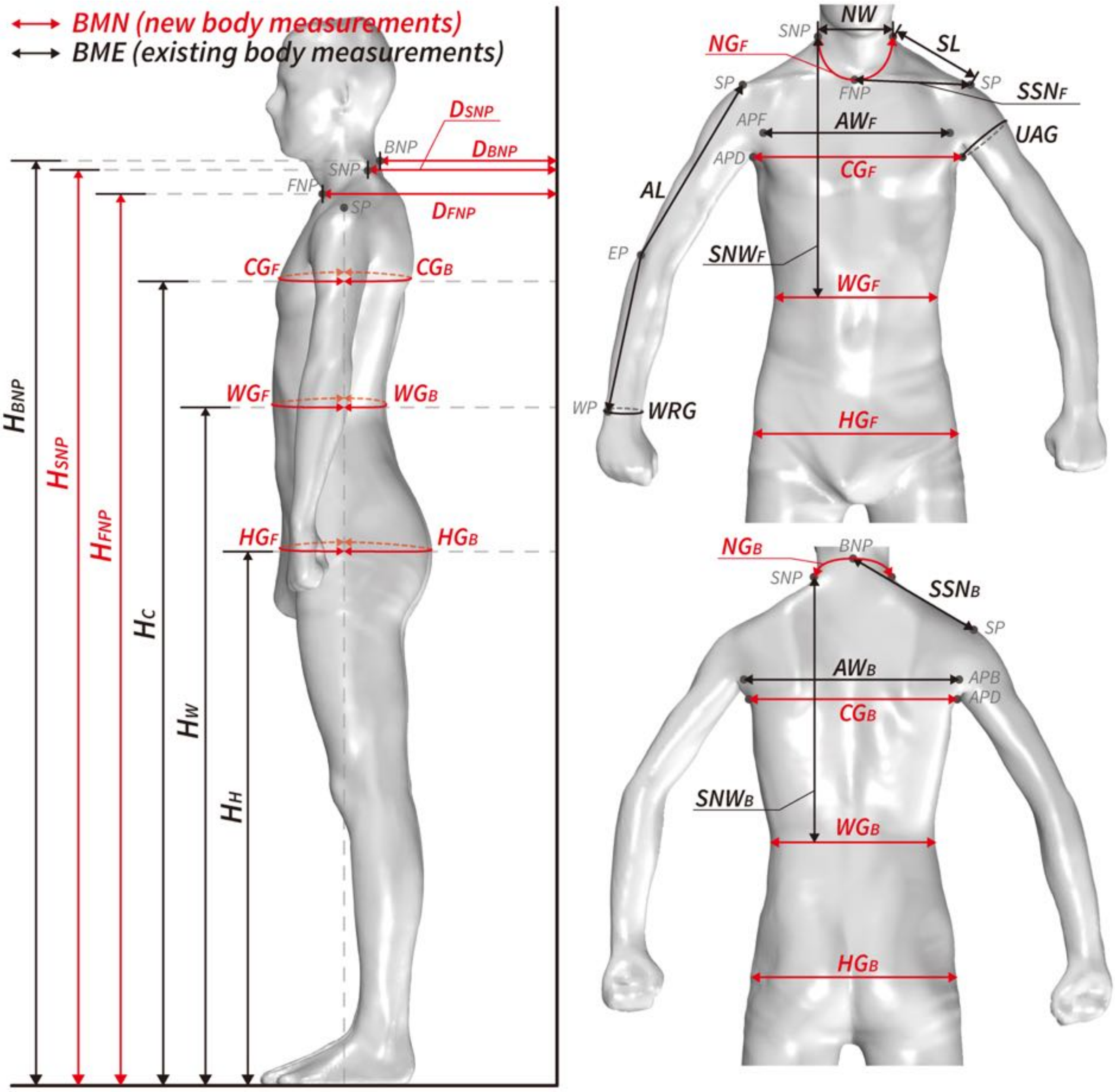


Figure 2.9 - Scheme of measuring of BM_N and BM_E

Table 2.5 - List of BM_N and BM_E

No.	Body segment	Body measurement		Definition
1	Torso	BM_E	H_C	vertical distance from the chest level (axilla) to the ground
2			H_W	vertical distance from the waist level to the ground
3			H_H	vertical distance from the hip level to the ground
4			SNW_F	surface length from SNP to front waist line
5			SNW_B	surface length from SNP to back waist line
6			AW_F	surface length across the front between the left and the right arm scye lines at the level of APF
7			AW_B	surface length across the front between the left and theright arm scye lines at the level of APB
8		BM_N	CG_F	horizontal front part of chest girth measuredat chest level
9			CG_B	horizontal back part of chest girth measured at chestlevel, $CG_F + CG_B = CG$
10			WG_F	horizontal front part of waist girth measuredat waist level
11			WG_B	horizontal back part of waist girth measured at waistlevel, $WG_F + WG_B = WG$
12			HG_F	horizontal front part of hip girth measured at hip level
13			HG_B	horizontal back part of hip girth measured at hip level,$HG_F + HG_B = HG$
14	Neck	BM_E	H_{BNP}	vertical distance from BNP to the ground
15			NW	vertical distance from FNP to the ground
16		BM_N	H_{FNP}	vertical distance from SNP to the ground
17			H_{SNP}	horizontal distance between left SNP and right SNP

18			D_{FNP}	horizontal distance from FNP to predefinedvertical plane
19			D_{SNP}	horizontal distance from SNP to predefinedvertical plane
20			D_{BNP}	horizontal distance from BNP to predefinedvertical plane
21			NG_F	front part of neck base girth
22			NG_B	back part of neck base girth, $NG_F + NG_B = NG$
23	Shoulder	BM_E	SL	distance from SP to SNP
24			SSN_F	surface length from SP to FNP
25			SSN_B	surface length from SP to BNP
26	Arm	BM_E	UAG	upper arm girth measured through APD
27			AL	distance from SP to WP through EP
28			WRG	wrist girth at the level of WP

As shown in Fig. 2.9 and Table 2.5, the morphological features of torso, neck, shoulder and arm were supposed to be described by 28 BM.

First, based on the torso BM, not only the three horizontal levels and their girths but also the anteroposterior proportions of transverse girths and vertical surface lengths were expressed. Moreover, the position of armscye line and SNP were accurately fixed by AW_F, AW_B and SNW_F, SNW_F, respectively.

Second, the spatial shape of neckline was identified. With the heights, widths and distances, the exact position of FNP, SNP and BNP were located. And front and back girths indicated the size of base neckline for one thing, and the anteroposterior proportions for another.

Third, the 3D special location of neckline was fixed by the three linearly independent neck BM. Last, the essential morphology of arm segment was expressed by the corresponding three BM.

Generally, the whole male torso (including hip level) could be characterized by the combination of BM_N and BM_E with critical levels and landmarks exactly located and anteroposterior proportions correctly balanced.

The scheme of BM_N and BM_E was proved validfor the subsequent experiments with the existing 150 subjects as Section 2.1.4.

2.3.2. Converted pattern-oriented body measurements

Mostof the BM_N and BM_E were able to be directly applied to pattern customizing according to equation (Chapter 4). However, some of the height and distance BM were independent to the pattern indexes. These BM were converted into six pattern-oriented BMN which could not be applied in pattern construction.

$$D_{CW} = H_C - H_W, \tag{2.2}$$

$$D_{WH} = H_W - H_H, \tag{2.3}$$

$$DN_F = H_{SNP} - H_{FNP}, \tag{2.4}$$

$$DN_B = H_{BNP} - H_{SNP}, \tag{2.5}$$

$$NWP_F = D_{FNP} - D_{SNP}, \tag{2.6}$$

$$NWP_B = D_{SNP} - D_{BNP}, \tag{2.7}$$

where: D_{CW} is the vertical depth from chest to waist, D_{WH} is the vertical depth from waist to hip, DN_F is the vertical depth from SNP to FNP, DN_B is the vertical depth from BNP to SNP, NWP_F is the profile width of front neck, and NWP_B is the profile width of back neck.

According to Equations (2.2 - 2.7), D_{CW} and D_{WH} described the vertical depths between chest, waist, and hip levels, which helped to draft the horizontal structure lines of the bodice. DN_F, DN_B, NWP_F and NWP_B depicted spatial neck shape on the profile view. Thus, the 25 final pattern-oriented BM for each segment were summarized as following:

1. 12 torso BM: D_{CW}, D_{WH}, AW_F,AW_B,CG_F,CG_B, WG_F,WG_B,HG_F,HG_B, SNW_F,SNW_B;

2. 7 neck BM: DN_F, DN_B, NWP_F, NWP_B,NW, NG_F,NG_B;

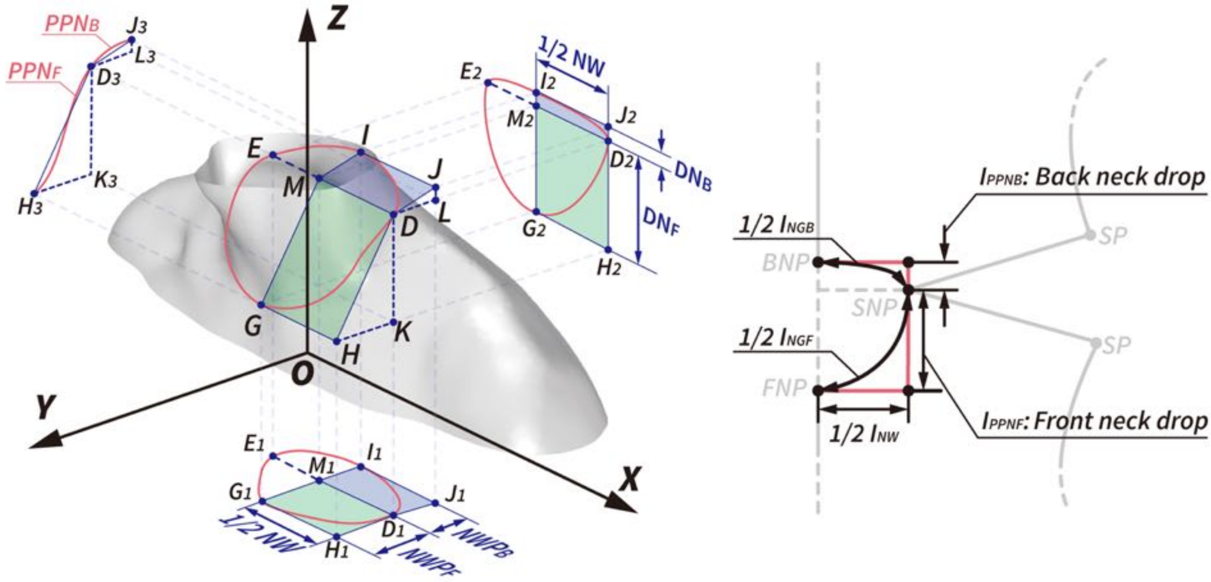
3. three shoulder BM: SL, SSN_F,SSN_B;
4. three arm BM: AL, UAG, WRG.

2.4. Geometric modeling of male torso

The pattern-oriented BM were applied to establish the graph-analytic geometric models of individual body segments (neck and shoulder, main torso and arm), which directly accurately reflected the segments and affected the proportionality of clothing and its spatial position.

2.4.1 Geometric modeling of neckline and shoulder line

Hitherto, the neckline construction could be drafted from NG_F and NG_B, while the front and back drop were still undefined. The lateral projections of front and back necklines corresponded to the neck drops; however, complex operations were necessary to measure them. To further reflect the individual neck morphology and apply to constructional lines, it was more convenient to calculate them with the BM immediately. Therefore, the geometrical neckline can be performed with BM (Fig. 2.9).



a *b*

Figure 2.10 - Geometric model of neckline and its application to pattern: *a* - neckline configuration and its projection of the VC in a 3D Cartesian coordinate system, *b* - neckline construction

As shown in Fig. 2.10, *a*, the neckline in the 3D Cartesian coordinate system was presented by five landmarks: G (FNP), D (left SNP), E (right SNP), M (midpoint of line DE) and I (BNP). The front and back parts of neckline were approximately located on the rectangular planes MDHG and MDJI, respectively. The neckline and its landmarks were projected on three axial planes XOY, XOZ and YOZ for showing the front, lateral and top views. On YOZ plane, the front and back necklines were projected as curves PPN_F (Profile projection of front neck) and PPN_B (profile projection of back neck), respectively, which corresponded to the front and back drops (indexes I_{LPNF} and I_{LPNB}) as shown in Fig. 2.10, *b*.

The vertical right triangles DHK, DJL and their lateral projections $D_3H_3K_3$ and $D_3J_3L_3$ were drafted. From the multi-view of the neckline model, the equivalence relations were distinctly observed as Equation (2.8 - 2.11). As a result, the lengths of hypotenuses HD and DJ were calculated in the right-angle triangles DHK and DJL as equation (2.12, 2.13):

$$HK = H3K3 = H1D1 = NWP_F, \quad (2.8)$$

$$DL = D3L3 = D1J1 = NWP_B, \quad (2.9)$$

$$DK = D3K3 = D2H2 = DN_F, \quad (2.10)$$

$$JL = J3L3 = D2J2 = DN_B, \quad (2.11)$$

$$HD = \sqrt{DK^2 + HK^2} = \sqrt{{DN_F}^2 + {NWP_F}^2}, \quad (2.12)$$

$$DJ = \sqrt{JL^2 + DL^2} = \sqrt{{DN_B}^2 + {NWP_B}^2}, \quad (2.13)$$

where HK, H_3K3 , and H_1D_1 are the lateral widths of front neck; DL, D_3L_3 and D_1J_1 are the lateral widths of back neck; DK, D_3K_3 and D_2H_2 are the vertical depths from SNP to FNP; JL, J_3L_3 and D_2J_2 are the vertical depths from BNP to SNP; HD and DJ are the straight line segments that approximated LPN_F and LPN_B, respectively.

As shown in Table 2.6, after comparison of projections PPN_F and PPN_B and approximate hypotenuses HD and DJ of 150 subjects, the maximum absolute error was up to 0.61 cm, which would affect the neck fitting for some bodies. To improve the prediction algorithm, the next indexes $PPN_{F–P}$ and $PPN_{B–P}$ (predicted PPN_F and PPN_B) were proposed to estimate the projection values, linearly expressed with HD and DJ.

Table 2.6 - Absolute errors of predicted front and back lateral neck projections

Absolut error	Mean, cm	Interval, cm
$\lvert PPN_F – HD\rvert$	0.24	0.05 … 0.61
$\lvert PPN_B – DJ\rvert$	0.06	0.06 … 0.25
$\lvert PPN_F – PPN_{F-P}\rvert$	0.08	0.00 … 0.21
$\lvert PPN_B – PPN_{B-P}\rvert$	0.03	0.00 … 0.19

Values of PPN_F, PPN_B, HD, and DJ of 150 subjects were imported in SPSS, and their linear relations were analyzed. $PPN_{F–P}$ and $PPN_{B–P}$ can be calculated by linear regression Equations (2.14) and (2.15), respectively.

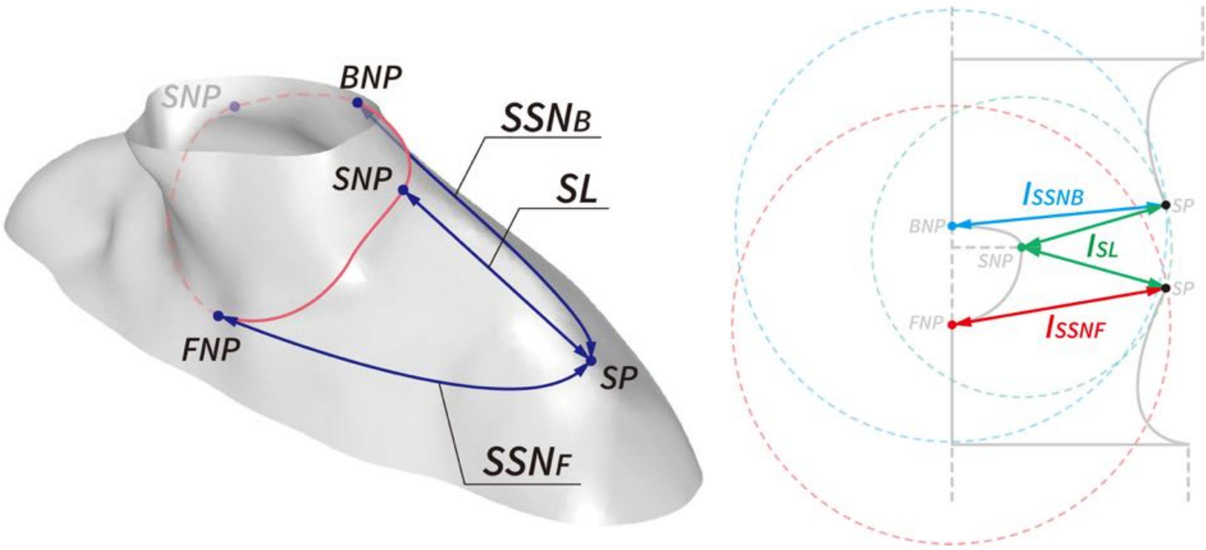
$$PPN_{F\text{–}P} = 1.057\ HD - 0.322 = 1.057\sqrt{DN_F{}^2 + NWP_F{}^2} - 0.322 \qquad (2.14)$$

$$PPN_{B\text{–}P} = 0.994\ HD + 0.076 = 0.994\sqrt{DN_B{}^2 + NWP_B{}^2} + 0.076 \qquad (2.15)$$

The correlation coefficients calculated were 0.998 between $PPN_{F\text{-}P}$ and HD, 0.999 between PPN_B and DJ, and both coefficients were significant at 0.01 level (two-tailed). Table 2.6 shows the accuracy of both indexes $PPN_{F\text{-}P}$ and $PPN_{B\text{-}P}$. The mean and maximum absolute errors decreased to a lower level, which is acceptable for individual neck drop drafting.

Therefore, the geometrical model of neckline was established with five variables: NW, NGF, NGB from BMN, and $PPN_{F\text{–}P}$, $PPN_{B\text{–}P}$ which linearly calculated by DN_F, NWL_F, DN_B, NWL_B, respectively. The neckline can be exactly reflected and its pattern can be drafted with corresponding indexes I_{NW}, I_{PPNF}, I_{PPNB}, I_{NGF}, and I_{NGB} (See details in Section 4.2.2.1), respectively, with FNP, SNP, and BNP correctly positioned.

During pattern drafting, the shoulder line is configurated by the bilateral points SNP and SP. Supposing that SNP is fixed, the shoulder line can be determined with SP located correctly. When FNP, SNP, BNP accurately fixed with the before-mentioned neckline model, the SP position and the model of SP can accordingly be determined with the BM measured between SP and FNP, SNP, BNP. The three shoulder BM (SL, SSN_F, SSN_B) were involved in transforming variables of 3D shoulder model on the VC into 2D constructional lines (Fig. 2.11).



a *b*

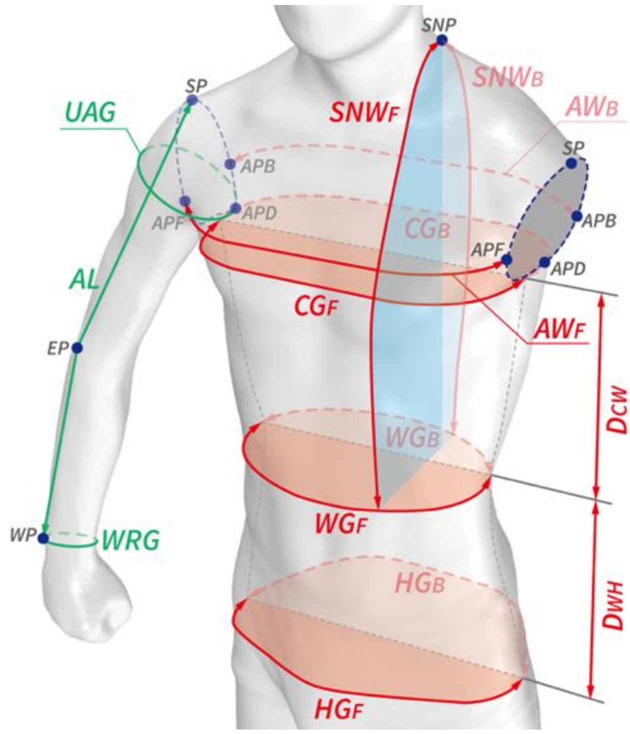
Figure 2.11 - Geometric model of shoulder line and its application to pattern:
a - shoulder area of the VC, *b* - shoulder line construction

As shown in Fig. 2.11, after neckline correctly located, SL determined shoulder length in the pattern, and SSN_F and SSN_B helped to reflected the shoulder sloping and direction (normal, forward thrust, back thrust, etc.) The corresponding shoulder line of 2D pattern was obtained by intersecting three circles of corresponding radius indexes (I_{SL}, I_{SSNF}, I_{SSNB}) and center points FNP, SNP, BNP. In this manner, the shoulder line of the pattern will coincide with the body shoulder area.

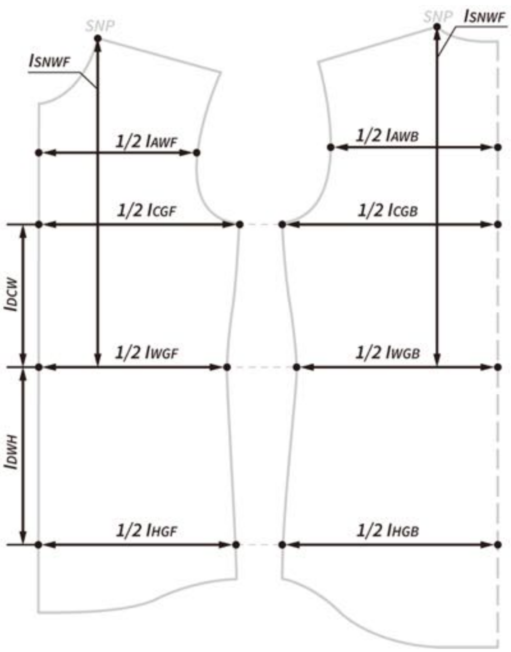
Thus, the pattern-oriented BM were applied successively to establish the graph-analytic geometric models of neckline and shoulder line, and to accurately accomplish the constructional lines of customized pattern.

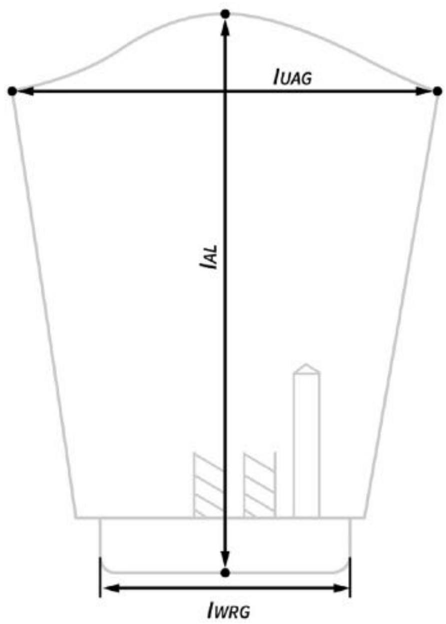
2.4.2. Geometric modeling of main torso and arm

The bodice of a men’s shirt is the most decisive part of the overall apparel fit. In this section, primary problems of misfits relating to the unbalanced anteroposterior proportions, which influence the smoothness of the surface and the straightness of structure lines, were solved with the geometric model of main torso. Fig, 2.12, *a* - *b* show the model of the main torso and the scheme of the bodice pattern.



a





b *c*

Figure 2.12 - Geometric model of main torso, arm and its application to pattern:
a - main torso segment of the VC, *b* - bodice pattern, *c* - sleeve pattern

As shown in Fig. 2.12, *a* - *b*, D_{CW} and D_{WH} and the corresponding pattern indexes IDCW and IDWH helped to determine the horizontal levels of chest, waist and hip. Below the chest level, the six girth BM_N variables CG_F, CG_B, WG_F, WG_B, HG_F, HG_B depicted the girths of three levels with detailed anteroposterior proportion. And their corresponding pattern indexes I_{CGF}, I_{CGB}, I_{WGF}, I_{WGB}, I_{HGF}, I_{HGB} determined the front and back proportional bodices segments. Moreover, the width variables AW_F and AW_B depicts the relativepositions of AP_F and AP_B. And the pattern indexes I_{AWF} and I_{AWB} helped to draft the armhole curves with certain proportion. Stress folds and tilt side seams will take place when these proportions are unbalanced.

Above the chest level, vertical proportional BM variables SNW_F and SNW_B and pattern indexes I_{SNWF} and I_{SNWB} controlled the vertical anteroposterior proportion by connecting SNP and waist level on the front and the back, which also connected the bodice below chest and neckline, shoulder line, armhole line. The chest, waist, and hip structure lines will be tilted when this proportion is unbalanced.

As shown in Fig. 2.12, *a*, *c*, the arm BM variables AL, UAG and WRG and sleeve indexes I_{AL}, I_{UAG}, and I_{WRG} were commonly used to exactly configurate the length and width of sleeve, and cuff width, respectively.

Conclusion after Chapter 2

1. The anthropometric database of male bodies has been established based on the new body measurements which can exactly describe the morphological features of torso, shoulder, neck and arm segments.

2. The geometric models for different segments of male body was graph-analytic proposed for connecting the individual body morphology and the construction of customized shirt pattern.

CHAPTER 3. CRITERIA FOR VIRTUAL FIT EVALUATION

Although the fundamental and extended criteria for evaluating men's shirt fit by the exterior appearance have been proposed, they are still inadequate in accurately determine the fit state of each fragment of the shirt and provide the constructive reasons for pattern improvement. In order to accurately conduct the fit evaluation in real and virtual environments, the more comprehensive fit criteria should be developed.

This chapter developed the criteria for virtual fit evaluation of men's shirt by integrating the existing fit problems, misfit photos, virtual images and constructive analysis through establishing the databases of consumers' opinions and try-on photos, and sensory analysis of the criteria with eye-tracking technology.

The results obtained in this chapter are published in four work [163 – 166,170].

3.1. Methods of research

The massive information of consumers' opinions and try-on photos were collected from the online resources to discover the misfit problems. The corresponding virtual and real shirt samples with different fit levels were sewed in CLO 3D and actually, which were validated by sensory analysis with eye-tracker.

3.1.1. Instruments and software of research

The digital camera was used to capture the photos of clothing in different views. A straight ruler was used to measure the vertical heights. The KES-F instruments were utilized to measure the mechanical properties (tensile, shearing, bending) of textile materials. Fig. 3.1 shows the KES-FB1, FB2, FB3 instruments.

Figure 3.1 - KES-FB1, FB2, FB3 instruments

The compatible software was applied: Adobe Photoshop for image processing and measuring the objects in photos. CLO 3D was applied for accomplish the virtual simulation of men’s shirt try-on.

3.1.2. Consumers’ opinions from the Internet

In order to investigate the fit problems took place in men’s shirt, the survey of existing shirts information on the internet was conducted in two directions simultaneously. The first was the consumers’ opinions towards purchased shirts, and the second was the photos of men’s shirt try-on photos.

As a result, in total 5,146 pieces of consumers’ opinions or feedbacks on their purchased shirt on the most famous and largest Chinese online shopping platform TMALL. In order to ensure the comphrehensiveness of the results, 81 shirts of 30 different brands (from normal to entry lux), prices (from about 100 to 3,000 RMB) and styles (from body-fit to loose-fit) were chosen. The thirty famous international and Chinese brands were: American Eagle, Baleno, Bershka, Gap, Giodano, Goldlion, GU, GXG, C&A, G2000, Hollister, Hugo Boss, H&M, JackJones, Jeanswest, Levi’s, Massimo Dutti, Metersbonwe, MUJI, Me&city, Peacebird, Pull&Bear, Selected, Seven, Teenie Weenie, Tommy Hilfiger, Trendiano, Uniqlo, Vancl, Zara.

3.1.3.Photos of men’s shirts from the Internet

Through browsing the official photos which shown the real try-on effect of shirts on models from hundreds of menswear brands, the 187 photos of different shirts from eighty brands were selected. These brands were: Black Monday, Calvin Klein, C&A, COS, Diesel, GAOSTUDIOS, Guess, G-STAR, H&M, Jian Shang, Lee, Mr. MIB, Ralph Lauren, Paul Smith, Theory, TOPMAN, Uniqlo, Zara. These photos weresupposedto exhibit the whole body or fragments of the shirts from different views (front, back and profile) with different fit problems. Fig. 3.2 shows the examples of the photos.

a *b* *c*

Figure 3.2 - Men's shirt try-on photos shot from the view of:
a – front, *b* – profile, *c* – back

Fig. 3.2, *a* shows the front view of a shirt with obvious excessive collar, Fig. 3.2, *b* shows the profile view of a shirt with unsmooth front contour, Fig. 3.2, *c* shows the back view of a shirt with a lot of folds around axilla on sleeves. All the photos revealed the good fit state or fit problems of several fragments from different views in the same way.

3.1.4.Digital twins and realsamples for validation

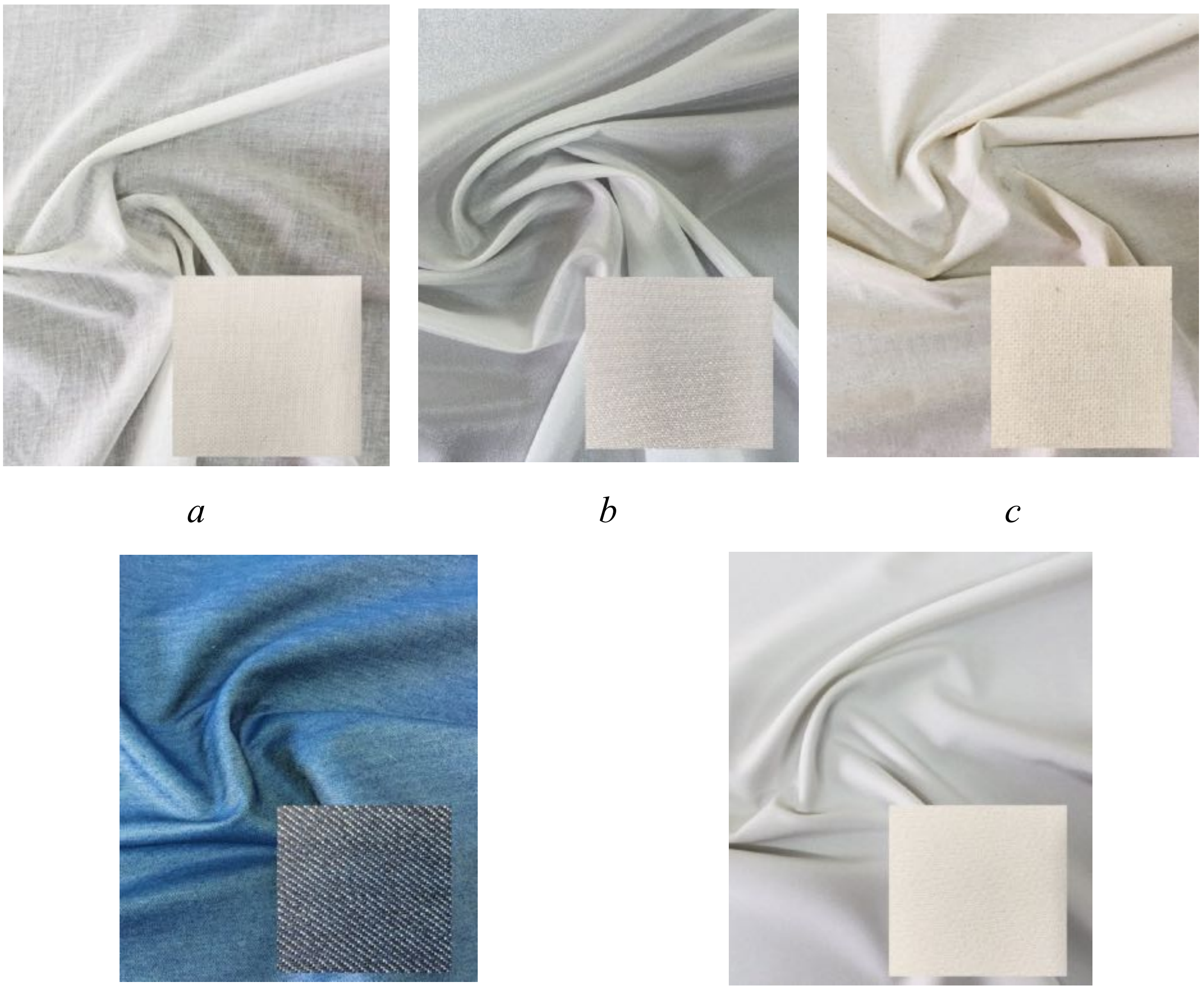
In order to represent the fit problems appeared in the existing men's shirts, the real samples were sewed and digital twins (DT) wre generated. For one thing, the virtual simulation was conducted in CLO 3D. One DT which transformed from the real scanned typical men's body with typical morphology (approximately fifty-fifty anteroposterior torso proportions, 170/92Y type) was utilized for virtual fitting. And one frequently-used digital fabric for shirt making (name - Cotton 40S Stretched Poplin, content - 96% cotton and 4% stretched yarn, density - 119.2g/cm^2, thickness – 0.26 mm) was selected from the default library in CLO 3D.

The real samples were sewed simultaneously with the 175/92A (CG = 92cm, WG = 78cm, HG = 94cm) men's dummy and five different textile materials. The mechanical properties of the five materials varied greatly as shown in Table 3.1 and Fig. 3.3.

Table 3.1 - Mechanical properties of five textile materials

Fabric	Basic information				Tensile						Shearing		Bending	
	Fiber content	Weave structure	Thickness, cm	Weight, g/m^2	EMT, %		RT, %		F, cN/cm		G, cN/[cm·(°)]		B,cN·cm²/cm	
					warp	weft	warp	weft	warp	weft	warp	weft	warp	weft
T_1	100% polyester	satin	0,20	67,2	3, 67	9,77	60,79	49,30	415,05	61,37	0,16	0,14	0,06	0,03
T_2	100% cotton	plain	0,25	69,0	4, 74	12,81	48,97	37,89	225,33	32,27	0,34	0,31	0,04	0,03
T_3	100% cotton	plain	0,41	147,8	6, 25	5,83	42,96	46,52	207,62	206,09	2,69	2,41	0,10	0,14
T_4	98% cotton, 2% spandex	twill	0,41	183,0	5, 37	7,07	41,93	52,82	273,88	130,68	3,00	2,09	0,00	0,25
T_5	95% polyester, 5% spandex	satin	0,50	206,7	24, 79	26,39	59,50	46,36	14,35	19,85	0,45	0,44	0,15	0,16

where are EMT is the elongation under 500 cN/cm, %; RT is the tensile resilience, %; F is the tensile strength when elongation is 3%, cN/cm; G is the shear rigidity, cN/[cm·(°)]; B is the bending stiffness, cN·cm²/cm. T_1 – T_5 represent the first to fifth textile materials, respectively.



a *b* *c* *d* *e*

Figure 3.3 - Five textile materials:*a* – T_1, *b* – T_2, *c* – T_3, *d* – T_4, *e* – T_5

As shown in Table 3.1, chosen fabrics have disparate formability due to various properties. T_1 and T_2 are the inelastic fabrics with lightweight and thin thickness. T_3 and T_4 are thick hard fabrics with high stiffness. T_5 is this thickest fabric with high elasticity. Owing to the variances of the materials, they exhibited different appearances.

3.2. Initial databases for subjective evaluation

3.2.1. Database of consumers' opinions

The consumers' opinion towards their shirts were diverse, but they could be generally divided to three main categories: positive, neutral and negative. Among the positive and neutral opinions, most consumers tended to compliment the good designs, comfortability, suitable size, etc.. While the negative opinions included four primary aspects: improper size or dimension, undesirable properties of textile materials, low quality of products or unsatisfactory services provided.

Thus, the consumers' opinions were analyzed and classified as shown in Table C.A in Appendix C. The proportions of consumers' opinions regarding to positive, neutral and negative are, %:

- positive and neutral opinions-81,9,

- negative opinions – 18,1, including regarding the size or shape – 10,9, textile materials – 2,8, the quality of shirts – 2,4, the quality of services – 2,0.

First and foremost, 10.9% of them declared the uncomfortableness and the undesired appearances caused by improper size or shape of the shirt, although they chose the shirts of closest dimensions to their own BM. Concretely, the opinions related to size or shape were in the following aspects:

a. related to shirt style:

1. the dimension or shape is too small or big overall or locally (especially on the levels of chest, waist);

2. the length from neck to hemline is too short or long;

3. the sleeve is too loose or tight;

b: related to clothing fit:

4. the neck or collar is too tight or loose;

5. the shoulder line is too short or long;

6. the sleeve is too short or long;

7. the cuff is too tight or loose;

8. the bodice (chest, belly, hip or back) is too tight;

9. the shirt is unsmooth with folds or creases after wearing.

Second, 2.8% consumers complained about the textile materials in the following aspects:

1. the material is easy to wrinkle;

2.the material is easy to pilling on the surface;

3. the material is too thick or thin;

4. the material is too soft or hard;

5. the wearing comfort of the material is terrible;

6. the shirt becomes larger or smaller after washing.

Third, 2.4% consumers complained about the product quality due to the terrible craftsmanship.

Last, 2.0% consumers were dissatisfied with the services provided during the purchasing, changing, refunding, after-sale, etc.

The results illustrated that most negative opinions towards men's shirts came from the problems of size or shape. The problems of shirt style greatly depended on the personal tastes or dress habit. While the problem of clothing fit was caused by the inadequacy between the individual morphology and the shirt construction based on RtW system.

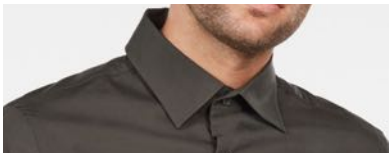
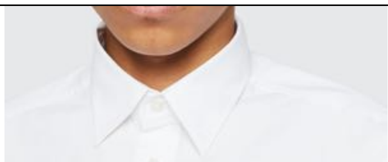
The database of the fit problem perceived from the consumers' subjective perspective was established accordingly.

3.2.2. Database of misfit photos

To investigate the exterior appearances of the misfit on men's shirt, the next database of misfit photos was established. The photos collected from the Internet were clipped to different fragments of clothing sections where the fit problems were perceived by consumers: bodice, neckline and collar, shoulder and sleeve. The fragments belonged to the same body section were compared and analyzed together to distinguish the fit or misfit situation in different levels.

A five-level scale (1 – worst, 2 – poor, 3 – medium, 4 – good, 5 - best) was applied for distinguishing the fit state in consideration of the exterior appearance of the shirt fragments. As Table 3.2 shown, the gradations of misfit in neckline and collar fragments were accomplished by the typical photos showing different levels of collar fit. The integral misfit gradations of neck and collar, shoulder seam, sleeve and bodice were shown in Appendix D.

Table 3.2-Misfit gradation of neckline and collar

Fit level	Neckline and collar	
	Too large neckline and collar	Too small neckline and collar
1		
2		
3		
4		
5		

As shown in Table 3.2, the neckline and collar segments involved one bilateral gradation (too largeor small).

Similarly, shoulder seam, sleeve and bodice were reflected by two bilateral gradations (too long, short; too down, up), two bilateral gradation (too long, short; too large, small sleeve cup height) and three gradation specifictoarmhole, chest, hip, respectively. From level 1 to level 5, the exterior appearance of the shirt varied from the worst one with most misfit to the best without misfit.

For the collar section, the obvious gap between collar and neck or the folds around neck were observable when the designed neck girth and collar were too large or too small, respectively.

For the shoulder section, the folds or the excessive bulges directing to SP appeared when the shoulder seam was too short or too long; the folds or convexbulges appeared when the shoulder seam were too down or too up, respectively.

For the sleeve section, the palm would be covered by the cuff hem or the wrist was not covered when the sleeve was too long or too short; the bulges or the folds on the sleeve cup were observable when the sleeve cap height is too large or too small, respectively.

For the bodice section, the folds around AP were observable when the armhole depth was too small; the folds on the front chest or back hip appeared when the chest or hip of bodice is too small, respectively.

Therefore, the second database of misfit photos with gradations for different fragments were established. For one thing, it reflected the exterior appearances of the fit problems from the consumers' opinions. For another, the both databases could be referred as the subjective criteria for evaluating the men's shirt by subjective perceptions and visualization of misfit.

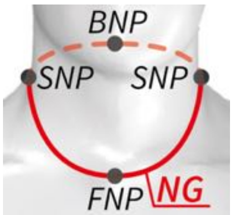
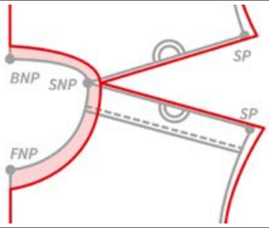
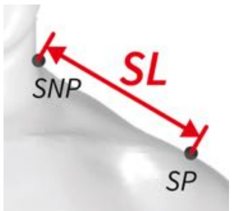
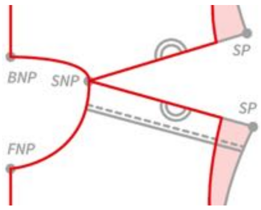
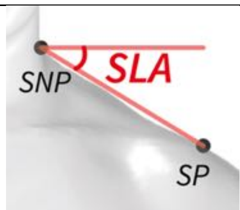
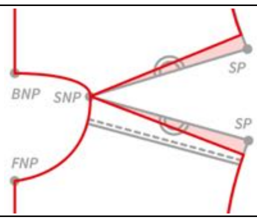
3.3. Criteria for evaluating men's shirt

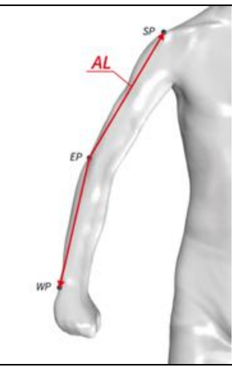
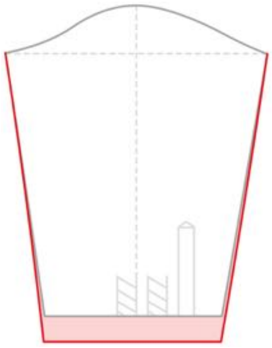
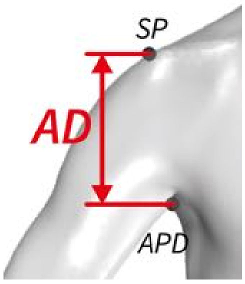
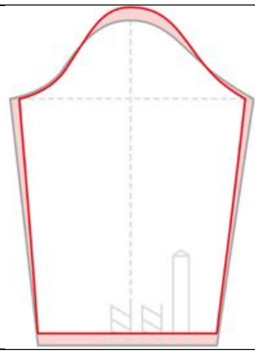
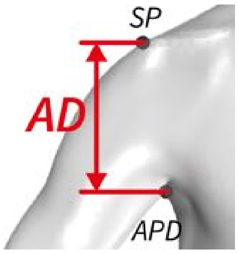
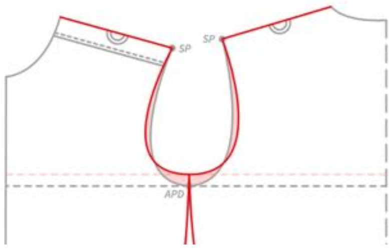
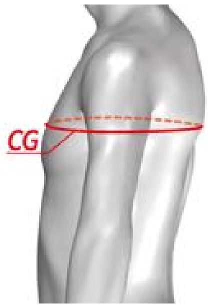
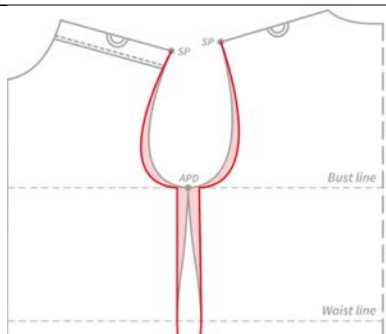
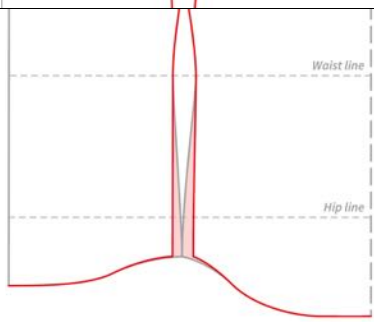
The established two initial databases were insufficient for objective evaluation with measurable indicators from body, pattern and shirt, etc.. The validation with virtual samples based on analysis of constructive reasons of the misfit and validation with real samples based on fit indicators were conducted simultaneously. The results of validations and two initial databases together integrated the comprehensive criteria for subjectively and objectively evaluating men’s shirt.

3.3.1. Constructive reasons

The emergence of the misfit was mainly caused by the incompatibility between the body morphology and the dimensions of different shirt sections. The former could be reflected by BM, and the latter was determined by shirt construction. Thus, the responsible BM and the constructive reasons for the misfit were analyzed as Table 3.3 (gray lines are well-fitted patterns, red lines are the misfit patterns).

Table 3.3 - Responsible body measurements and constructive reasons for the misfit

Section	Misfit	responsible BM	Constructive reason
Neck			
Shoulder seam			
			

<table>
<tr><td rowspan="2">Sleeve</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td rowspan="3">Bodice</td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

NG was the decisive BM applied in neckline and collar design. The too large or small collar was constructed by the neckline pattern with excessive ease or inadequate (and negative) ease.

SL and SLA (shoulder sloping angle) was the common BM applied in shoulder seam design. The corresponding responsible pattern is the length which should be equal to SL and angle of shoulder seam. The misfit on shoulder section was caused by wrong length and angle of shoulder seam.

Sleeve length was determined and equal to BM AL. Sleeve cap height was determined by BM AD (armhole depth). The misfit on sleeve section was caused by the too long or short length and sleeve cap.

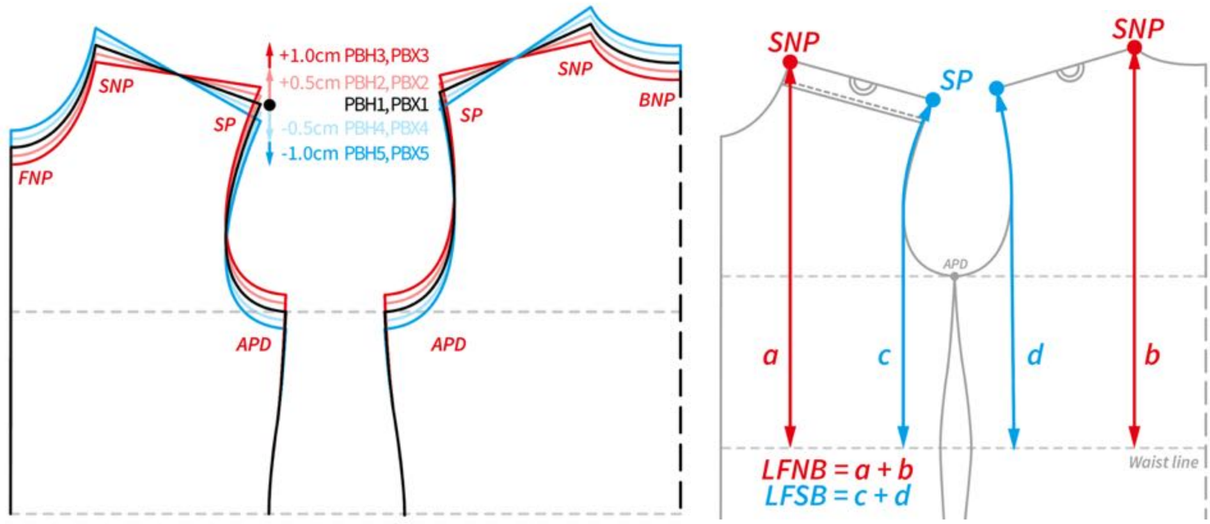
In bodice section, the depth of armhole line depended on the level of chest line, corresponding to BM AD. The too upchest line would lead to the misfit around axilla. The chest and hip area were related to BM CG, HG and the pattern index chest width, hip width, respectively. The inadequate widths on pattern caused the deformation around front chest and back hip.

Finally, the criteria with the photos of virtual shirts, pattern configuration was concluded in Appendix D.

3.3.2. Fit indictors with real validation

In order to further investigate the influence of pattern on shirt fit, the real validation was executed by sewing real shirt bodices with five textile materials with different mechanical properties (Table 3.1, Fig. 3.3).

In this experiment, the men's dummy of 175/92A was applied for shirt fitting. Derived from the method in Chapter 4, the customized bodice patterns with horizontal bottom in body-fit and loose-fit styles were drafted at the same time. Ten variant bodice patterns (PBX1, PBX2, PBX3, PBX4, PBX5 in body-fit style, PBH1, PBH2, PBH3, PBH4, PBH5 in loose-fit style) with gradually changed shoulder seam angles were drafted accordingly as shown in Fig. 3.4, *a*.



a *b*

Figure 3.4 - Configuration and measurement of bodice pattern:
a - scheme of variant bodices, *b* - shoulder sloping index SS

Fifty bodice samples with different misfit situations were sewed eventually. And each sample were photographed in front, profile and back views with the exactly same camera installation. The front, profile and back bottom height (BHF, BHP, BHB) were measured by straight ruler.

Therefore, the new fit indicators were proposed to be measured and analyzed with the photos and measurements:

1. Shoulder sloping index of pattern SS were expressed by the vertical difference between SNP and SNP:

$$SS = LFNB - LFSB, \quad (3.1)$$

$$LFNB = a + b, \quad (3.2)$$

$$LFSB = c + d, \quad (3.3)$$

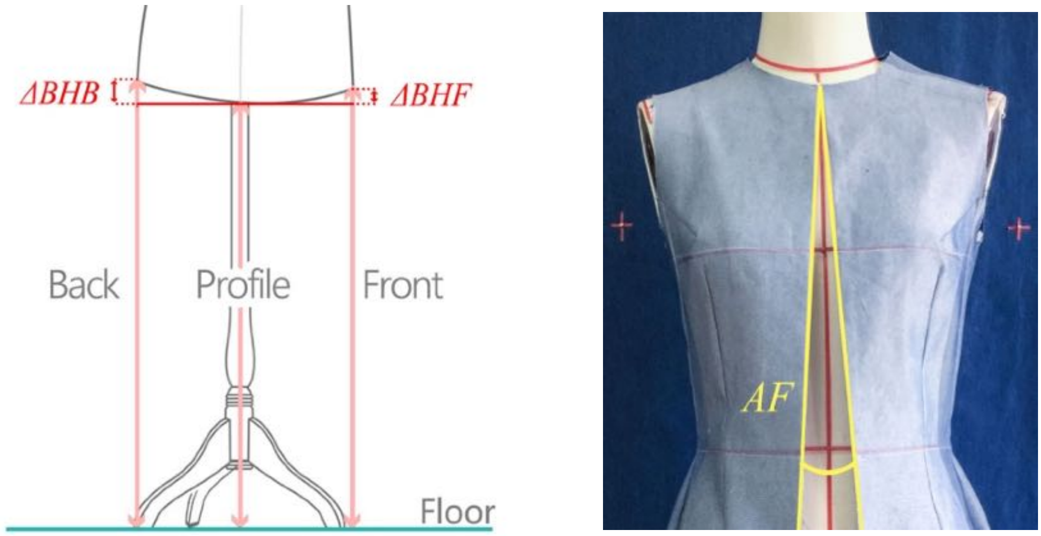
where: LFNB is the length from front waist line to back waist line across SNP, LFSB is the length from front waist line to back waistline across SP, as shown in Fig. 3.4. The value of SS on variant patterns were respectively 7, 5.5, 1.8, 8.7 and 9.9 cm.

2. Due to the change of shoulder slope and textile materials, the bottom

shape was changed accordingly. As shown in Fig. 3.5, *a*, the differences between BHP and BHF, BHP and BHB were calculated as ΔBHF and ΔBHB as Equation (3.4), (3.5).

$$\Delta BHF = BHP - BHF, \quad (3.4)$$

$$\Delta BHB = BHP - BHB, \quad (3.5)$$



a *b*

Figure 3.5 - Fit indicators:
a - bottom height differences, *b* - angle of front contours

3. With the photos of unbuttoned bodices, the angles of front contours on loose-fit and body-fit bodices (AFH, AFX) were measured in Photoshop as shown in Fig. 3.5, *b*.

The relations between each fit indicator, pattern, property of textile material were concluded.

When SS = 7 … 9.9 cm, the loose-fit shirts shown horizontal bottom line in three projections, but when SS = 8.7 cm, the body-fit shirts were close to show horizontal bottom. And bottom heights of the loose-fit shirts were inclined to be more horizontal than the body-fit shirts.

In addition, the shirts from PBH2 and PBH3 (1.8 cm ≤ SS ≤ 5.5 cm) shown AFH as 0°, which indicated that the front center lines were vertical and dress shape would be immobile after front contours were seamed. Moreover, the shirts from PBH4 and PBH5 (8.7 cm ≤ SS ≤ 9.9 cm) shown bigger AFH, AFX (2.1° … 10.5°).

Moreover, based on the fabric properties, the pattern parameters and the fit indicators, the linear regression equations were obtained after linear regression analysis in SPSS as:

$$AFH = 4.3 - 19.3B_{warp}, \quad (3.6)$$

$$AFH = 0.80SS - 2.69, \quad (3.7)$$

$$AFX = 5.4 - 12.0B_{warp}, \quad (3.8)$$

$$AFX = 0.69SS + 0.04, \quad (3.9)$$

Where: B_{warp} is bending stiffness in warp direction of fabrics.

From equations (3.6) - (3.9), AFH and AFX were expressed with B_{warp} and SS. With B_{warp} increasing, fabrics were less flexible to bending, the front center lines were more inclined to keep vertical with the bending strength from shoulder part and back torso, the angles of front contours would be bigger. Furthermore, as SS increasing, the shoulder slope of shirt changed accordingly, the supporting point of shirt moved from SNP to SP, the shirt shape changed, which led to bigger angle of front contours.

Taking body-fit shirts as an example, the bottom height variance in front and back projections were described as:

$$\Delta BHF = -0.194 - 0.0007F_{warp}, \quad (3.10)$$

$$\Delta BHB = -1.216 + 0.0007\ F_{warp}, \quad (3.11)$$

$$\Delta BHB = -0.147 - 0.031SS, \quad (3.12)$$

Where: F_{warp} is tensile strength in warp direction of fabrics.

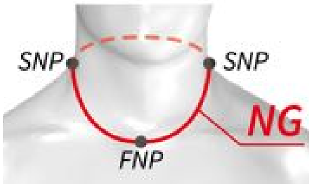
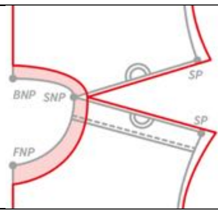
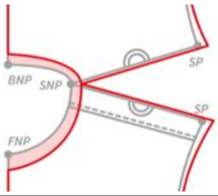
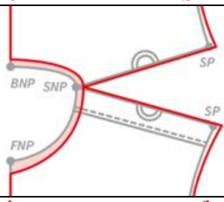
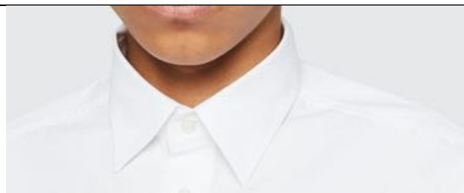
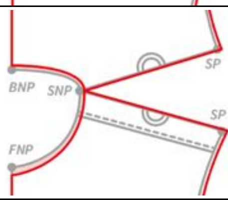
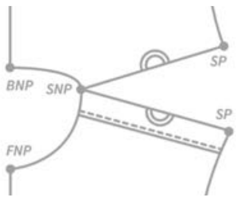
From equations (3.8) - (3.10), ΔBHF and ΔBHB were described with F_{warp} and SS. With F_{warp} and SS varied, the length and proportion of front and back shirt were changed, therefore resulting in changes of ΔBHF and ΔBHB. Furthermore, ΔBHB were more inclined to vary with SS rather than ΔBHF.

Therefore, the new algorithms and relations between shirt construction, mechanical properties of textile materials and fit indicators were established, which could be used as the objective criteria with real shirts and improve the existing database of virtual fitting.

3.3.3. Final criteria of fit evaluation

Based on the initial databases and the analysis of constructive reasons, the final fit criteria charts composed with fit level, description of misfit, photos and constructive reasons was established. (gray lines are the well-fitted patterns, red lines are the misfit patterns).

Table 3.4 - Criteria of neckline and collar fit (when the neckline and collar are too large)

Fit level	Description	Photo	Scheme of pattern block
			Responsible BM: Neck girth (NG)
1	Obvious large gap between neck and collar		
2	Obvious gap between neck and collar		
3	Observable gap between neck and collar		
4	Tiny gap between neck and collar		
5	Fit without gap		

As shown in Table 3.4, the five-level fit criteria described in detail the misfit photo andconstructive reasons of each level. With the level varying from 5 to 1, the gap between neck and collar became larger, the neckline girth and collar width accordingly became more excessive.Thus, the level of fit of the shirt collar could be determined based on the criteria, and the corresponding design considerations were recommended for further adaptation of the pattern.

Based on the similar criteria of the other segments, the segmental and integral fit state of a shirt and the constructive reasons for the existing misfit situation could also be determined.The integral fit criteria of neckline and collar, shoulder seam, sleeve and bodice were concluded as Table D.A – D.D in Appendix D. Table 7 shows the example of fit criteria of neckline and collar.

Conclusion after Chapter 3

1. The initial databases of consumer's opinions towards men's shirts and misfit photos were established, which could be applied as the subjective criteria for evaluating clothing fit of shirt.

2. The validation were conducted with both virtual and real shirt samples. The proposed new fit indicators could be used to conduct objective evaluation.

3. The comprehensive five-level criteria for evaluating different fragments of men's shirt was established with subjective items (descriptions, real photos, virtual images) and objective indexes (patternparameters, BM). These criteria can be used to check the fit state of sewed shirts and to provide the constructive reasons for the misfit situations.

CHAPTER 4. DEVELOPMENT OF E-BESPOKE MEN'S SHIRT PATTERN

The proposed BM_N and corresponding geometric models of different segments enhanced the adequacy between individual body morphology and fit and exterior shape of men's shirt. However, the existing methods of pattern drafting which were often applied in constructing the RtW and MtM patterns were incompatible and inadequate to accomplish a e-bespoke pattern with BM_N and the models.

This Chapter proposed the new method of pattern drafting and checking for e-bespoke shirt in different styles on the basis of individual BM, pattern indexes and ease allowances, showing massive differences with the RtW and MtM patterns.

The results obtained in this chapter are published in three work [161, 167, 168].

4.1. Methods of research

The BM of seven 170/92Y VC, ease allowances, and the shirt type were determined for subsequent experiments. The e-bespoke shirts were customized, which were compared with the RtW and MtM shirts for the same VC.

4.1.1.Software

The 2D clothing CAD software ET CAD (BUYI Technology, China) were utilized to drafting shirt patterns which were saved as .dxf format. The files of .dxf format were operable in comprehensive software, e.g., CLO 3D, Illustrator.The graphic software Adobe Illustrator were utilized to arrange the vectorgraph of different patterns for exact comparisons.

4.1.2. Subjects of research

The VC of 150 male bodies were exactly classified into different body type by height, chest girth (CG) and drop value between chest and waist in accordance with the Chinese national standard [64]. Fig. 4.1 shows the diagram of the distribution of each body type.

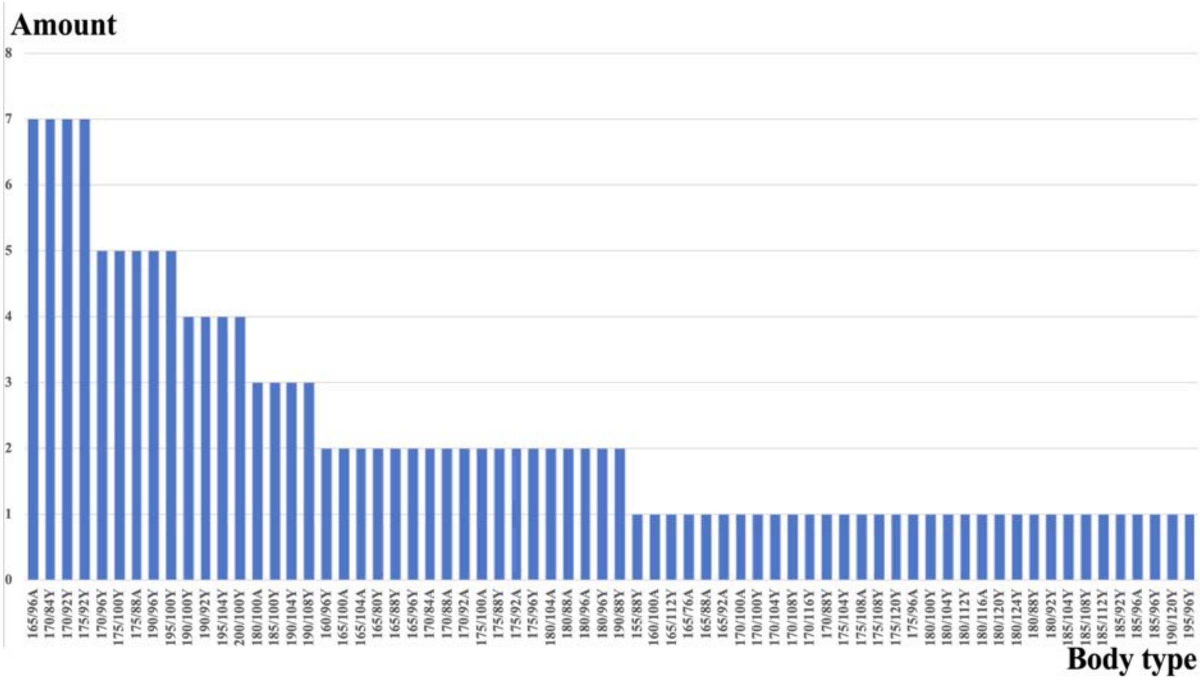


Figure 4.1 - Distribution of body types of the 150 subjects

As shown in Fig. 4.1, 150 VC were distributed across 68 shape types. And 165/96A, 170/84Y, 170/92Y, 175/92Y were the most frequent body types.Therefore, as one of the frequently appeared types, the seven 170/92Y VC (Fig. 4.2, Table 4.1) were selected as the subjects for subsequent pattern customization and virtual try-on. Fig. 4.2 shows the variance of seven 170/92Y subjects in profile view, the differences of some segments between each body were observable although they belonged to the same type.According to the sequence of scanning, the seven 170/92Y subjects were abbreviated as S_3, S_8, S_{34}, S_{37}, S_{56}, S_{72}, S_{87}.

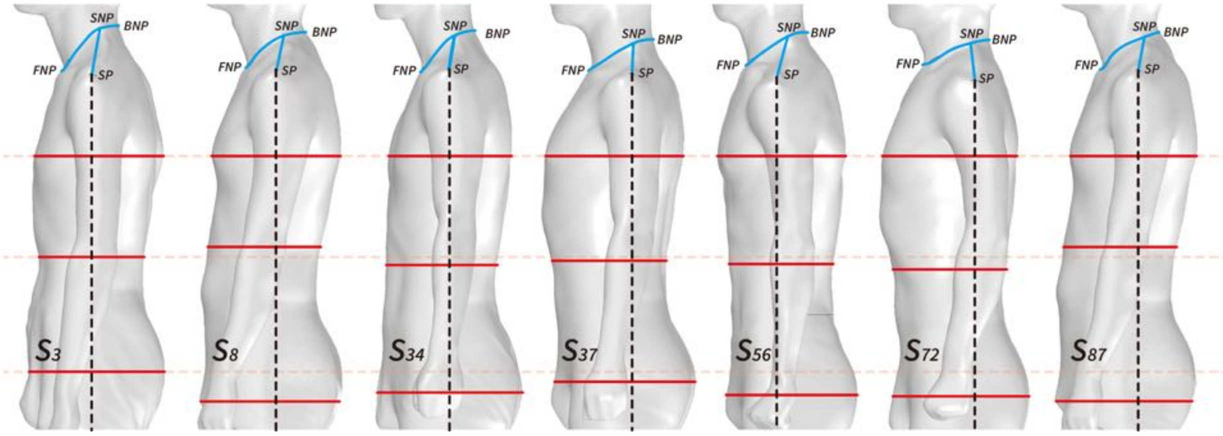


Figure 4.2 - Seven 170/92Y virtual clones

And Table 4.1 shows a part of the final converted BM that calculated from the raw BM measured in Rhinoceros in accordance with the corresponding geometric models (See Section 2.4).

Table 4.1 - BM of seven 170/92Y subjects

subject	Body measurement, cm											
	CG_F	CG_B	WG_F	WG_B	HG_F	HG_B	SNW_F	SNW_B	NG_F	NG_B	PPN_F	PPN_B
S_3	41.7	50.2	35.8	36.2	46.6	47.3	42.2	42.5	27.5	15.6	10.1	3.5
S_8	46.0	45.7	40.9	31.1	51.5	43.3	40.6	40.7	24.3	14.8	8.5	3.7
S_{34}	42.8	49.5	37.8	36.0	44.8	47.0	43.1	43.4	24.8	15.3	8.5	3.5
S_{37}	51.4	41.4	43.8	27.8	49.9	43.1	43.4	41.0	26.3	16.6	9.6	3.6
S_{56}	39.1	52.7	30.8	39.6	38.7	50.4	43.0	43.2	23.2	16.0	8.0	3.8
S_{72}	53.2	40.7	45.2	28.2	49.9	41.5	46.2	42.4	25.6	15.0	9.6	3.2
S_{87}	46.3	45.4	41.3	30.7	51.9	42.9	40.8	40.4	24.6	14.5	9.0	3.4

Fig. 4.2 and Table 4.1 comprehensively illustrated the variance of some segment:

1. torso – horizontal and horizontal anteroposterior proportions on chest, waist and hip levels, vertical distances between adjacent two levels;
2. shoulder – spatial direction (thrust and sloping angle);
3. neck – girth and its anteroposterior proportion.

4.1.3. Objects of research

The subsequent experiments of pattern constructing and virtual try-on were conducted with the object - a men's shirt as shown in Fig. 4.3.

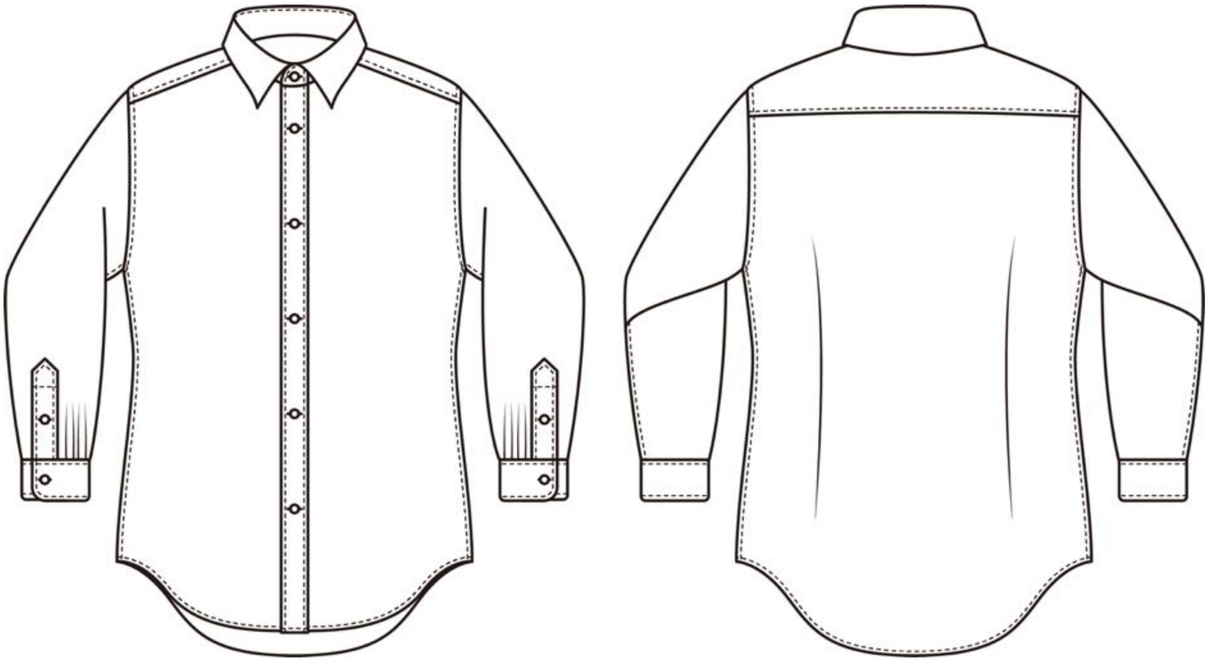


Figure 4.3 - Illustration of the men's shirt used in the research

As shown in Fig. 4.3, the men's shirt was designed with the classic and common components and elements: front and back bodice with curved tails without opening on sideseams;one-piece yoke covering the back shoulder segment;placket front with five buttons;back wait darts or no waist darts;turnover spread collar; long sleeves with plackets and pleats, Barrel round cuffs with one button.

Moreover, four typical styles were simultaneously considered in the experiments: body-fit, slim-fit, regular-fit, loose-fit. These styles shown the different contours and volumes around the torso and arm and the same shapes of shoulder seam and collar.

4.2. Patterns of men's shirt

According to the BM of the selected VC and the certain styles of men's shirt, the new method of constructing an e-bespoke men's shirt patterns were proposed. Compared with the RtW and MtM patterns, e-bespoke patterns could better fit the individual morphology and be used for estimating the final fit of a shirt.

4.2.1. Database of ease allowances

For constructing the shirt pattern in different styles, it was inevitable to understand and apply the ease allowances of different fragments by several steps.

Firstly, according to the corresponding BM and body segment (as Section 2.4), the ease allowances utilized in pattern of men's shirt were classified into three groups:

1. zero ease E_0: the pattern was constructed without eases to the following BM: SNW_F, SNW_B, D_{CW}, D_{WH} and AL;

2. constant ease E_C: the ease to the specific part was a constant value, which provided appropriate space for movements or comfort regardless of the variance of styles. $E_C$were constructed for the following BM: NG_F, NG_B, NW, PPN_F, PPN_B and WRG;

3. variant ease E_V: the ease to the specific part was a changeable value varied with shirt style, which provided appropriate space for one thing, and helped to shape the exterior contour of the shirt in different styles for another. $E_C$were constructed for the following BM: CG_F, CG_B, WG_F, WG_B, HG_F, HG_B, AW_F, AW_B, SL, SSN_F, SSN_B, UAG and to the depth of axilla depth.

Secondly, different methods were applied to determine the concrete values of E_C and E_V. Eases to body measurements WRG, AW_F, AW_B, UAG, SLwere directly referred from the existing books for pattern making [69, 104 –

107, 156].

Eases to CG_F, CG_B, WG_F, WG_B, HG_F, HG_Bdepended on both of the individual BM_N and the ease to full girths (CG, WG, HG). The former were impossible to investigate with the existing resources, but the latter was accessible. Therefore, eases to CG, WG, HGfor different shirt style were surveyed by measuring the real shirts in physical stores and recording the useful information of the shirts sold in the online shops.

In total, 62 shirts of the specific sizes (e.g., 170/92A) from 15 brands (Beanpole, C&A, Fun Day, GAP, Gloria Jeans, Hugo Boss, H&M, Modis, Jack&Jones, K-Boxing, Oodji, O’Stin,SANTA BARBARA POLO＆RACQUET CLUB, Scofield, Urban Revivo) were included. The ease values of each shirt were calculated by subtracting BM in the sizing systems from the shirt measurements as Equation (4.1).

$$E = SM - BM, \tag{4.1}$$

where: E represented the eases (to CG, WG, HG), SM represented the shirt measurements (CG, WG, HG of the shirt), BM were referred from the BM of typical bodies in sizing system.

And the round average ease values were concluded as E_{CG}, E_{WG}, E_{HG}. These eases were shown as Table A.B - A.E. in Appendix A.

EasestoNG_F, NG_B, NW, PPN_F, PPN_B were unknown from the existing resources, with the only useful information that E_{NG} (ease to full neck girth) was usually 2 … 3cm. The gradient virtual try-on experiments were conducted by gradually change the five eases values. The applied eases values were determined when the shirt achieved the best fit and the neckline were located exactly.

Therefore, the constant and variant ease values were concluded as Table 4.2.

Table 4.2 - Constant and variant eases for constructing an e-bespoke shirt

Body measurement	Ease allowance, cm, for different shirt style			
	body-fit	slim-fit	regular-fit	loose-fit
constant ease E_C				
NW	2.0			
PPN_F	0.5			
PPN_B	- 0.5			
NG_F	1.5			
NG_B	0.5			
WRG	6.0			
Variant ease E_V				
CG	5.0	10.0	16.0	25.0
WG	14.0	18.0	23.0	33.0
HG	7.0	8.0	12.0	20.0
AD	1.5	3.0	4.5	6.0
UAG	8.0	10.0	12.0	15.0
AW_F	2.0	4.0	6.0	8.0
AW_B	2.0	4.0	6.0	8.0
SL	0	0.5	1.0	1.5
SSN_F	0	0.5	1.0	1.5
SSN_B	0	0.5	1.0	1.5

As shown in Table 4.2, the constant and variant eases could be utilized in pattern making to assure both the appropriate space for movements and the desired shape of different styles. By systematically using the two types of eases $E_C$and E_V, the integral shirt pattern could be designed with preferred shirt style, exact landmark position and adequate air volume.

4.2.2. Generation of shirt patterns

4.2.2.1. E-bespoke shirt patterns

Several procedures were required to generate the e-bespoke men's shirt pattern stepwise.Firstly, the converted BM_N which could be directly utilized in pattern designing were generated from the individual VC after 3D body scanning.Secondly, the shirt style was selected among the four existing ones. Hereby the ease allowances for different fragments were determined.Thirdly, the pattern indexes for different fragments were calculated by adding the values of corresponding BM and ease together as equation (4.2).

$$I_P = BM_N + E, \tag{4.2}$$

where: I_P was the pattern index, BM_N was the individual new body measurement and E was the ease allowance of the same fragment.

According to Equation (4.2), three type of I_P were proposed for pattern drafting:

Index 1 (I_1) - equaled to the raw corresponding BM, e.g., shoulder length I_1-AL;

Index 2 (I_2) - equaled to the sum of corresponding BM and constant ease E_2, e.g., cuff length I_2-WRG;

Index 3 (I_3) - equaled to the sum of corresponding BM and variant ease E_3, e.g., front and back chest width I_3-$CG_F$and I_3-CG_B;

Index 4 (I_4) -– equaled to the variant ease E_3 without BM, e.g., armhole depth downwards from chest line I_4-AD.

All of the four types of pattern indexes were calculated as Table 4.3.

Table 4.3 - Pattern indexes for the e-bespoke shirt

Type	I_P-	Equation, cm	Type	I_P-	Equation, cm
I_1	SNW_F	SNW_F	I_3	SSN_F	$SSN_F + E_V$- SSN_F
	SNW_B	SNW_B		SSN_B	$SSN_B + E_V$- SSN_B
	D_{CW}	D_{CW}		CG_F	CG_F + part E_V-CG
	D_{WH}	D_{WH}		CG_B	CG_B + left E_V-CG
	AL	AL		WG_F	WG_F + part E_V-WG
I_2	NG_F	$NG_F + 1.5$		WG_B	WG_B + left E_V-WG
	NG_B	$NG_B + 0.5$		HG_F	HG_F + part E_V-HG
	NW	NW + 2.0		HG_B	HG_B + left E_V-HG
	PPN_F	PPN_F+ 0.5		AW_F	AW_F+ E_V-AW_F
	PPN_B	PPN_B - 0.5		AW_B	AW_B+ E_V-AW_B
	WRG	WRG+ 4.0		UAG	UAG+ E_V-UAG
I_3	SL	SL + E_V-SL	I_4	AD	E_V-AD

As shown in Table 4.3, in total 24 final indexes were proposed, including five I_1 which assured the correct positions of landmarks and structural lines, six I_2 which assured the appropriate air volume or space between cloth and body and 12 I_3 which assured the variable shirt styles, and one I_4 which configurated the armhole depth.

Fourthly, the e-bespoke shirt pattern fragments could be drafted with I_P through the short measure method (See Section 1.3.2) as shown in Fig. 4.4.

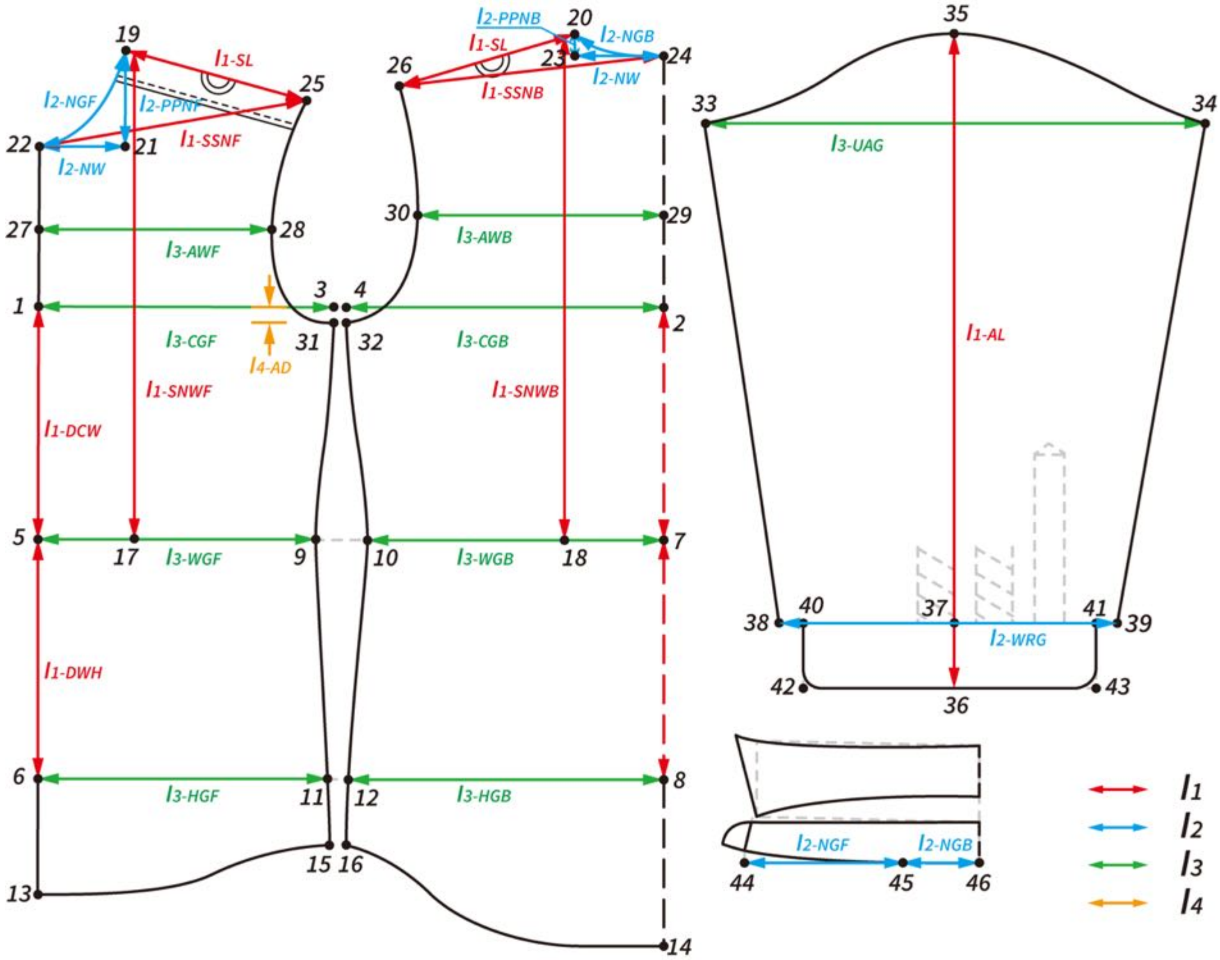


Figure 4.4 - Scheme of customizing an e-bespoke shirt pattern

As shown in Fig. 4.4, the main fragments of e-bespoke shirt patterns were customized by connecting 46 referential points in sequence by applying corresponding I_P (Table 4.3). The black curve lines depended on the design of shirt, and the collar piece was generated by conventional proportional method. The main bodice, neckline, shoulder line, armhole line, sleeve and collar were determined stepwise. The final patterns were generated after certain adaptions (e.g., yoke making) and checking (e.g., length of seamed counterparts, smoothness of adjacent curves).

4.2.2.2. RtW and MtM shirt patterns

The RtW and MtM shirt patterns for the seven 170/92Y VC were drafted at the same time for comparison.

The RtW shirt pattern were referred from the proportional method. Four BM_E (CG, BL, NG, AL) from the sizing system were applied to calculate I_P for all fragments by predefined regression equations (as Fig. 1.16).

The MtM shirt patterns were drafted thorough the combined method which involved both proportional and short measure. After the survey of the BM used in the clothing customization ateliers [29-38], 14 BM_E for calculating I_P for MtM pattern making were concluded: CG, WG, HG, NG, BL, AL, WRG, UAG, SNW_F, SNW_B, D_{CW}, D_{HW}, AW_F, AW_B. The eases$E_C$and E_V(Table 4.2) were also used in constructing RtW and MtM patterns.

4.2.3. Comparison between shirt patterns

To illustrate the influence of BM_N and the ability of the new database created to present the morphological features of male bodies, the RtW and e-bespoke shirt patterns in body-fit style were designed for the seven 170/92Y subjects. The contours of each pattern were overlapped as Fig. 4.5. As usual, the armhole dart is only applied in women's wear. However, the front breasts of S_{37} and S_{72} were too bulgy, and the armhole darts were applied to make the scye and chest area smooth.

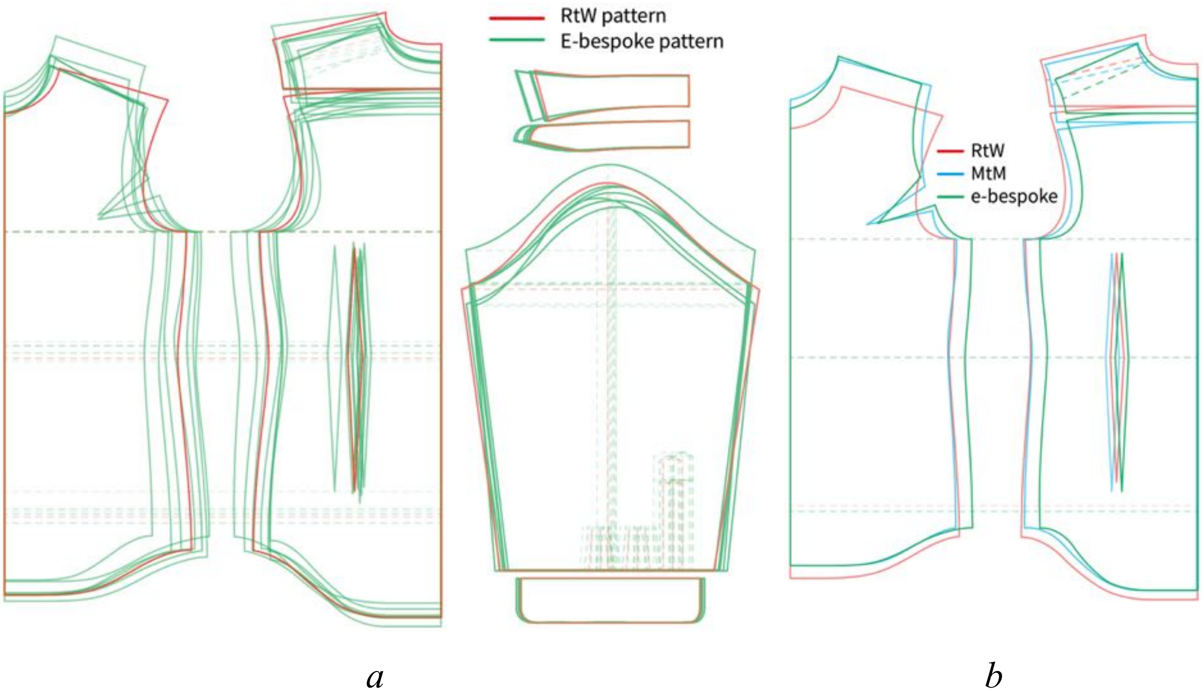


Figure 4.5 - Overlapped patterns:
a - RtW, e-bespoke patterns for 170/92Y subjects,
b - RTW, MtM, e-bespoke patterns for subject S_{72}

As shown in Fig. 4.5, *a*, significant differences not only existed between the two categories of RtW and e-bespoke, but also existed between seven e-bespoke patterns in the horizontal and vertical anteroposterior proportions of the bodices, shapes and proportions of necklines, size of collars, lengths and directions of shoulder lines, lengths and widths of sleeves, and lengths of cuffs. These distinct characteristics of each e-bespoke pattern followed the individual morphological features, which were incapable to be reflected by BM_E and conventional constructing methods.

S_{72} were featured by the more untypical morphology with very bulging chest and larger proportion of front torso. Thus, the RtW, MtM and e-bespoke bodice patterns for S_{72} were compared as an example (Fig. 4.5, *b*), sleeves and collar patterns were not shown due to the similar contours. Compared with the RtW pattern, MtM pattern modified the proportion of vertical lengths (from SNP to anteroposterior waist), neck girth, and shoulder length with more individual BM_E. E-bespoke and MtM patterns were similar in the proportion of vertical lengths, shoulder length, and neck girth due to the same BM (e.g., SNW_F, SNW_B, SL, NG = $NG_F + NG_B$) and corresponding I_P used. However, the anteroposterior proportion of bodice, neckline shape (front and back neck drop, proportion) and the direction of shoulder line shown great differences owing to the BM_N (e.g., CG_F, CG_B, WG_F, WG_B, HG_F, HG_B, PPN_F, PPN_B, NG_F, NG_B, SSN_F, SSN_B) and corresponding I_P used in e-bespoke.

To illustrate the influence of BM_N and I_P on the different shirt styles, four patterns in body-fit, slim-fit, regular-fit and loose-fit style which were designed for subject S_{72} were overlapped as Fig.4.6. The patterns of collar and cuff are not shown because they are invariable with the style.

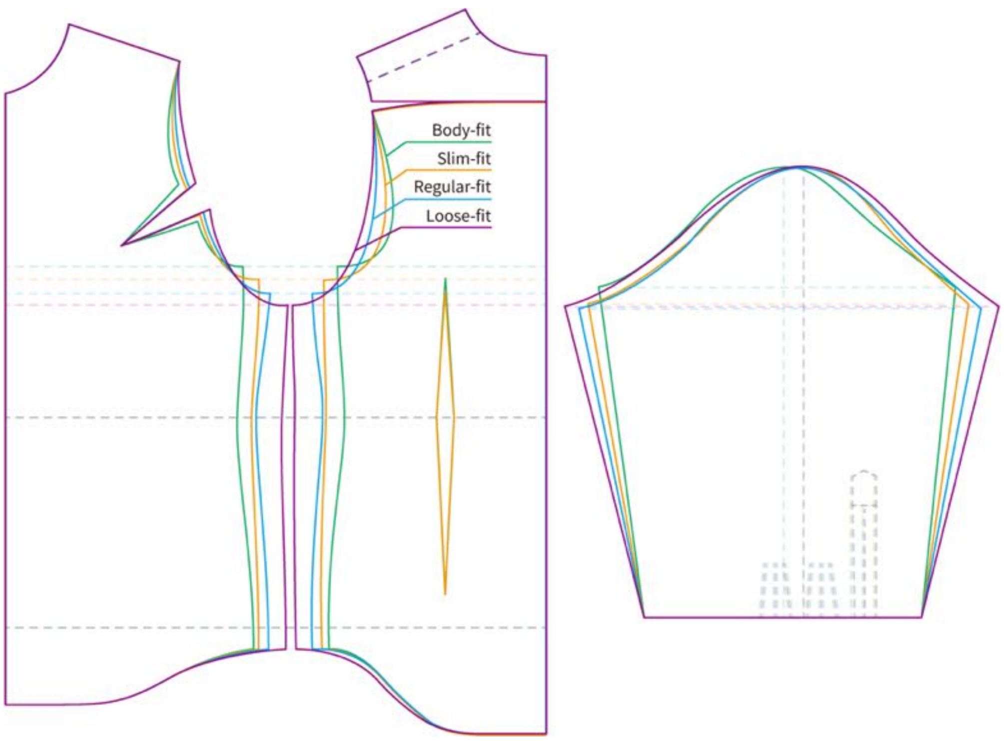


Figure 4.6 - E-bespoke shirt patterns in different styles for subject S_{72}

As shown in Fig. 4.6, the proportions of vertical lengths, neckline shape, shoulder line shape and sleeve length were the same due to the and constant eases E_C used in these fragments. Moreover, the configuration of e-bespoke bodice and sleeve patterns was escalating from the body-fit style to loose-fit style with incremental ease allowances E_V.

4.2.4. Fit prediction with patterns

The e-bespoke pattern involved more individual morphological features than RtW and MtM patterns by using the next BM_N which were measured at the new positions of the body. Moreover, the new pattern indexes I_P were confirmed by adding BM_N and new ease allowances (E_C, E_V) together as in equation (4.2). In reverse, the new ease allowances value could be calculated by subtracting BM_N from corresponding I_P as in Equation (4.3).

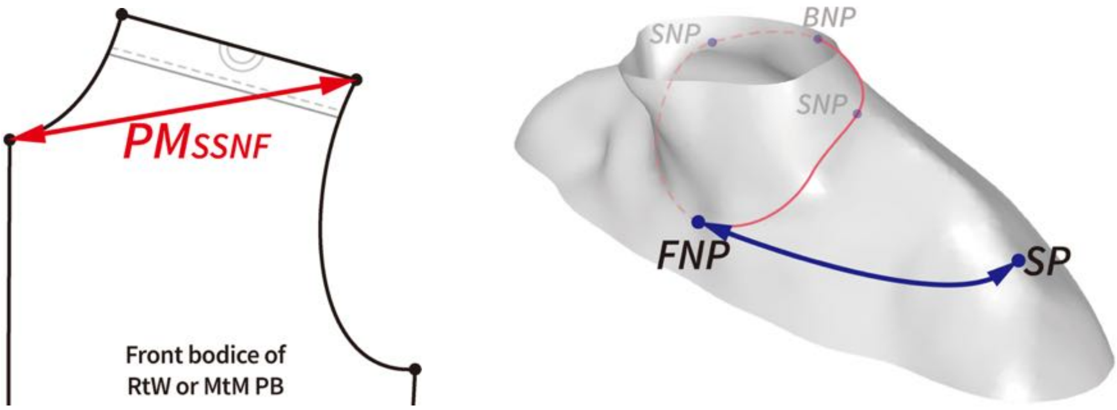
$$E = I_P - BM_N, \quad (4.3)$$

For e-bespoke shirt, E_C, $E_V$was predefined with concrete values to ensure adequate volume and space for particular body segments. However, BM_N were not adopted by the RtW and MtM shirts, and consequently the ease allowances and corresponding I_P were unknown during pattern designing. For instance, BM NG and ease to neck girth E_{NG} were adopted when drafting the necklines of RtW and MtM pattern.

To estimate the fit state of the RtW or MtM final shirts and explain the impact of BM_N on e-bespoke pattern, ease allowances of three types of patterns were compared as equation (4.4) and Fig. 4.7.

$$E_P = PM - BM_N, \quad (4.4)$$

where E_P was the predicted ease, PM was the pattern measurement (from RtW or MtM pattern).



a *b*

Figure 4.7 - PM and corresponding BM:
a - PM_{SSNF}, *b* - SSN_F

As shown in Fig. 4.7, the pattern measurement PM_{SSNF} was measured by connecting the center point of front neckline and the shoulder point on the RtW or MtM pattern, SSN_F was the surface length from FNP to SP on the body surface. And $E_{P\text{-}SSNF}$ could be calculated by subtracting the values of SSN_F from PM_{SSNF}.

PM was exactly equal to I_P in the e-bespoke pattern, while PM were posteriorly measured after RtW and MtM patterns completed by BM_E. Table 4.4 shows BM_N of S_{72} and E_P, PM of three types of patterns.

Table 4.4 - BM_N and PM, E_P of RtW, MtM and e-bespoke patterns of subject S_{72}

Method of pattern drafting	Value of the body measurement BM_N, pattern measurements PM and the predicted ease allowance E_P, cm, for different patterns												
	NW	LPN_F	LPN_B	NG_F	NG_B	SSN_F	SSN_B	CG_F	CG_B	WG_F	WG_B	HG_F	HG_B
	13.6	9.6	3.2	25.6	15.0	21.4	20.2	53.2	40.7	45.2	28.2	49.9	41.5
Value of PM													
RtW	14.4	8.8	1.4	25.2	13.9	23.0	22.2	48.5	48.5	44.0	44.0	50.1	50.1
MtM	15.7	8.8	2.7	25.4	17.2	21.7	21.1	49.5	49.5	43.8	43.8	49.2	49.2
e-bespoke	14.6	10.1	2.7	27.1	15.5	21.4	20.2	55.7	43.2	50.0	37.5	55.5	43.0
Value of E_P													
RtW	0.8	-0.8	-1.8	-0.4	-1.1	1.6	2.0	-4.7	7.8	-1.2	13.8	0.2	8.6
MtM	2.1	-0.8	-0.5	-0.2	2.2	0.3	0.9	-3.7	8.8	-1.4	13.6	-0.7	7.7
e-bespoke	1.0	0.5	-0.5	1.5	0.5	0	0	2.5	2.5	4.8	9.2	5.5	1.5

E_P of e-bespoke pattern were predefined as the new ease allowances E_C and E_V. However, E_P of RtW and MtM patterns were varied: too small values, too large values, or acceptable values. According to the criteria for fit evaluation, the fit state of the final shirt could be predicted with E_P.

Table 4.5 shows the principles to predict misfit with E_P. When $E_{P0} \neq 0$, the imbalance or the malposition of structural lines and landmarks will appear. When E_{PC}, $E_{PV} < 0$, the tight stretched cloth, unnecessary folds or creases will appear at the corresponding segments. When E_{PC}, $E_{PV} > E_C(E_V)$, the loose cloth or excessive size, volume will appear.

Table 4.5 - Principles for predicting fit or misfit with E_P

E_P	Relation	Predicted fit or misfit
E_{P0}	$E_{P0} = 0$	good fit – right position of structural lines and landmarks
	$E_{P0} \neq 0$	misfit – imbalance or the malposition of structural lines and landmarks
E_{PC},E_{PV}	$E_{PC}(E_{PV}) < 0$	misfit –tight stretched cloth, unnecessary folds or creases
	$0 < E_{PC}(E_{PV}) < E_C(E_V)$	misfit – small size with less volume
	$E_{PC}(E_{PV}) = E_C(E_V)$	good fit – balanced structural lines and landmarks without folds
	$E_{PC}(E_{PV}) > E_C(E_V)$	misfit – large size with more volume

As shown in Table 4.4 and 4.5, E_P were used to predict the possible misfit appeared on the RtW and MtM shirts by comparing with the e-bespoke ones.

Both of the two types of patterns neglected the proportion of front and back neck. For the RtW pattern, except for $E_{P2\text{-}NW}$, the other four eases (E_{PC}-PPN_F, E_{PC}-PPN_B, E_{PC}-NG_F, E_{PC}-NG_B) were negative (PM < BM), resulting in the small and tight neckline above natural FNP and BNP. For MtM pattern, too large E_{PC}-NW and E_{PC}-NG_B led to the profile and back necklines lower than natural SNP and BNP, and negative E_{PC}-LPN_F and E_{PC}-NG_F led to the upper front neckline.

Moreover, excessive E_{P0}-SSN_F and E_{P0}-SSN_B gave rise to the improper position and sloping of shoulder line of the shirts with deformation around shoulder. Lastly, inadequate front girths of the pattern with negative E_{PV}-CG_F, E_{PV}-WG_F and E_{PV}-HG_F resulted in the stressed folds and deformed structural lines of the bodice.

The virtual try-on experiments of three types of shirts were simultaneously executed in CLO 3D to examine the accuracy of these principles and to prove the influence of BM_N and e-bespoke pattern (See Section 5.3).

Conclusion after Chapter 4

1. The database of new ease allowances were established, which could be utilized to calculate the pattern indexes for e-bespoke shirt. A part of the eases could also be applied in RtW and MtM shirt patterns.

2. The method of drafting e-bespoke pattern could exactly generate the individualized shirt patterns with assured high-level fit. The e-bespoke shirt pattern shown distinct difference with the RtW and MtM ones owing to the involvement of BM_N.

3. The fit state of a RtW or MtM patterns could be predicted by comparing with the e-bespoke pattern based on specific principles.

CHAPTER 5. VIRTUAL E-BESPOKE MEN'S SHIRT

With the enhancement of VR technology, the digital twin of system "male body - shirt" (DT_S) were created by integrating the virtual twins of male bodies (VT) which transformed from the VC, digital twin of textile materials (DT_M) which generated by algorithms and sensory experiments, and the e-bespoke shirt patterndraftedbased on BM_N.

The generated virtual e-bespoke shirts were evaluated subjectively and objectively, showing good clothing fit which was much better than the exiting RtW and MtM shirts. Moreover, the practical production of the real and virtual e-bespoke shirts that were produced for distinct male consumers proved the validity and feasibility of the approach to e-bespoke shirt generating.

The results obtained in this chapter are published in three work [161, 168, 169, 171].

5.1. Methods of research

With the help of virtual fitting visualization in CLO 3D, the virtual e-bespoke shirts were produced based on the selected subjects for generating VT and mechanical properties of textile materials for generating DT_M.

5.1.1 Instruments and software

KES-F instruments FB1, FB2, FB3 was used to measure the mechanical properties of the fabrics.

3D CAD software CLO 3D (version 5.0.156.38765, CLO Virtual Fashion, Republic of Korea) was applied as the VR platform to accomplish the whole virtual fitting and evaluation procedures. Different modules were involved for realistic fitting effects: avatar editing modules that could generate different types of fitting body models, 3D sewing modules that could edit the craftsmanship and details of the shirt sewing, digital fabric module that provided certain number of default fabrics and generated individualized fabrics, 3D virtual simulation module that could visualize and evaluate the virtual sewed clothing effects (See Section 1.5.2).

Moreover, ET CAD were utilized for exporting shirt pattern in .dxf format to CLO 3D. Rhinoceros was applied to process and measure the VC and VT. Online platform Mixamo was utilized for inserting virtual skeletons and joints in VC. Adobe Photoshop and Illustrator were used for post-processing the images and creating the graphs, respectively.

5.1.2. Properties of textile materials

For more realistic effects of the digital fabrics, the mechanical properties (tensile, shearing, bending) of five distinct textile materials were measured by KES-F (as shown in Table 3.1). The property indexes were imported to CLO 3D to generate the corresponding digital fabrics.

5.1.3 Subjects of the research

The before-mentioned seven male bodies of 170/92Y type with various morphological features (see Section 4.1.2) were selected as the subjects (S_3, S_8, S_{34}, S_{37}, S_{56}, S_{72}, S_{87}). These subjects were transformed to VT which acted as the virtual fitting body model in CLO 3D.

5.2. Generation of e-bespoke shirt

The virtual e-bespoke men’s shirts were generated stepwise based on the generation of boned VT with the same morphology as real body, the DT_M as the counterpart of the real fabrics and the e-bespoke pattern designed for each individual body.

5.2.1. Virtual twins of male bodies

VT is the morphed virtual human body that is applied BM either through manual or automatic measurements [91], which often acts as the 3D body model for clothing try-on in VR. One of the primary factors that influence on the quality and reliability of the virtual clothing is the correspondence between VT and real body.

As discussed in Section 1.5.2, four kinds of VT (Fig. 1.34) could be generated by different methods:

VT_D: default VT with typical morphological features and BM selected from the existing library in CLO 3D;

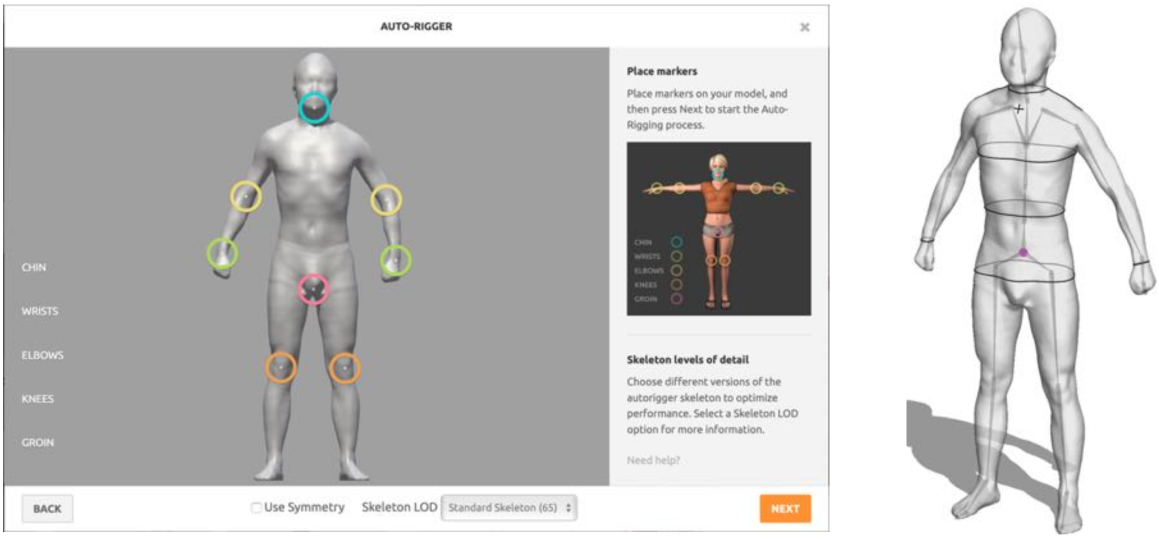
VT_P: parametric VT with adaptive morphology generated by inputting basic BM;

VT_C: VT that transformed from the VC after 3D body scanning;

VT_I: individualized VT that automatically generated by inputting VC, which were the latest function released by CLO 3D.

As shown in Fig. 1.34, VT_C possessed the original individual morphology because all the mesh data was collected from real scanned body, VT_I looked much similar as VT_C, while VT_D shown totally different body shape and height, VT_P had obvious morphology although the height is controlled. Therefore, the adequacy between VT_C and VT_I was further analyzed with subject S_{72} who had the untypical morphology.

The VC was still just like a virtual solid clay rather than a virtual model or avatar, which was difficult to apply in CLO 3D. On the one side, the VC was inserted with the virtual skeletons and joints in Mixamo to generate VT_C (.fbx format) which maintained the real body morphology with changeable poses (Fig. 5.1).



a *b*

Figure 5.1 - Acquisition of VT_C of male body
a - locating of joints in Mixamo, *b* - VT_C with virtual joints and skeletons

On the other side, the VT_I were generated with the same VC inputted in CLO. Hereby, the VT_C and VT_I could be compared from different aspects: the cross-sections in different directions, positions, and BM of different sections.

To conduct the comparisons,the VT_C and VT_I were sliced simultaneously in different directions in Rhinoceros to obtain the coronal, profile and horizontal cross-sections of the torsos, and the 3D contours of necklines (Fig. 5.2).

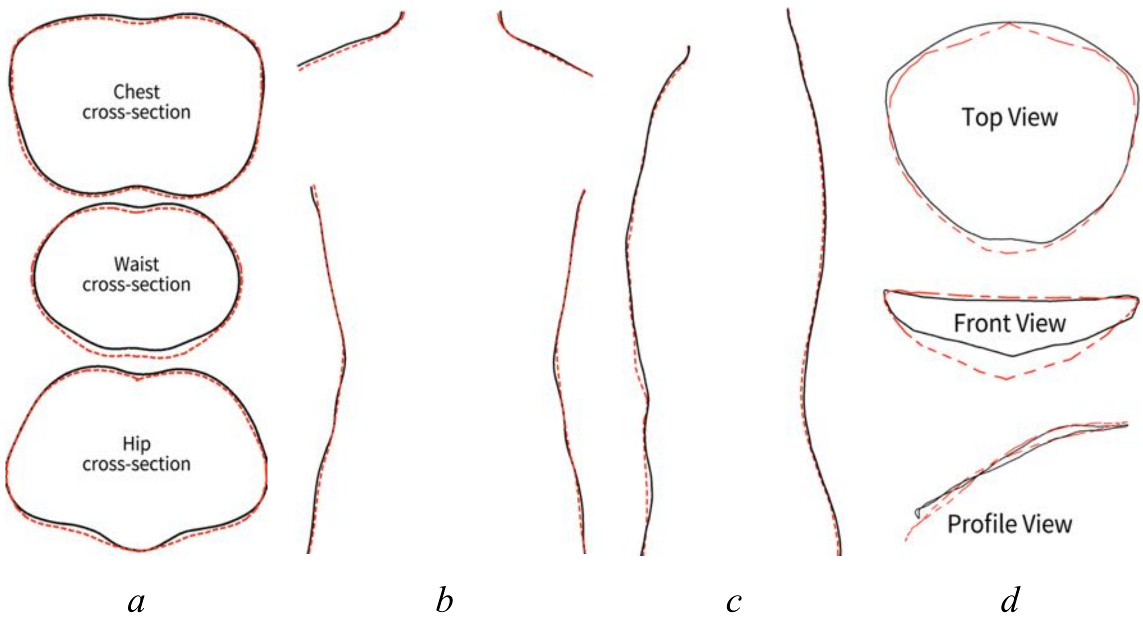


Figure 5.2 - Cross-sections of VT_C (solid lines) and VT_I (dashed lines):
a - torsos in horizontal view, *b*- torsos in coronal view,
c- torsos in sagittal view, *d* - contours of necklines

As shown in Fig. 5.2, the main torso sections of VT_C and VT_I were highly similar as the cross-sections were overlapped at the close positions. Two necklines also generally shown similar shape. However, the detail differences (back neck line contour, front neck depth, profile projection of front neck) were observable.

Some of the BM_N that could reflected the important morphological features (As Section 2.3) were measured with VT_C and VT_I at the same levels or positions. Table 5.1 shows the BMN of VT_C and VT_I.

Table 5.1 - Primary new body measurements of VT_C and VT_I

Type of virtual twin	Result of measurement BM_N of virtual twin, cm									
	CG_F	CG_B	WG_F	WG_B	HG_F	HG_B	NG_F	NG_B	SL	AL
VT_C	53.3	40.9	44.6	28.1	49.9	41.7	25.6	15.0	13.7	55.5
VT_I	54.2	40.9	46.5	28.1	50.2	41.5	26.0	15.3	13.3	58.6
Difference	0.9	0.0	1.9	0.0	0.3	0.2	0.4	0.3	0.4	3.1

As shown in Table 5.1, VT_C and VT_I generally possessed the similar

BM.However, certain differences were also observed with CG_F, WG_F, NG_F, NG_B, SL and AL. The differences between CG_F and WG_F would lead to the imbalance of body-fit bodice. The differences between NG_F, NG_B and SLled to malposition of neckline and shoulder line. AL of VT_I was too large comparing with VT_C.

Although VT_C and VT_I had the generally similar exterior shapes and appearances, the detailed morphological features were different in their contours and BM. For the higher accuracy and more realistic results, VT_C of the seven selected subjects were imported to CLO 3D as the virtual body model.

5.2.2. Digital twins of textile materials

Another primary factor that influence on the quality and reliability of the virtual clothing is the correspondence between DT_M and real textile materials.

The mechanical properties of real fabrics and the digital properties of virtual fabrics were totally different. Therefore, two procedures were employed to generate the DT_M as the counterpart of real fabrics.

Firstly, the initial virtual fabrics were generated. According to the types and contents of the real fabrics, the proximate virtual fabrics could be selected from the fabric library in CLO 3D. The thickness (mm), density (g/m^2) of virtual fabrics were adapted as the basic information of real fabrics (Table 3.1). Then the conversion algorithms (5.1-5.3) proposed [149] were utilized based on mechanical property parameters (RT, EMT, Fmax, G) measured by KES-F (Table 3.1).

$$Y_1 = (1/RT_{warp} + 1/EMT_{warp})\ 10^5 + F_{max.warp} + a, \quad (5.1)$$

$$Y_2 = (1/RT_{weft} + 1/EMT_{weft})\ 10^5 + F_{max.weft} + a, \quad (5.2)$$

$$Y_3 = (G_{warp} + G_{weft})\ 10^4, \quad (5.3)$$

where: RT is the recoverability, %; EMT is the elongation under 500 cN/cm, %; Fmax is the same as $F(_{Emax})$, which is the load/tension force at E_{max}, where the range is 6.1–448.5 gf/cm; G is the shear rigidity in the bias direction. The digital parameters in CLO 3D are: Y_1 is brought into the "stretch of stiffness-warp (g/s^2)" without units; Y_2 is brought into the "stretch of stiffness-weft (g/s^2)" without units; Y_3 is brought into the "shear of stiffness (g/s^2)" without units; a is the correcting factor, without units.

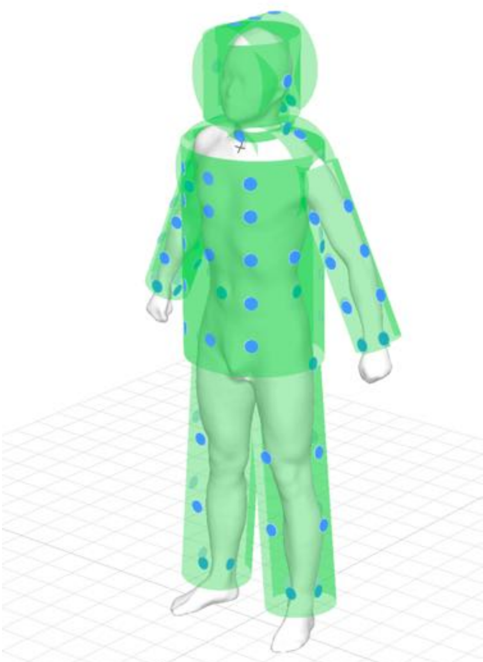
Secondly, the final DT_Mwere generated. the sensory experiment was carried out to adjust the digital properties by comparing the images of real and virtual fabric draping by the method proposed [157, 158].

Therefore, The DT_M were capable of simulating the realistic wearing effect, helping us to precisely analyze and evaluate the apparel fit of simulated e-bespoke shirts.

5.2.3.Digital twins of e-bespoke shirts

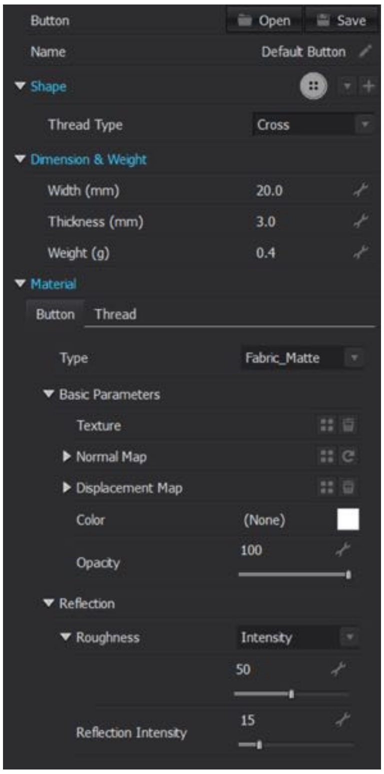
According to the common process of virtual clothing making, a virtual e-bespoke was generated by following five steps in CLO 3D.

Firstly, the VT_C (.fbx format) transformed from VC was imported to CLO 3D. As shown in Fig. 5.3, *a*, each body segments (Arm_L, Arm_R, Wrist_L, Wrist_R, Body_L, Body_R, Shoulder_L, Shoulder_R, Head_L, Head_R, Head_vertical, Neck_L, Neck_R, Leg_L, Leg_R, Ankle_L, Ankle_R) were defined in avatar editor, which made it easier for arranging the 3D pattern piece on the right positions around VT_C in the subsequent step.

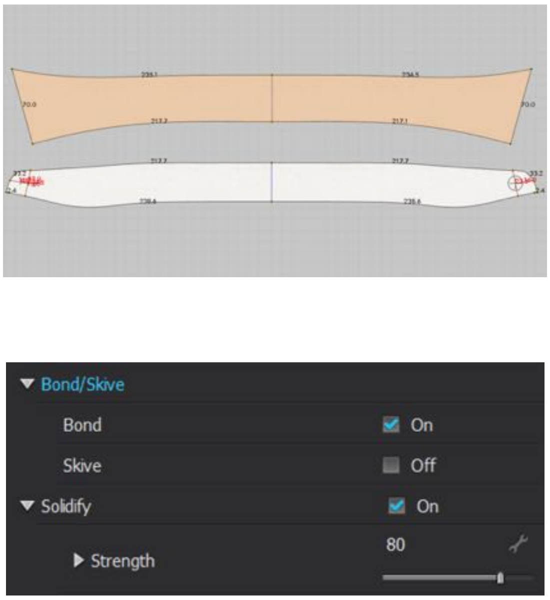


a

b



c



d

Figure 5.3 - Processes of virtual shirt making in CLO 3D:
a - defining of body segments on VT_C, *b* – craftsmanship, arrangement of 3D pieces and seams, *c* - design of buttons, *d* - arrangement of lining in collar piece

Secondly, the e-bespoke patterns (.dxf format) drafted in ET CAD was imported to CLO 3D.

Thirdly, the sewing craftsmanship for the 3D pattern pieces was edited (Fig. 5.3, *b*-*d*). Each 3D pattern piece (front bodice, back bodice and placket, collar stand and turnover collar, sleeve, its placket and cuff) were arranged on the corresponding body segments (body, neck, arm), respectively. Moreover, the buttons and buttonholes were located and designed, the lining was made on the placket, collar and cuff pieces. Finally, the seams of the adjacent pairs were defined and the darts were sewed up.

Fourthly, the DT_M was determined as Section 5.2.2.

Finally, the 3D virtual fitting visualization of e-bespoke shirt was conducted automatically with all pieces sewed up and draped on the VT_C.

5.3. Evaluation of virtual e-bespoke shirts

To check the proposed scheme of BM_N, mew method of pattern drafting and the virtual e-bespoke shirts, the fit evaluation was conducted subjectively and objectively in CLO 3D. The comparative experiments with RtW and MtM shirts proved the validity and advantages of the e-bespoke method.

5.3.1.Subjective evaluation

In subjective evaluation, the experts who were professional in clothing and pattern design were enrolled to subjectively evaluate the virtual images of e-bespoke shirts generated by CLO 3D. They were required to learn the criteria for evaluating men's shirt (Section 3..3.3) and to rate the wearing effects of each shirt by using a five-point scale (1 = worst, 2 = poor, 3 = medium, 4 = good, 5 = best) in consideration of smoothness, locations of structural lines and landmarks, anteroposterior balances, etc.

Among the shirts in four different styles, the body-fit shirts tend to exhibit the more misfits due to the thinnest air volume between the cloth and the body.When the configuration is incongruent with the morphology and proportions of VT_C, the evident misfit could be observed. Thus, the body-fit shirt is most sensitive to show the misfit caused by defective designs. Fig. 5.4 shows the exterior appearances of e-bespoke body-fit shirts on seven 170/92Y subjects (S_3, S_8, S_{34}, S_{37}, S_{56}, S_{72}, S_{87}).

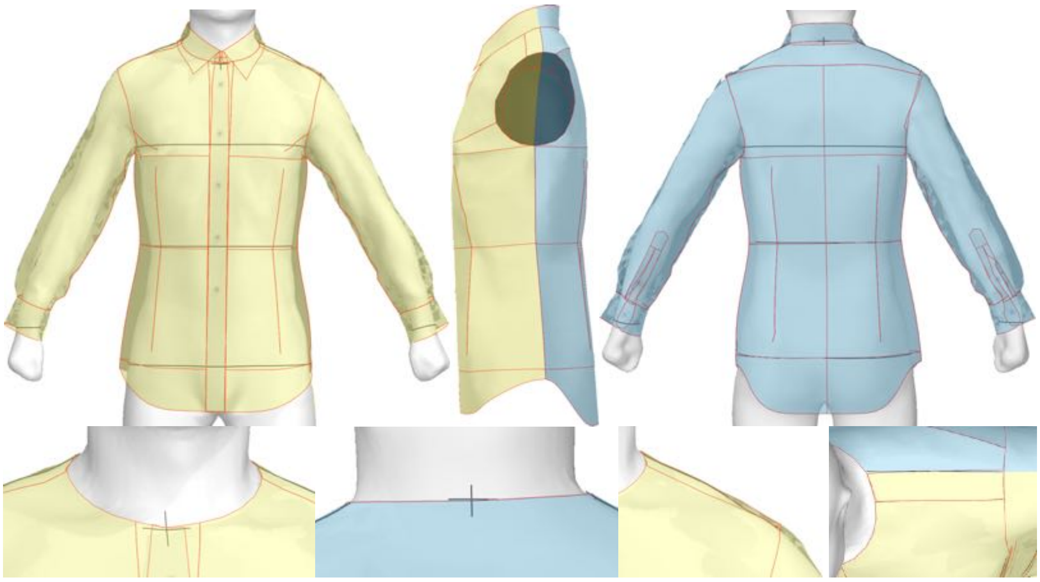
a

b

c

d

e



f

g

Figure 5.4 - Front, profile, back holistic views and details of neck and shoulder of virtual e-bespoke shirts in body-fit style for the 170/92Y subjects:
a - S_3, *b* - S_8, *c* - S_{34}, *d* - S_{37}, *e* - S_{56}, *f* - S_{72}, *g* - S_{87}

As shown in Fig. 5.4, the black lines were the primary landmarks (chest, waist, hip, FNP, SNP, BNP, shoulder line) on the surface of VT_C, the red lines were the essential structural lines of the shirts, the yellow and blue areas represented the front and back parts, respectively.

Seven e-bespoke shirts exhibited good clothing fit despite the significantly different morphological features and pattern constructions. In general, the bodice, shoulder and armhole segments were smooth; chestlines, waistlines and hiplines were horizontally located near the natural levels; side seams were vertical to the ground; necklines and shoulder liens precisely coincide with the natural landmarks.

Concretely, the diagonal fold existed on the profile of S_{56} as a result of an overlarge back proportion (CG_F = 39.1 cm, CG_B = 52.7 cm, HG_F = 38.7 cm, HG_B = 50.4 cm), and the slight bulge on the front of S_{87} was caused by an overlarge front proportions (CG_F = 41.3 cm, CG_B = 30.7 cm, HG_F = 51.9 cm, HG_B = 42.9 cm). Those whose shoulder is forward thrust (S_3, S_{56}, S_{87}) tended to show a slightly unsmooth armhole with pointed bulges. Moreover, the yoke part could not cling to the shoulder due to the concave mid shoulders of subjects S_8, S_{34}, S_{37}, S_{56}. Based on images of seven virtual e-bespoke shirts try-on models, the scores of the subjective evaluation were given by the experts (Table 5.2).

Table 5.2 - Subjective evaluation of seven e-bespoke shirts in body-fit style

Subject	Evaluation of shirt section				Overall score
	Bodice	Neck, collar	shoulder	Armhole, sleeve	
S_3	5	4	3	4	4
S_8	4	5	5	5	5
S_{34}	5	4	4	4	4
S_{37}	4	5	4	5	5
S_{56}	4	5	4	4	4
S_{72}	4	5	5	4	5
S_{87}	4	5	4	4	4

As shown in Table 5.2, seven e-bespoke shirts were rated as good or best clothing fit with overall scores ranging from 4 to 5. For most subjects, scores of bodice, neck, shoulder and sleeve were equal to or greater than 4 point. Exceptionally, the shoulder of S_3 was evaluated as the medium fit due to the minor asymmetry of left and right shoulder sloping.

Comparative virtual try-on experiments of RtW, MtM and e-bespoke shirts were conducted in CLO 3D at the same time. To concretely illustrate the differences between three types of shirts, the case of subject S_{72} was exhibited as an example. Fig. 5.5 shows the virtual try-on effects of RtW and MtM shirts on S_{72}.

a

b

c

Figure 5.5 - Front, profile, back holistic views and details of neck and shoulder of virtual shirts in body-fit style for subject S_{72}:
a- RtW, *b* - MtM, *c* - e-bespoke

As shown in Fig.5.5, the RtW and MtM shirts were worse fitted on the subject than e-bespoke one. The RtW shirt exhibited an evident poor clothing fit with distortion in the back and armhole, tight upper neckline, too long shoulder with big bulge and too long sleeves.

With more individual BM_E applied, the MtM shirt was better fitted to the subject with smoother back contour and armhole, looser neckline, and shorter shoulder and sleeve. However, some misfit features still remained in the MtM shirt: oblique side seam, chest, waist and hip lines, malposition of landmarks (FNP, BNP, SNP, SP), and small bulge on SP. The reason was that BM_E were still incapable of characterizing the primary body morphology. First, NG alone could not well reflect the concrete neckline shape and landmarks. Second, SW alone could not precisely locate the shoulder and SP. Third, the anteroposterior proportion of the bodice could not be balanced with only CG, WG, and HG. Although SNW_F and SNW_B helped to balance the proportion of vertical lengths, it would also be implicated by the unbalanced girth proportions.

In accordance with the aforementioned criteria of fit evaluation and the five-point rating scale, the subjective evaluation of the RtW and MtM shirts for the seven subjects was simultaneously executed by the experts. Table 5.3 shows the mean scores of the subjective evaluation of three types of shirts.

Table 5.3. Mean scores of subjective evaluations of RtW, MtM, and e-bespoke shirts in body-fit style

Shirt type	Evaluation of shirt section				Overall score
	Bodice	Neck, collar	shoulder	Armhole, sleeve	
RtW	1.3	1.3	1.1	1.6	1.4
MtM	2.6	1.6	2.1	2.9	2.6
E-bespoke	4.1	4.7	4.1	4.3	4.4

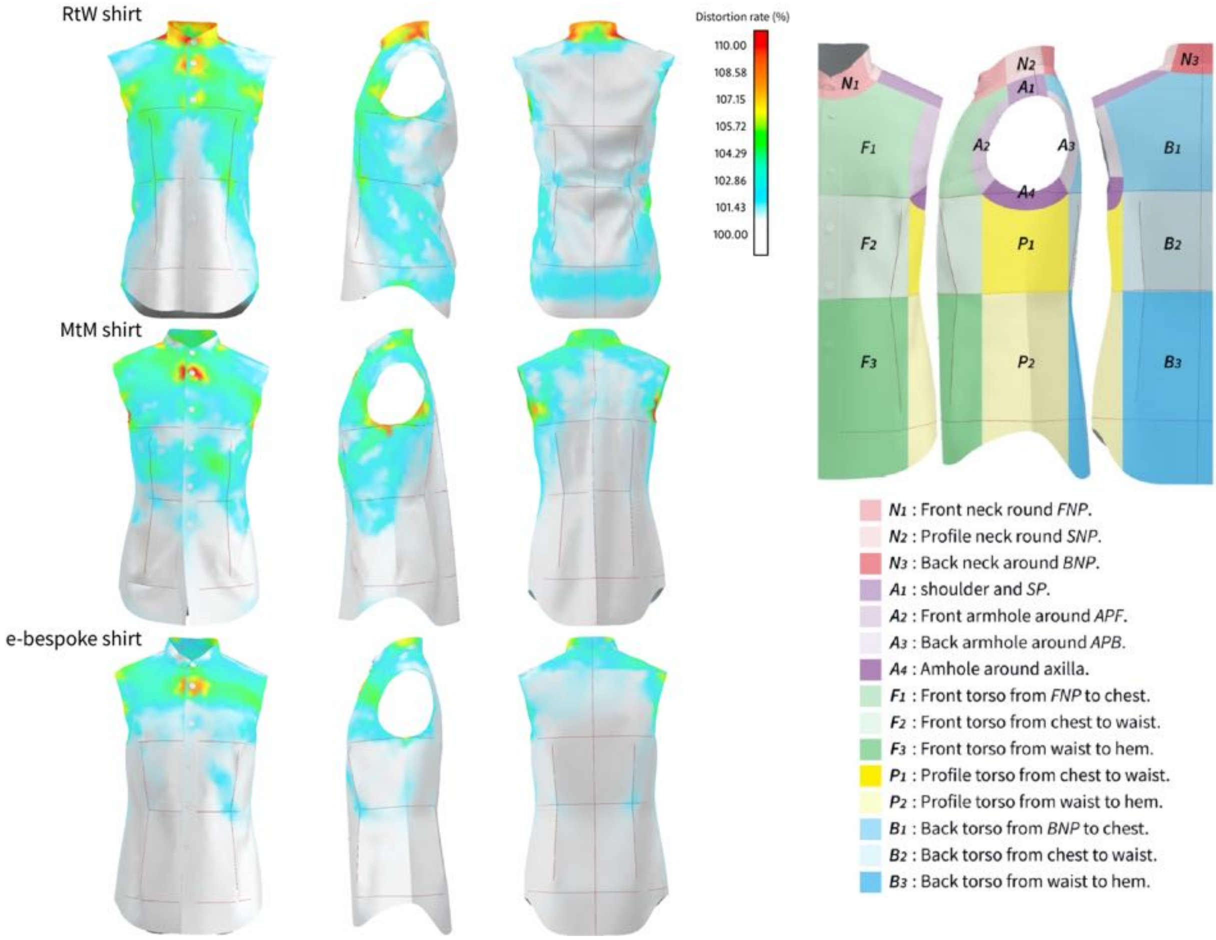
As shown in Table 5.3, RtW, MtM, and e-bespoke shirts in body-fit style were generally rated as worst fit, medium fit, and good fit levels, respectively. Although MtM shirts were made by the individual BM_E, the clothing fit obtained was not satisfactory, especially in bodice, neck, and shoulder. By contrast, the e-bespoke exhibited good apparel fit of every segment with the next BM_N and new customized pattern involved.

Therefore, from the results of subjective evaluation of three types of body-fit shirts, the e-bespoke method could assure the invariable good fit for the Y-type and A-type subjects, which was superior to the contemporary RtW and MtM shirts.

5.3.2. Objective evaluation

The strain map and measurements of distortion rate of three types of shirts were utilized in CLO 3D to shown the impact of BM_N and e-bespoke pattern. A Clothing's distortion rate represented the distortion caused by external stress appeared in percentage. The high distortion rate was often observable when misfit appeared or ease allowance was inadequate. A strain map reflected the distortion on the clothing by gradient colors. In this evaluation, color from white to blue, green, yellow and red illustrated the distortion rate from100% (no distortion) to 110%.

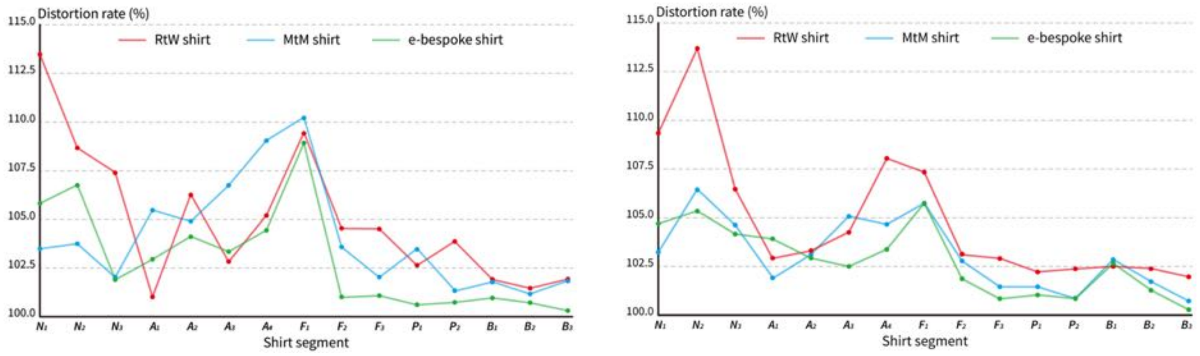
The turnover collars were concealed for better observation of necklines, and sleeves were concealed due to the similar pattern as RtW and MtM. Fig. 5.6 shows the strain maps of three types of shirts and segmentation for measuring the distortion rate.



a *b*

Figure 5.6 - Strain maps of RtW, MtM and e-bespoke shirts in body-fit style on subject S_{72}:
a - stain maps, *b* - segments for measuring the distortion rates

Fig. 5.6, *a* shows the strain maps of three types of shirts, Fig. 5.6, *b* and Fig. 5.7, *a* show the distortion rates of different segments of three types of shirts. As shown in Fig. 5.6, *b*, the shirt bodice was segmented in to fifteen parts (three on neck, four on armhole, three on front bodice, two on profile bodice and three on back bodice) to exactly demonstrate the distortion distribution of different areas.



a *b*

Figure 5.7 - Variation of distortion rates of RtW, MtM and e-bespoke shirts in body-fit style of:
a - subject S_7, *b* - of mean values of seven 170/92Y subjects

As shown, the e-bespoke shirt exhibited the least distortion area. The asymmetric neck, the large front chest, and the prominent tissue on the front waist led to the relatively higher distortion rates in the left neck, second button on the placket, and front waistline, respectively.

By contrast, the MtM shirt showed more distortion in front chest and waist, scapula, and back armhole owing to the stress force generated by the negative eases of the front torso. Moreover, the front and profile neck segments were distorted the least, not because of the fitted neckline, but because of the loose neck width and unfitted neckline distant from natural FNP and SNP.

The whole body of the RtW shirt was distorted from neck to the hem because of the too small neckline and front girths. The reason for less distortion in the SP area was the excessive up shoulder sloping and long shoulder width (shoulder line and natural shoulder were not contiguous with the big bulge around according to Fig. 5.5, *a*). Similarly, the unfitted excessive back armhole led to less distortion in the back armhole area.

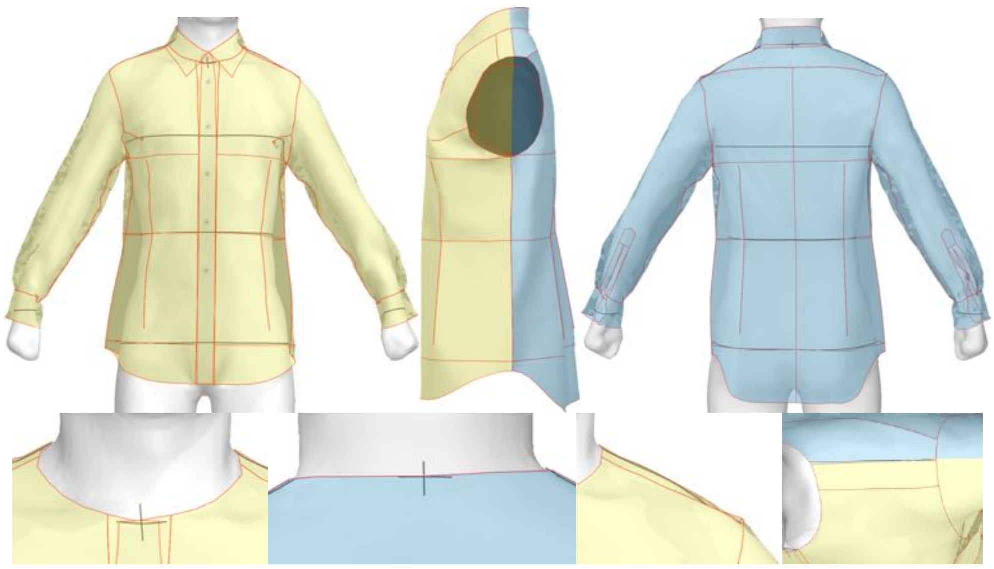
In the same way, the average distortion rates of virtual RtW, MtM, and e-bespoke body fit shirts for seven 170/92Y subjects (in total twenty-one pieces) were measured in CLO 3D. As shown in Fig. 5.7, *b*, most segments of e-bespoke shirts were distorted the least among the three types. As usual, the collar should surround the neck through landmarks, and the whole shirt should overhang on the torso above the chest level (from the upper chest, shoulder, to scapula) with inevitable distortion on the cloth.

Exceptionally, the lowest rate in N_1 of MtM shirts was caused by the unfitted necklines upper than the natural necks of most subjects (as Fig. 5.5, *b*), the lower rate in A_1 of RtW and MtM shirts was caused by the excessive up shoulder sloping of most subjects (as Fig. 5.5, *a*, *b*), and the lowest rate in B_1 of RtW shirts was caused by the malposition of front and back piece (more strain on the front and less strain on the back).

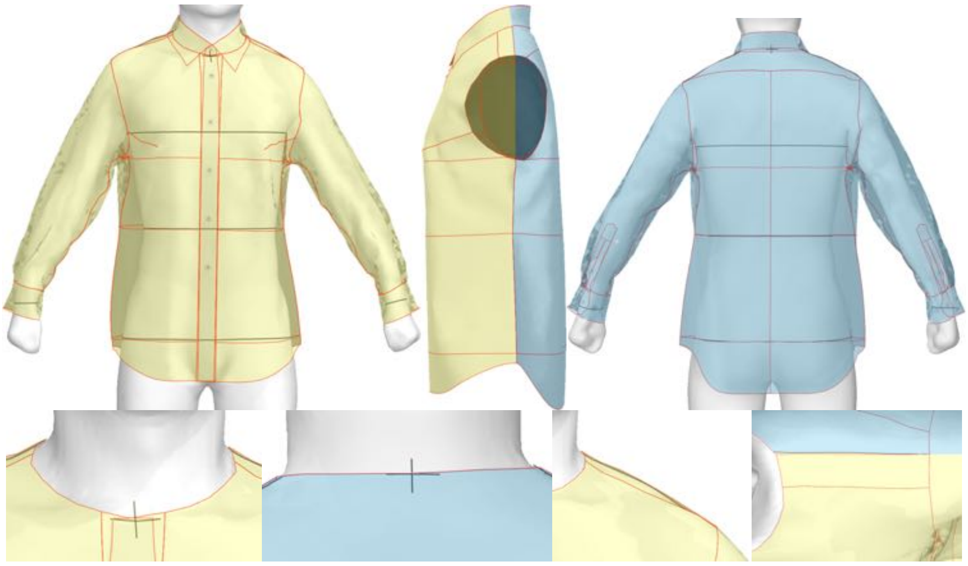
Therefore, the results of objective evaluation confirmed the misfit appeared on three types of shirts, and prove the validity of the principle of fit prediction with pattern (in Section 4.2.4). The e-bespoke method could also assure the less distortion on shirt cloth for the Y-type and A-type subjects than RtW and MtM ones.

5.3.3. E-bespokeshirtsin different styles

Shirt patterns in slim fit, regular fit and loose fit styles were verified simultaneously in CLO 3D. As an example, the results of S_{72} are shown in Fig. 5.8.



a



b

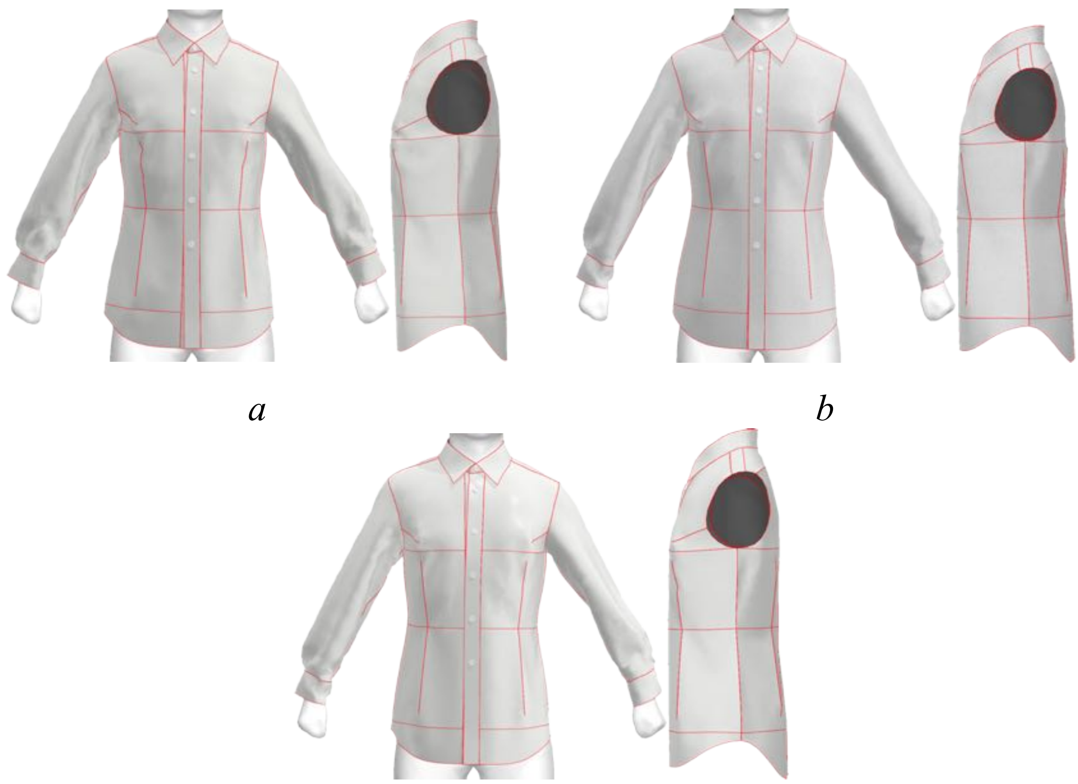
c

Figure 5.8 - Try-on effects of e-bespoke shirts for subject S_{72}
in different styles:
a - slim-fit, *b* - regular fit, *c* - loose fit

As shown in Fig.5.8, for every type kind of style, the shirts exhibited overall good apparel fit. From body-fit to loose-fit style, the amount of stressed folds (misfit) decreased, the amount of natural draping folds increased, and the volume of bodice and sleeve became bigger. Meanwhile, the positions of necklines, shoulder lines, and cuff hems were invariable due to the constant ease allowances in the corresponding pattern sections. Exceptionally, the bodice pieces were not vertical due to the slightly slant torso. The huge volumes of bodices and sleeves of regular fit and loose fit shirts were inevitably collided, giving rise to the slightly deformed armholes.Therefore, the e-bespoke method could be applied to different shirt styles from body-fit to loose-fit with assured high-level apparel fit.

5.3.4. E-bespoke shirts made of different fabrics

Five aforementioned digital fabrics DT_M were applied to the same body-fit shirt for subject S_{72}. Due to the close properties of fabric DT_{M1} and DT_{M2} , the shirts made of DT_{M1} and DT_{M2} exhibited similar appearances and fit. The shirts made of DT_{M3} and DT_{M4} were of similar appearance likewise. Fig. 5.9 shows the representative appearances of virtual shirts made of fabrics DT_{M1}, DT_{M4}, and DT_{M5}.



a *b* *c*

Figure 5.9. Try-on effects of e-bespoke shirts for subject S_{72} made from different DT_M:
a - DT_{M1}, *b* - DT_{M4}, *c* - DT_{M5}

As shown in Fig.5.9, some tiny differences were observable in the three shirts. Fabric DT_{M1} was inelastic and soft, and some tiny folds existed on the front chest and the back of the shirt. DT_{M5} was of high elasticity and low rigidity, and the shirt showed less folds and a smoother surface. DT_{M4} was of high shearing rigidity, and the shirtshowed a starched appearance with fewest folds. Nonetheless, the structure lines of all the three shirts are well-located and the proportions are balanced.

Therefore, the e-bespoke method could also assure a similar good fit for shirts made from different fabrics.

5.4. Practical production testing

In order to inspect the availability and practicality of the beforementioned method of generating e-bespoke men's shirt, a practical production testing was carried out at Texel (Moscow) company who was famous of 3D body scanning and virtual fitting.

The whole practical testing was operated by the following procedures:

a. in Texel company, eight individual male consumers were scanned standardly. All scanned virtual clones were (Fig. 5.10) saved as .obj files and uploaded by Texel;

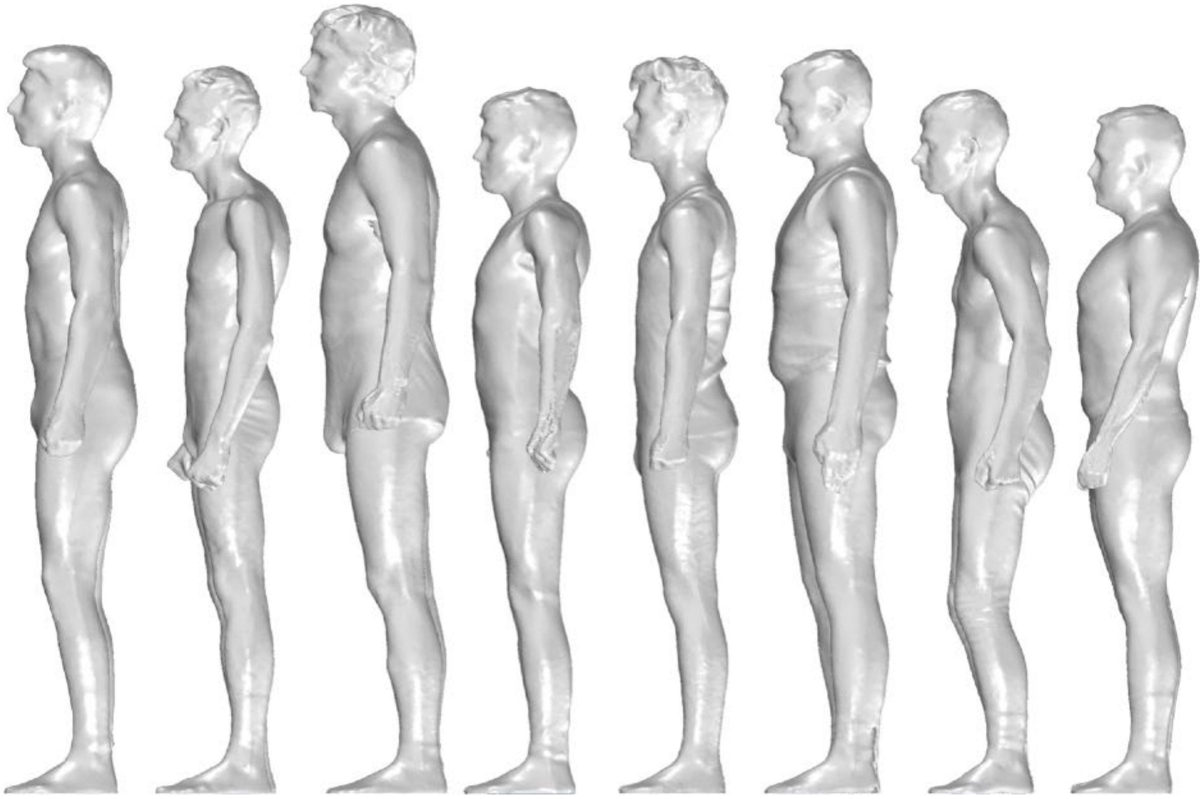


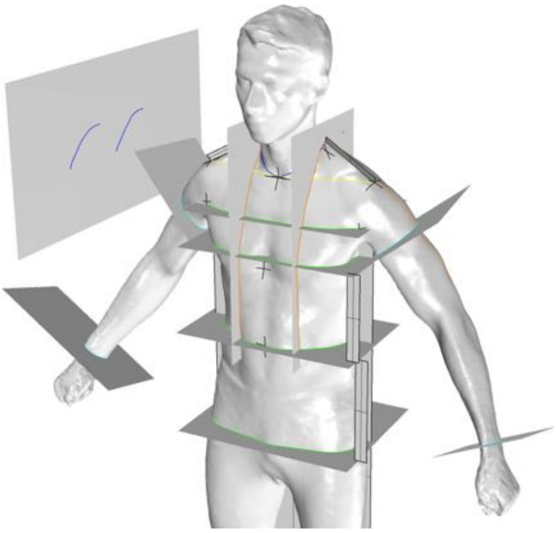
Figure 5.10 - Profile views of the eight virtual clones of individual male from Texel company

b. in IVGPU, the virtual clones were processed in Rhinoceros for marking landmarks and body measurements (Fig. 5.11, *a*), and transformed to virtual twin in Mixamo;

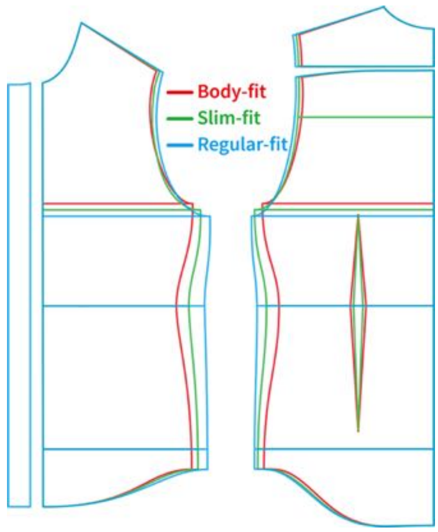
c. with the virtual twin and their body measurements, the e-bespoke patterns (Fig. 5.11, *b*) and virtual shirt in different styles were processed in CLO 3D. All digital patterns in .dxf format were transmitted to Texel;

d. the finished virtual shirts (Fig. 5.11, *c*) for consumers were generated in IVGPU, and the real shirt samples (Fig. 5.11, *d*) were simultaneously produced in the factory;

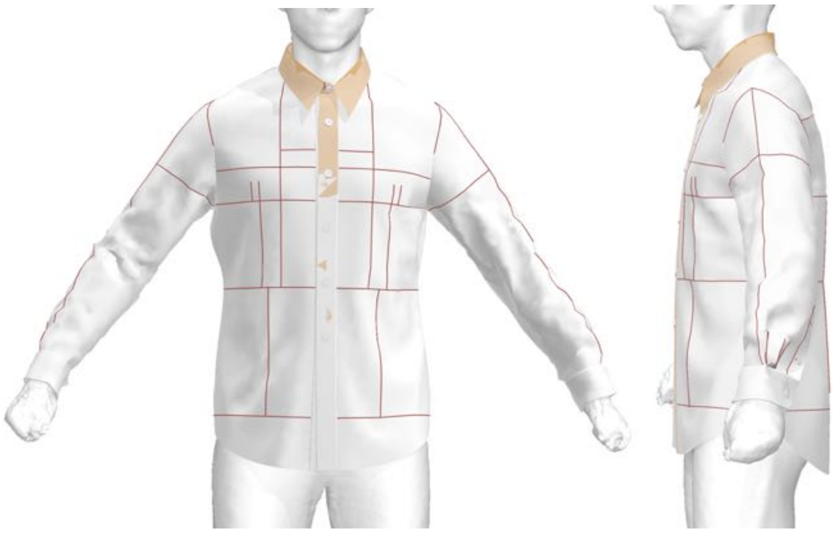
e. the evaluation of the virtual and real shirts were conducted with the virtual images, photos of real shirts and the opinions from customers after trying on.



a



b



c

d

Figure 5.11 – Procedures of the practical production testing for Sergey K.:
a – mark landmarks and body measurements on the virtual clones,
b – customized shirt bodice patterns in different styles,
c – finished virtual slim-fit shirt, *d* – sewed real slim-fit shirt sample

As shown in Fig. 5.10, the eight virtual clones had the different and atypical morphological features. Fig. 5.11 shows the procedure of generating virtual and real customized shirt for one of the customer, Sergey K.. The real and virtual slim-fit shirt exhibited the similar smooth exterior contours with vertical side-seam, appropriate lengths of bodice and sleeve and few undesired folds. In general, the testing results showed a high degree of satisfaction from eight individual consumers (Appendix E).

Thus, the practical production testing validated the new method for generating the e-bespoke men's shirt.

Conclusion after Chapter 5

1. The systematic method of generating a e-bespoke men's shirt in different styles and made from different fabrics has been developed based on the establishment of virtual twins of male bodies and digital twins of textile materials.

2. The advantages and validity of the e-bespoke method have been examined by subjective and objective evaluations. The e-bespoke shirts could assure the high-level fit better than contemporary RtW and MtM.

3. The practical production testing showed a high degree of satisfaction. This method is recommended to be applied in men's shirt customization and the other categories.

CONCLUSIONS

Final results of research

1. The technology of customized men's shirt design e-bespoke has been developed through an integrated system of hardware and software that could generate, process, transmit and receive the data of 2D or 3D objects to generate the digital twins of system "body - shirt" with predictable fit.

2. A new anthropometric database of male bodies has been established on the basis of a new scheme of 25 pattern-oriented body measurements measured by straight lines, outlines and flat planes on the virtual clones, which exactly described the spatial shape, location and proportions of torso, shoulderarea, neck and arm segments. The geometric models of different segments have been developed for demonstrating and visualizing the functionality of each new body measurements, and investigating the mechanism of applying the body measurements in the customized shirt pattern.

3. In accordance with the internet resources of consumers' opinion towards men's shirts and photos of misfit, the initial referential databases have been established for revealing the existing misfit phenomena on men's shirt. The influence of pattern construction, textile material and style of shirt and their mathematical relations have been validated by the variant real sample experiments. The final comprehensive five-level criteria for evaluating different fragments of men's shirt have been developed with subjective elements (descriptions, photos) and objective indexes (pattern parameters, body measurements), which can be used to predict the fit of unfinished shirt, check the sewed shirt and provide constructive reasons for the misfit.

4. An algorithm for exactly generating the customized shirt pattern with assured high-level fit has been developed with the databases of anthropometric measurements and models, and scheme of new ease allowances and pattern indexes for different shirt styles.

5. The system of utilization of hardware and software for virtual design of e-bespoke men's shirt has been generated by integrating together different approaches including scanning, processing and measuring the male body, testing the textile materials, constructing the pattern block, visualizing the 3D virtual system "body - shirt" and its objective and subjective evaluation.

6. The technology of customized design of e-bespoke men's shirt in laboratory and practical production has been tested with real and virtual samples. The results shown great feasibility from experiment results and high satisfaction from individual consumers' feedbacks, which confirmed the correctness of the developed databases and the integral structure of the hardware and software system.

7. It is recommended to utilize the results in the following aspects:

- as theoretical content of anthropometry, men's shirt design, customization or evaluation;
- in the educational process of higher and secondary educational institutions in the preparation of clothing designers or pattern makers, including added professional education;
- to develop the national technology initiative FashionNet;
- to develop of new modules or libraries of CAD for clothing;
- to open an online atelier of digital clothing design and customization.

Recommendations, perspectives of future research

1. Due to the limitation of the scanned subjects, the proposed approaches have been only proved valid for Y and A type male bodies (or 1, 2, 3 drops in Russia) who had the relatively normal stature. In the future, the other male bodies (e.g., the obese and skinny population) will be involved to enrich the anthropometric database and improve the technology of e-bespoke shirt design for each individual body.

2. In the present research, the fitting and evaluation stages have been mostly performed by the usual scenario of men's shirt dressing: without underwear, untucked shirt hem, static standing posture. In the future, more scenarios (e.g., with underwear or coat, tucked hem, active posture) will be included for more comprehensively develop and evaluate the digital twin of system "body - shirt".

3. The separated databases and modules generated by hardware or software will be trained and tested to establish the integral AI-based men's shirt customizing model which can automatically analyze the body morphology, generate the customized pattern and evaluate the fit state.

REFERENCES

1. Gill, S. A review of research and innovation in garment sizing, prototyping and fitting / S. Gill // Textile Progress, 2005, 47(1), pp. 1-85.

2. Bespoke [Электронныйресурс] //URL: en.wikipedia.org/wiki/Bespoke (датаобращения: 30.07.2018).

3. Song, G.Improving comfort in clothing / G. Song // Woodhead Publishing, 2011, -459p.

4. Pargas, R.P. Automatic measurement extraction for apparel from a three-dimensional body scan / R.P. Pargas, N.J. Staples, J.S. Davis // Optics and Lasers in Engineering, 1997, 28(2), pp. 157-172.

5. Fairhurst, C. Advances in apparel production / C. Fairhurst // Woodhead Publishing, 2008, -311p.

6. Chinese standard GB/T 22187-2008 / General requirements for establishing anthropometric databases.

7. ISO standard ISO 15535:2006 / General requirements for establishing anthropometric databases.

8. Ashdown, S. Sizing in clothing / S. Ashdown // Woodhead Publishing, 2007, -384p.

9. Anderson, L.J. Understanding fitting preferences of female consumers: Development of an expert system to enhance accurate sizing selection / L.J. Anderson, E.L. Brannon, P.V. Ulrich, A.B. Presley // National Textile Center Annual Report, 2001, 198, pp. 1-10.

10. Brackelsberg, P. Unit method of clothing construction / P. Brackelsberg, R. Marshall // Waveland PressInc, 1990.

11. Ashdown, S.P. A study of automated custom fit: Readiness of the technology for the apparel industry / S.P. Ashdown, L. Dunne // Clothing and Textiles Research Journal, 2006, 24(2), pp. 121-136.

12. Amed, I. The State of Fashion 2018/ I. Amed, A. Berg, S. Kappelmark, S. Hedrich, J. Anderson, M. Drageset, R. Young // The Business of

Fashion and McKinsey & Company, 2017, pp. 44-45.

13. Kang, Y. From tool-driven revolution to decision-making revolution: a path to smart manufacturing transformation / Y. Kang, W. Wang, L. Meng, Y. Zheng, P. Xiao, F. Song, X. Cheng // KPMG and AliResearch Institute, 2019, pp. 1-16.

14. Fenech, C. Made-to-order: The rise of mass personalization / C. Fenech, B. Perkins // The Deloitte consumer review 2015, 11(1), pp. 1-20.

15. China National Garment Association.2016–2017 China garment industry development report / China National Garment Association // Beijing: China Textile & Apparel Press, 2017, pp. 84–90.

16. Compilation and publishing center of Changshu men's wear index of China. Report on the development of China men's wear industry in 2017 / Compilation and publishing center of Changshu men's wear index of China // Beijing: China Textile & Apparel Press, 2017, pp.173-177.

17. Walters, J. Five profiles that explain China’s consumer economy / J. Walters, H. Gao, V. Hui, A. Wang, J. Yang, Z. Lyu // The Boston Consulting Group and Aliresearch Institute, 2017, pp. 2-8.

18. China Electronic Commerce Research Center. 2015-2016 China Garment E-Commerce Industry Report / China Electronic Commerce Research Center // China Electronic Commerce Research Center, 2016, pp.12-25.

19. Zhong, R.Y. Intelligent manufacturing in the context of industry 4.0: a review / R.Y. Zhong, X. Xu, E. Klotz, S.T. Newman // Engineering, 2017, 3(5), pp. 616-630.

20. Zheng, P. Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives / P. Zheng, H. Wang, Z. Sang, R.Y. Zhong, Y. Liu, C. Liu, K. Mubarok, S. Yu, X. Xu // Frontiers of Mechanical Engineering, 2018, 13(2), pp. 137-150.

21. Ministry of Industry and Information Technology. Development plan of textile industry (2016 - 2020) / Ministry of Industry and Information Technology // Ministry of Industry and Information Technology of China, 2016,

99. 1-31.

22. Foresight. The future of manufacturing: a new era of opportunity and challenge for the UK Summary Report / Foresight // The Government Office for Science, London, 2013.

23. Kagermann, H. Recommendations for implementing the strategic initiative INDUSTRIE 4.0: Securing the future of German manufacturing industry; final report of the Industrie 4.0 Working Group / H. Kagermann, J. Helbig, A. Hellinger, W. Wahlster // Forschungsunion, 2013, pp. 1-78.

24. Dragcevic, Z. Investigating the development of digital patterns for customized apparel / Z. Dragcevic, Y. Yang, W. Zhang, C. Shan // International Journal of Clothing Science and Technology, 2007, 19(3/4), pp. 167-177.

25. Thomassey, S. Artificial intelligence for fashion industry in the big data era / S. Thomassey, X. Zeng // Singapore: Springer, 2018, -288p.

26. Walter, L. Transforming clothing production into a demanddriven, knowledge-based, high-tech Industry. Transforming Clothing Production into a Demand-Driven, Knowledge-Based, High-Tech Industry / L. Walter, G.A. Kartsounis, S. Carosio // The Leapfrog Paradigm, Springer, London, 2009, -212p.

27. Lehmann, M. Pulse of the fashion industry / M. Lehmann, S. Tärneberg, T. Tochtermann, C. Chalmer, J. Eder-Hansen, J.F. Seara, S. Boger, C. Hase, V.V. Berlepsch, S. Deichmann // Global Fashion Agenda and The Boston Consulting Group, 2018, pp. 86-96.

28. Wang, Y. Industry 4.0: a way from mass customization to mass personalization production / Y. Wang, H.S. Ma, J.H. Yang, K.S. Wang // Advances in Manufacturing, 2017, 5(4), pp. 311-320.

29. BrooksBrothers [Электронный ресурс] //URL: www.brooksbrothers.com/on/demandware.store/Sites-brooksbrothers-Site/ru_RU/Page-FitSizeGuide?guideID=men-dress-shirts&activeTab=fit (дата обращения: 09.09.2020).

30. BuddShirtmakers [Электронный ресурс] //URL:

www.buddshirts.co.uk/shirts/made-to-measure (дата обращения: 30.07.2019).

31. Bivolino.com [Электронный ресурс] //URL: www.bivolino.com/en/made-to-measure-shirts (дата обращения: 30.07.2019).

32. UniqloCo. Ltd. [Электронный ресурс] //URL: www.uniqlo.com/us/en/page/customizedforyou-easycareshirts-fit.html (дата обращения: 30.07.2019).

33. Spier&Mackay [Электронный ресурс] //URL: www.spierandmackay.com/design-your-customshirt.html (дата обращения: 30.07.2019).

34. ProperCloth [Электронный ресурс] //URL: propercloth.com/sizes/measure-body (дата обращения: 30.07.2019).

35. iTailor [Электронный ресурс] //URL: www.itailor.com/designshirts/ (дата обращения: 30.07.2019).

36. TailorStoreSweden [Электронный ресурс] //URL: www.tailorstore.com/mens-body-measurements (дата обращения: 30.07.2019).

37. MatchUTailor [Электронный ресурс] //URL: www.matchutailor.com/collections/matchu-dressshirts/products/indigo-triangle-houndstooth-cotton (дата обращения: 30.07.2019).

38. Indochino [Электронный ресурс] //URL: www.indochino.com/measurements (дата обращения: 30.07.2019).

39. Ross, F. Refashioning London's bespoke and demi-bespoke tailors: new textiles, technology and design in contemporary menswear / F. Ross // Journal of the Textile Institute, 2007, 98(3), pp. 281-288.

40. Li, P. A model of an e-customized co-design system on garment design / P. Li, J.H. Chen // International Journal of Clothing Science and Technology, 2018, 30(5), pp.628-640.

41. Elbrecht, P. Information Processing for Mass-Customized Clothing Production / P. Elbrecht, K.J. Palm // 2016 IEEE Tenth International Conference on Semantic Computing (ICSC), Laguna Hills, CA, USA, 4-6 Feb. 2016, pp.362-365.

42. Lee, W. Heuristic misfit reduction: A programmable approach for 3D garment fit customization / W. Lee, H.S. Ko // Computers & Graphics, 2018, 71, pp.1-13.

43. Wang, C.C. Design automation for customized apparel products / C.C. Wang, Y. Wang, M.M. Yuen // Computer-aided design, 2005, 37(7), pp.675-691.

44. Tailor-i [Электронныйресурс] //URL: api.textronic.online/demo/custom.html?p=Men-Shirt (датаобращения: 09.05.2018).

45. Meepl. [Электронный ресурс] //URL: www.meepl.com/solutions/made-to-measure (дата обращения: 09.05.2018).

46. Dong, Z. A web-based 3D virtual display framework for warp-knitted seamless garment design / Z. Dong, G. Jiang, G. Huang, H. Cong // International Journal of Clothing Science and Technology, 2018, 30(3), pp.332-346.

47. Kuzmichev, V.E. Virtual design of knitted compression garments based on bodyscanning technology and the three-dimensional-to-two-dimensional approach / V.E. Kuzmichev, I.V. Tislenko, D.C. Adolphe // Textile Research Journal, 2019, 89(12), pp.2456-2475.

48. Chan, A.P. Prediction of men's shirt pattern based on 3D body measurements / A.P. Chan, J. Fan, W.M. Yu // International Journal of Clothing Science and Technology, 2005, 17(2), pp.100-108.

49. Liu, K. Parametric design of garment pattern based on body dimensions / K. Liu, C. Zhu, X. Tao, P. Bruniaux, X. Zeng // International Journal of Industrial Ergonomics, 2019, 72, pp.212-221.

50. Gu, B. Individualizing women’s suit patterns using body measurements from two-dimensional images / B. Gu, G. Liu, B. Xu // Textile Research Journal, 2017, 87(6), pp.669-681.

51. Liu, K. Construction of a prediction model for body dimensions used in garment pattern making based on anthropometric data learning / K. Liu, J.

Wang, E. Kamalha, X. Zeng // The Journal of The Textile Institute, 2017, 108(12), pp.2107-2114.

52. Kim, K. Individualized male dress shirt adjustments using a novel method for measuring shoulder shape / K. Kim, N. Innami, M. Takatera, M. Kanazawa, Y. Kitazawa // International Journal of Clothing Science and Technology, 2017, 29(2), pp.215-225.

53. Morphology (biology) [Электронныйресурс] //URL: en.wikipedia.org/wiki/Morphology_(biology) (датаобращения: 09.05.2020).

54. Anthropometry [Электронныйресурс] //URL: biologydictionary.net/anthropometry/ (датаобращения: 09.05.2020).

55. Zakaria, N. Anthropometry, apparel sizing and design / N. Zakaria, D. Gupta // Cambridge, Woodhead Publishing, 2019, -413p.

56. Faust, M.E. Designing apparel for consumers: The impact of body shape and size / M.E. Faust, S. Carrier // Cambridge, Woodhead Publishing, 2014, -322p.

57. August, B. The complete Bonnie August dress thin system: 642+ ways to correct figure with clothes / B. August // New York, Rawson, Wade Publishers, 1981.

58. Simmons, K.P. Body shape analysis using three-dimensional body scanning technology / K.P. Simmons // Unpublished doctoral dissertation, Raleigh, North Carolina State University, 2003, -196p.

59. Connel, L.J. Body shape assessment scale: Instrument development for analyzing female figures / L.J. Connell, P.V. Ulrich, E.L. Brannon, M. Alexander, A.B. Presley // Clothing and Textiles Research Journal, 2006, 24(2), pp. 80–95.

60. Rasband, J.A. Fabulous fit: Speed fitting and alteration / J.A. Rasband, E.G. Liechty // New York, Fairchild, 2006.

61. ISO standard ISO 8559-2:2007(E) / Size designation of clothes - Part 2: Primary and secondary dimension indicators.

62. Japanese standard JIS L4004:2001 / Sizing systems for men's

garments.

63. German standard DIN EN 13402-3 / Size designation of clothes - Part 3: Size labelling based on body measurements and intervals.

64. Chinese standard GB/T 1335.1-2008 / Standard sizing systems for garments - Men.

65. USA standard ASTM D8241/D8241M-19 / Standard Tables of Body Measurements for Young Men Type, Size Range 32-48.

66. USA standard D6240/D6240M-12e1 / Standard Tables of Body Measurements for Mature Men, ages 35 and older, Sizes Thirty-Four to Fifty-Two (34 to 52) Short, Regular, and Tall.

67. USA standard ASTM D8077/D8077M-16 / Standard Tables for Body Measurements for Mature Big Men Type, Size Range 46-64.

68. Yang, X.M. Treatment of special body form pattern sheet in MTM system of men′ s shirts / X.M. Yang, J.J. Yan // Journal of Tianjin Institute of Textile Science and Technology, 2005, 2, pp. 19-23.

69. Miyoshi, M. Costumes: Theoretical papers / M. Miyoshi // Beijing: China Textile & Apparel Press, 2006, -340p.

70. Naglic, M.M. A method for body posture classification of three-dimensional body models in the sagittal plane / M.M. Naglic, S. Petrak // Textile research journal, 2019, 89(2), pp.133-149.

71. ISO standard ISO 7250-1 / Basic human body measurements for technological design – Part 1: Body measurement definitions and landmarks.

72. ISO standard ISO 8559-1:2017(E) / Size designation of clothes – Part 1: Anthropometric definitions for body measurements.

73. Winks, J.M. Clothing sizes: international standardization / J.M. Winks / Manchester, Textile Institute, 1997.

74. Jang, S.E. A study on a men's dress shirt pattern by somatotype for mass customization system / S.E. Jang, J.H. Chang // Journal of the Korean Society of Clothing and Textiles, 2008, 32(2), pp.294-306.

75. Han, H. Investigation of chest girth and height variation affecting

other body dimensions for men’s upper body clothes pattern grading / H. Han // International Journal of Clothing Science and Technology, 2019, 31, pp.415-430.

76. Luo, S. A novel method for determining skin deformation of lower limb in cycling / S. Luo, J. Wang, X. Yao, L. Zhang // The Journal of The Textile Institute, 2017, 108(9), pp.1600-1608.

77. Simmons, K.P. Body measurement techniques / K.P. Simmons, C.L. Istook // Journal of Fashion Marketing and Management, 2003, 7(3), pp.306-332.

78. Vitronic 3Dbodyscanner [Электронный ресурс] //URL: www.vitronic.com/industrial-and-logistics-automation/sectors/3d-body-scanner.html (дата обращения: 19.09.2020).

79. [TC]^2 3Dbodyscanner [Электронный ресурс] //URL: www.tc2.com/tc2-19m-3d-body-scanner.html (дата обращения: 19.09.2020).

80. FIT3D 3Dbodyscanner [Электронныйресурс] //URL: fit3d.com/product (датаобращения: 19.09.2020).

81. TechMed3DBodyScanScanner [Электронныйресурс] //URL: techmed3d.com/products/bodyscan-scanner/ (датаобращения: 19.09.2020).

82. SizeStream SS20 Classic 3D body scanner [Электронныйресурс] //URL: sizestream.com/ss20-classic/ (датаобращения: 19.09.2020).

83. Avalutionbodyscanning [Электронный ресурс] //URL: www.avalution.net/en/solutions/body-scanning/index.html (дата обращения: 19.09.2020).

84. SizeUSA [Электронный ресурс] //URL: www.sizeusa.com (дата обращения: 19.09.2020).

85. SizeKorea[Электронный ресурс] //URL: sizekorea.kr (дата обращения: 19.09.2020).

86. Pei, J. Female breast shape categorization based on analysis of CAESAR 3D body scan data / J. Pei, H. Park, S.P. Ashdown // Textile Research Journal, 2019, 89(4), pp.590-611.

87. Šajatović, B.B. Analysis of body proportions of Croatian basketball players and the untrained population and their influence on garment fit / B.B. Šajatović, S. Petrak, M.M. Naglić // Textile research journal, 2019, 89(23-24), pp.5238-5251.

88. Scott, E. Novel Methods to Drive Pattern Engineering Through and For Enhanced Use of 3D Technologies / E. Scott, S. Gill, C. Mcdonald // Proceedings of 3DBODY.TECH 2019 Lugano, Switzerland, 22-23 Oct. 2019, pp.211-221.

89. Cheng, Z. Research on the male lower torso for improving underwear design / Z. Cheng, V.E. Kuzmichev // Textile Research Journal, 2019, 89(9), pp.1623-1641.

90. Wang, S. Finite element modelling of Chinese male office workers' necks using 3D body measurements / S. Wang, Y. Xu, H. Wang // The Journal of The Textile Institute, 2017, 108(5), pp.766-775.

91. ISO standard ISO 18825-1 / Clothing – Digital fittings – Part 1: Vocabulary and terminology used for the virtual human body.

92. Vuruskan, A. Modeling of half-scale human bodies in active body positions for apparel design and testing / A. Vuruskan, S.P. Ashdown // International Journal of Clothing Science and Technology, 2017, 29(6), pp.807-821.

93. Kumichev V.E. Real and virtual shaping of skirts / V.E. Kuzmichev, M.T. Yan, J.Q. Yan, Q.Z. Yan, Y.Y. Zhou // Proc. Of 16th World Textile Conference AUTEX 2016, Ljubljana, Slovenia, 8-10 Jun. 2016, pp. 138.

94. Guo, M. Human-friendly design of virtual system "female body-dress" / M. Guo, V.E. Kuzmichev, D.C. Adolphe // Autex Research Journal, 2015, 15(1), pp. 19-29.

95. Gu, B. Predicting distance ease distributions on crotch curves of customized female pants / B. Gu, W. Lin, J. Su, B. Xu // International Journal of Clothing Science and Technology, 2017, 29(a), pp.47-59.

96. Hong, Y. Visual-simulation-based personalized garment block design

method for physically disabled people with scoliosis (PDPS) / Y. Hong, P. Bruniaux, X. Zeng, K. Liu, A. Curteza, Y. Chen // Autex Research Journal, 2018, 18(1), pp.35-45.

97. Hong, Y. Interactive virtual try-on based three-dimensional garment block design for disabled people of scoliosis type / Y. Hong, X. Zeng, P. Bruniaux, K. Liu // Textile Research Journal, 2017, 87(10), pp.1261-1274.

98. Lee, H. Development of 3D patterns for functional outdoor pants based on skin length deformation during movement / H. Lee, K. Hong, Y. Lee // International Journal of Clothing Science and Technology, 2017, 29(2), pp.148-165.

99. Stark, R. Innovations in digital modelling for next generation manufacturing system design / R. Stark, S. Kind, S. Neumeyer // CIRP Annals, 2017, 66(1), pp.169-172.

100. Coffin, D.P. The shirtmaking workbook Pattern, Design, and Construction Resources/ D.P. Coffin // Quarry Books, 2015, -176p.

101. Mossakowska-Gaubert, M. Tunics worn in Egypt in Roman and Byzantine times: The Greek vocabulary / M. Mossakowska-Gaubert // Textile Terminologies from the Orient to the Mediterranean and Europe, 2017, 1000, pp.321-345.

102. Zhang, W.B. Chinese Basic Block--Structure Designing Principle and Technical of Donghua Basic Block / W.B. Zhang, W.Y. Zhang // Journal of Donghua University, Natural Science, 2002,28(3), pp.45-50.

103. Xie, J. The comparative research on Donghua prototype, Japanese culture style new prototype and Russia Mgutd prototype / J. Xie // Melliand China, 2014, 3, pp.71-72, 74-76.

104. Liu, R.P. Pattern making theory & technology / R.P. Liu // Beijing, China Textile & Apparel Press, 2005, -227p.

105. Armstrong, H.J. Pearson New International Edition - Pattern making for fashion design Fifth Edition/ H.J. Armstrong // Pearson, 2014, -918p.

106. Kershaw, G. Pattern Cutting for Menswear / G. Kershaw //

Laurence King Publishing, 2013, -320p.

107. Aldrich, W. Metric Pattern Cutting for Menswear / W. Aldrich // John Wiley & Sons, 2011, pp. -173p.

108. Hong, Z.L. Pattern forming research of custom shirt / Z.L. Hong / Master dissertation of Soochow University, China, 2017, -108p.

109. Duan, J. Research on relational model for pattern of menswear based on digitizing 3D human model / J. Duan / Master dissertation of Xi'an Polytechnic University, China, 2017, -91p.

110. Zhang, L.L. Parametric flat pattern design for clothing based on matlab / L.L. Zhang, G.P. Zhang // Journal of Textile Research, 2019, 40 (a), pp.130 - 135.

111. Qi, L. Intelligent pattern forming research on custom men's shirt / L. Qi // Master dissertation of Soochow University, China, 2019, -92p.

112. Wang, Q.M. Theory and technical research of the menswear basic block base on the character of male build in Zhejiang province- study on male body measurement and the shape of standard manikin / Q.M. Wang, W.B. Zhang // Journal of Donghua University, Natural Science, 2003, 29(6), pp.31-34.

113. Peng, Z.Y. Optimal design of the side seam of the young man's shirt based on anthropometric measurements / Z.Y. Peng // Master dissertation of Wuhan Textile University, China, 2018, -62p.

114. Surikova, O.V. Improvment of Clothes Fit for Different Female Bodies / O.V. Surikova, V.E. Kuzmichev, G.I. Surikova // Autex Research Journal, 2017, 17(2), pp.111-119.

115. Gill, S. Improving garment fit and function through ease quantification / S. Gill // Journal of Fashion Marketing and Management, 2011, 15(2), pp.228-241.

116. Monobe, A. Effect of the difference between body dimensions and jacket measurements on the appearance of a ready-made tailored jacket / A. Monobe, K. Kim, M. Takatera // International Journal of Clothing Science and Technology, 2017, 29(5), pp.627-645.

117. Gill, S. Determination of Functional Ease Allowances Using Anthropometric Measurement for Application in Pattern Construction / S. Gill // Ph.D. dissertation of Manchester Metropolitan University, 2009.

118. Zeng, X. A new method of ease allowance generation for personalization of garment design / X. Zeng, L. Koehl, Y. Chen, M. Happiette, P. Bruniaux, R. Ng, W. Yu // International journal of clothing science and technology, 2008, 20(3), pp.161-173.

119. Lage, A. Virtual try-on technologies in the clothing industry. Part 1: investigation of distance ease between body and garment / A. Lage, K. Ancutiene // The Journal of The Textile Institute, 2017, 108(10), pp.1787-1793.

120. Xue, Z. An intelligent method for the evaluation and prediction of fabric formability for men's suits / Z. Xue, X. Zeng, L. Kohel // Textile Research Journal, 2018, 88(4), pp.438-452.

121. Chen, C.M. Fit evaluation within the made-to-measure process / C.M. Chen // International Journal of Clothing Science and Technology, 2007, 19(2), pp.131-144.

122. Fujii, C. Effects of combinations of patternmaking methods and dress forms on garment appearance / C. Fujii, M. Takatera, K. Kim // Autex Research Journal, 2017, 17(3), pp.277-286.

123. Du, H. Clothing Comfort Evaluation Model Based on Adaptive Fuzzy Neural Network / H. Du, R. Wang, D. Deng, Y. Liu // 2012 Fourth International Conference on Digital Home IEEE, Guangzhou, China, 23-25 Nov. 2012, pp. 128-132.

124. Kim, K.O. Effect of bust line position on appearance of upper garment / K.O. Kim, M. Sakaguti, M. Takatera // IOP Conference Series: Materials Science and Engineering, 2017, 254, p.172014.

125. Yu, W.M. Assessment of garment fit / W.M. Yu, K.W. Yeung, Y.L. Lam //Proceedings of HKITA and CTES Conference on Hand-in-hand Marching into the 21st Century, 1998, pp.1125-129.

126. BOĞDAY SAYĞILI, B. Determination of Body-Clothing Pattern

Fit Problems In Men's Jacket and Pattern Proposal / B. BOĞDAY SAYĞILI, Ş, ÇİVİTCİ // Journal of Textile & Apparel/Tekstil ve Konfeksiyon, 2015, 25(3). pp.270-279

127. Huck, J. Protective overalls: Evaluation of clothing design and fit / J. Huck, O. Maganga, Y. Kim // International journal of clothing science and technology, 1997, 9(1), pp.45-61.

128. Guo, M.N. Pressure and comfort perception in the system “female body–dress” / M.N. Guo, V.E. Kuzmichev // AUTEX research journal, 2013, 13(3), pp.71-78.

129. Liu, K. Wearing comfort analysis from aspect of numerical garment pressure using 3D virtual-reality and data mining technology / K. Liu, J. Wang, Y. Hong// International Journal of Clothing Science and Technology, 2017, 29(2), pp.166-179.

130. How A Men’s Dress Shirt Should Fit [Электронныйресурс] //URL: www.realmenrealstyle.com/proper-dress-shirt-fit/ (датаобращения: 09.09.2020).

131. Zvereva, J.S. Identification of textile materials properties in “Body-clothes” scanned systems / J.S. Zvereva, V.E. Kuzmichev, D. Adolphe, L. Schacher // 3rd International Conference on 3D Body Scanning *Technologies*, Lugano, Switzerland, October 2012, pp. 335-342.

132. Computer-aided-design [Электронныйресурс] //URL: en.wikipedia.org/wiki/Computer-aided_design (датаобращения: 09.09.2020).

133. Wu, H.F. CAD for clothes/ H.F. Wu, Y.M. Xing, Z.J. Wang// Hefei,Hefei University of Technology Press, 2010, -96p.

134. Accumark pattern design software [Электронныйресурс] //URL: www.gerbertechnology.com/accumark-pattern-design-software/ (датаобращения: 09.09.2020).

135. Assyst. Cad [Электронный ресурс] //URL: www.assyst.de/en/products/cad/index.html (дата обращения: 09.09.2020).

136. ETSYSTEM [Электронный ресурс] //URL:

www.etsystem.cn/index.html (дата обращения: 09.09.2020).

137. GRAFISCADClothing [Электронный ресурс] //URL: www.grafis.com/clothing (дата обращения: 09.09.2020).

138. MODARIS AND QUICK ESTIMATE: 3D PATTERNMAKING SOFTWARE [Электронныйресурс] //URL: www.lectra.com/en/products/modaris-quick-estimate (датаобращения: 09.09.2020).

139. PADCAD [Электронный ресурс] //URL: www.padsystem.com/en/ (дата обращения: 09.09.2020).

140. RichforeverCAD/CAM [Электронный ресурс] //URL: www.richforever.cn (дата обращения: 09.09.2020).

141. TUKAcad [Электронный ресурс] //URL: tukatech.com/tukacad/ (дата обращения: 09.09.2020).

142. Yin, Y. The evolution of production systems from Industry 2.0 through Industry 4.0 / Y. Yin, K.E. Stecke, D. Li // International Journal of Production Research, 2018, 56(1-2), pp.848-861.

143. ASSOL CAD [Электронный ресурс] //URL: assol.org/en/ (дата обращения: 09.09.2020).

144. CLO [Электронный ресурс] //URL: www.clo3d.com (дата обращения: 09.09.2020).

145. MarvelousDesigner [Электронный ресурс] //URL: www.marvelousdesigner.com (дата обращения: 09.09.2020).

146. OPTITEX [Электронный ресурс] //URL: optitex.com/products/2d-and-3d-cad-software/ (дата обращения: 09.09.2020).

147. VStitcher [Электронный ресурс] //URL: browzwear.com/products/v-stitcher/ (дата обращения: 09.09.2020).

148. Sandra, K. IEEE SA Industry Connections The Measurement of Fabric Properties for Virtual Simulation—A Critical Review / K. Sandra, L. Christiane, G. Hugh // IEEE, 2020, -42p.

149. Cheng, Z. A digital replica of male compression underwear / Z.

Cheng, V. Kuzmichev, D. Adolphe // Textile Research Journal, 2020, 90(7-8), pp.877-895.

150. Kim, M. Comparison and analysis of men's classic-fit and slim-fit shirt patterns-Utilizing the 3D virtual try-on system / M. Kim, M.O. Kim, S. Park // The Research Journal of the Costume Culture, 2014, 22(2), pp. 209-224.

151. Kuzmichev, V. Computer reconstruction of 19th century trousers / V. Kuzmichev, A. Moskvin, E. Surzhenko, M. Moskvina // International Journal of Clothing Science and Technology, 2017, 29(4), pp.594-606.

152. Moskvin, A. Digital replicas of historical skirts / A. Moskvin, V. Kuzmichev, M. Moskvina// The Journal of The Textile Institute, 2019, 110(12), pp.1810-1826.

153. Mixamo [Электронный ресурс] //URL: www.mixamo.com/#/ (дата обращения: 09.09.2020).

154. ISO standard ISO 20685:2010(E) / 3-D scanning methodologies for internationally compatible anthropometric databases.

155. Charan, J. How to calculate sample size for different study designs in medical research? / J. Charan, T. Biswas // Indian Journal of Psychological Medicine, 2013, 35, pp.121-126.

156. Xiong, N. World classic clothing design and pattern volume 5: men’s clothing / N. Xiong // Nanchang, Jiangxi Fine Arts Publishing House, 2007, pp.121-123.

157. Chen, X. Optimization of human perception on virtual garments by modeling the relation between fabric properties and sensory descriptors using intelligent techniques / X. Chen, X. Zeng, L. Koehl, X. Tao, J. Boulenguez-Phippen // Information Processing and Management of Uncertainty in Knowledge-Based Systems. IPMU 2014. Communications in Computer and Information Science, 2014, 443, pp.606-615.

158. Lee, M.J. A study on representation of 3D virtual fabric simulation with drape image analysis II—focus on the comparison between real clothing and 3D virtual clothing / M.J. Lee, H.S. Sohn, J.J. Kim // Journal of Fashion

Business, 2019, 15, pp.97-111.

159. Янь, Ц. Сценарные технологии виртуального проектирования: переход от схемы "фигура-чертеж" к "потребитель-одежда" / Ц.Янь, В.Е.Кузьмичев // Информационная среда вуза: материалы XXIV межд. научн.-техн. конф. 22-23 ноября 2017 года. Иваново, ИВГПУ, с.142-146.

160. Yan, J.Q. VirtualtechnologyofMade-to-MeasureMenShirt (Виртуальная технология сорочек MtM) / J.Q. Yan, V.E. Kuzmichev // IOPConf. Series: Materials Science and Engineering: 18th World Textile Conference AUTEX , 2018, 460,pp. 012014.

161. Yan, J.Q. A virtual e-bespoke men’s shirt based on new body measurements and method of pattern drafting (Виртуальныекастомизированныемужскиесорочки, основанныенановыхразмерныхпризнакахиметодеконструирования) / J.Q. Yan, V.E. Kuzmichev // Textile Research Journal, 2020, 90(19-20), pp.2223-2244.https://doi.org/10.1177/0040517520913347

162. Янь, Ц. Генерирование новой информации о морфологических особенностях мужских фигур после их оцифровывания / Ц. Янь, Ц. Пэн, В.Е. Кузьмичев // Информационная среда вуза: материалы XXIV межд. научн.-техн. конф. 22-23 ноября 2017 года. Иваново, ИВГПУ, с.138-141.

163. Yan, J.Q. Newdatabaseforimprovingvirtualsystem “body-dress” (Новая база данных для совершенствования виртуальных систем "фигура-платье") / J.Q. Yan, V.E. Kuzmichev, S.C. Zhang, D.C. Adolphe // IOPConf. Series: Materials Science and Engineering: 17th World Textile Conference AUTEX, 2017, 254, pp. 172029.doi:10.1088/1757-899X/254/17/172029

164. Yan, J. Virtual design of system "body-dress" improving with scanning technologies (Виртуальное проектирование систем "фигура-платье", улучшаемое за счет технологий сканирования) / J. Yan, S. Zhang, V.E. Kuzmichev // Book of abstracts 7th International conference on 3D Body scanning technologies. Lugano, Switzerland, 30 Nov. - 1 Dec. 2016, pp.

132-138. http://dx.doi.org/10.15221/16.132

165. Янь, Ц. Инструменты для формообразования одежды свободной формы в виртуальном проектировании / Ц.Янь, В.Е.Кузьмичев // Информационная среда вуза: материалы XXII международной науч.-техн. конф.23-25 ноября 2016. ИВГПУ, Иваново, с. 192-195.

166. Янь, Ц. Разработка критериев посадки сорочек на виртуальных двойниках / Ц.Янь, В.Е.Кузьмичев // Молодые ученые -развитию текстильно-промышленного кластера (ПОИСК 2019): сб. материалов межвуз. науч.-техн. аспирантов и студентов(с межд. участием).Ч.1.-Иваново: ИВГПУ, 2019, с.181-184.

167. Yan, J.Q. Hierarchical fit criteria of made-to-measure men shirt with virtual technology (Иерархия критериев посадки MtM мужских сорочек с помощью виртуальных технологий) / J.Q. Yan, V.E. Kuzmichev // IOP Conf. Series: Materials Science and Engineering: Aegean International Textile and Advanced Engineering Conference AITAE, 2019, 459, pp. 012086. doi:10.1088/1757-899X/459/1/012086

168. Янь, Ц. Совершенствование технологии кастомизированного проектирования мужских сорочек (A development of men’s e-bespoke shirt) / Ц.Янь, В.Е.Кузьмичев // Известия вузов. Технология текстильной промышленности, 2020. (в печати)

169. Янь, Ц. Проверка адекватности сканатаров и их аватаров, генерируемых в CLO 3D / Ц. Янь, В.Е.Кузьмичев // Молодые ученые – развитию Национальной технологической инициативы (ПОИСК–2020): сб.материалов Национальной молодёжной научно-технической конференции. – Иваново: ИВГПУ, 2020, с.771-774.

170. Yan, J.Q. Fitevaluationforvirtualmen’sshirt (Оценка посадки виртуальной мужской сорочки) / J.Q. Yan, V.E. Kuzmichev // IOPConf. Series: Materials Science and Engineering: International Conference on Technics, Technologies and Education ICTTE 2020, 2020.

171. Кузьмичев, В.Е. Цифровое дизайн-проектирование и оценка

виртуальной одежды: перспективы развития после FhubCongressIvanovoI /В.Е. Кузьмичев, Ц. Янь, П. Ся, С. Ван // Международный научно-практический форум SMARTEX. 20-23 октября 2020 года. Иваново, ИВГПУ, с. 56-63.

APPENDIX A

Easeallowancesofmen'sshirts

The styles and shirt measurements (SM: full chest width, waist width and hip width) of sixty-two men's shirts from seventeen brands (Beanpole, C&A, Funday, GAP, GJ, Hugo Boss, H&M, Jack&Jones, K-Boxing, Oodji, O'Stin, Santa Barbara Polo&Racquet Club, Scofield, Uniqlo, Urban Revivo, Zara) were measured or surveyed in the physical or online mean's stores, respectively. Some of the shirts which sold online lacked parted of the measurements. Table A.A shows the styles and shirt measurements of the surveyed sixty-four men's shirts.

Table A.A - Styles and measurements of men's shirts

Brand	No.	Style (fit)	Size	Shirt measurement, cm		
				chest width	waist width	hip width
O'Stin	1	Slim	175/96A	111	101	109
	2	Shaped	175/96A	111	109	109
	3	Regular	175/96A	122	117	117
H&M	4	Slim fit	170/92A	104	97	103
	5	Regular fit	170/92A	112	108	110
	6	Regular fit	175/100A	120	113	114
Modis	7	Slim fit	48	110	106	110
	8	Regular fit	48	118	112	112
Oodji	9	Extra slim	182/40	104	94	104
	10	Slim	182/40	108	96	108
GJ	11	Slim fit	182/92/39	106	98	104
	12	Regular fit	182/96/40	112	106	110
Fun Day	13	Super slim fit	46	106	92	100
	14	Slim fit	46	110	94	102
	15	Regular fit	46	110	106	106
	16	Neat fit	170/92A	101	97	
	17	Slim fit	170/92A	101	94	
	18	Slim fit	170/92A	101	96	
	19	Straight fit	170/92A	101	97	
	20	Regular fit	170/92A	103	99	
	21	Boxy fit	170/92A	109	108	
	22	Oversize fit	170/92A	111	109	
	23	Oversize fit	170/92A	112	112	
BEANPOLE	24	Standard	175/92A	108	98	

	25	Standard	175/92A	112	107	
	26	Standard	175/92A	110	102	
SANTA BARBARA POLO＆ RACQUET CLUB	27	Standard	175/92B	114	108	
	28	Standard	175/92B	118	111	
K-BOXING	29	Regularfit	180/96A	109	101	109
	30	Regular fit	180/96A	110.5	105	110
	31	Slim fit	180/96A	109	101	109
	32	Slim fit	180/96A	106	99	107
Urban Revivo	33	Loose	170/92A	116	114	
	34	Loose	170/92A	127	126	
	35	Loose	170/92A	122	117	
	36	Loose	170/92A	114	109	
	37	Regular	170/92A	103.5	97	
	38	Regular	170/92A	112.2	112.2	
C&A	39	Loose fit	170/92A	114		110
	40	Loose fit	170/92A	116		112
	41	Loose fit	170/92A	122		124
	42	Regular fit	170/92A	110		106
	43	Regular fit	170/92A	108	104	106
	44	Regular fit	170/92A	112		112
	45	Regular fit	170/92A	106	102	104
	46	Slim fit	170/92A	104	98	102
Scofield	47	Regular fit	170/92A	98	94	99
	48	Regular fit	170/92A	97	96	101
	49	Regular fit	170/92A	103	98	101
	50	Regular fit	170/92A	105	98	103
	51	Regular fit	170/92A	109	102	105
	52	Regular fit	170/92A	97	91	101
	53	Slim fit	170/92A	101	98	99
	54	Slim fit	170/92A	103	95	99
HugoBoss	55	Slim fit	170/92A	102	96	
	56	Slim fit	170/92A	101	92	
	57	Regular fit	170/92A	108	102	
GAP	58	Regular fit	175/92A	110	104	
	59	Regular fit	175/92A	105	98	
	60	Slim fit	175/92A	106	98	
Uniqlo	61	Regular fit	165/84A	106	98	104
Zara	62	Slim fit	175/92A	106	96	102

According to Table A.A, the four representative shirt styles were concluded as: body-fit, slim-fit, regular-fit and loose-fit.

The ease to chest girth, waist girth and hip girth were calculated by subtracting SM from the BM from the sizing systems as equation (A. 1).

$$ECG = SM_{CW} - CG \quad (A.1)$$

$$EWG = SM_{WW} - WG \quad (A.2)$$

$$EHG = SM_{HW} - HG \quad (A.3)$$

where: ECG, EWG, EHG were the ease to chest girth, ease to waist girth and ease to hip girth, respectively; SM_{CW},SM_{WW},SM_{HW}were the shirt measurements full chest width, full waist width and full hip width, respectively; CG, WG and HG were the BM chest girth, waist girth and hip girth from the sizing systems, respectively.

Due to the various criteria of defining shirt styles from different brands, the style of a shirt was firstly classified to the belonged group according to the officially-defined style. Then, the shirt with unusual eases different from the others in the group were reclassified to the closer group.

Therefore, ECG, EWG, EHG of four styles were calculated as Table A.B, A.C, A.D and A.E. The round average values of three eases were applied in shirt pattern construction.

Table A.B – Ease allowances of body-fit shirts

Shirt No.	ECG, cm	EWG, cm	EHG, cm
47	6	12	6
48	5	18	8
52	5	13	8
Round average	5 (5.3)	14 (14.3)	7 (7.3)

Table A.C – Ease allowances of slim-fit shirts

Shirt No.	ECG, cm	EWG, cm	EHG, cm
4	8	12	
9	9	19	

10	9	16	
16	9	18	
17	9	19	
18	10	17	11
19	9	20	6
20	10	18	
32	9	14	
37	12	19	10
46	12	14	
49	11	21	
53	11.5	19	
54	12	20	9
55	11	20	8
56	11	17	6
Round average	10 (10.2)	18 (17.7)	8 (8.3)

Table A.D – Ease allowances of regular-fit shirts

Shirt No.	ECG, cm	EWG, cm	EHG, cm
1	15	19	12
2	15	27	12
5	20	30	17
6	20	27	14
7	14	22	
11	14	22	
12	16	24	
13	14	12	5
14	18	14	7
15	18	26	11
21	17	30	
22	19	31	
23	20	34	
24	16	20	
25	20	29	
26	18	24	
29	13	19	13
30	14.5	23	14
31	13	19	13
42	18		13
43	16	26	13
44	20		19
45	14	24	11
50	13	20	10

51	17	24	12
57	16	24	
58	18	26	
59	13	20	
60	14	20	
62	14	18	9
Round average	16 (16.3)	23 (23.4)	12 (12.1)

Table A.E – Ease allowances of Loose-fit shirts

Shirt No.	ECG, cm	EWG, cm	EHG, cm
3	26	35	20
8	22	28	
27	22	26	
28	26	29	
33	24	36	
34	35	48	
35	30	39	
36	22	31	
38	20.2	34.2	
39	22		17
40	24		19
41	30		31
61	22	28	15
Round average	25 (25)	33 (33.4)	20 (20.4)

APPENDIX B

Body measurements of male bodies

Body measurements of ninety-five Y-type male body subjects are shown in Table B.A, B.B.

Table B.A – Torso measurements of Y-type subjects

No.	H_C, cm	H_W, cm	H_H, cm	SNW_F, cm	SNW_B, cm	AW_F, cm	AW_B, cm	CG_F, cm	CG_B, cm	WG_F, cm	WG_B, cm	HG_F, cm	HG_B, cm
1	126.3	106.7	84.6	20.0	20.1	44.4	36.4	48.9	44.6	46.7	27.1	51.5	40.5
3	125.5	108.2	88.4	20.8	22.2	37.6	39.8	41.7	50.2	35.8	36.2	46.6	47.3
4	122.4	102.8	81.7	19.0	18.4	37.3	33.0	47.6	37.4	41.8	21.0	54.9	31.7
6	125.0	106.2	85.3	20.8	21.3	45.1	37.0	50.8	47.6	49.6	29.9	53.0	47.4
7	126.0	105.6	82.7	21.0	22.2	41.2	41.1	44.3	53.2	36.4	38.3	47.9	49.8
8	122.3	103.0	79.9	20.2	20.6	39.9	35.7	46.0	45.7	40.9	31.1	51.5	43.3
9	140.4	118.9	94.8	21.4	22.3	41.1	40.4	46.7	49.6	39.9	33.1	55.3	40.0
10	141.8	121.9	99.4	21.3	22.4	41.6	42.3	43.7	57.4	34.6	42.8	38.6	52.0
11	146.5	125.9	100.8	21.1	22.0	45.9	37.7	52.9	46.8	45.3	30.6	59.7	37.8
12	138.7	119.2	94.9	20.7	23.0	35.7	44.6	40.8	58.0	23.8	48.2	39.5	56.2
13	143.9	123.0	100.1	22.0	22.5	48.7	39.4	53.3	49.4	46.7	27.8	59.5	36.5
14	139.2	117.9	94.0	21.2	21.3	40.4	36.2	49.9	42.4	47.2	27.0	58.0	39.3
15	143.0	120.8	95.4	21.3	21.2	38.7	38.5	49.3	48.3	41.8	32.2	58.7	38.2
16	139.3	118.6	94.3	20.6	20.5	45.2	44.8	52.2	54.0	41.8	32.6	48.3	47.7
17	136.4	117.2	93.9	21.8	23.4	43.3	44.9	47.5	58.3	36.6	39.7	46.7	45.7
18	139.3	120.0	97.6	22.1	22.5	42.1	41.5	46.7	52.2	38.7	38.4	45.1	48.5
19	137.7	119.8	98.2	20.6	20.9	42.3	42.6	45.8	55.9	38.9	36.9	43.8	46.0
20	143.8	121.7	99.3	21.5	21.6	40.2	40.4	48.9	46.3	44.5	27.7	51.9	41.3
21	142.9	121.5	98.8	21.9	22.4	45.3	39.4	49.3	49.6	41.5	31.7	48.7	46.5
25	121.2	103.9	83.4	19.8	20.8	42.2	39.5	46.6	48.8	40.1	37.1	45.0	50.1
28	141.4	118.0	93.9	20.9	19.7	41.2	35.0	48.2	39.3	47.0	20.3	56.6	38.9
29	126.7	108.9	87.4	20.7	22.0	39.9	36.1	47.1	45.9	40.1	31.8	47.8	44.3
34	122.8	104.0	82.1	19.6	20.5	38.7	38.7	42.8	49.5	37.8	36.0	44.8	47.0
37	122.2	104.0	83.2	19.7	19.3	42.2	34.9	51.4	41.4	43.8	27.8	49.9	43.1
38	115.4	100.0	82.0	20.3	21.9	40.3	38.3	46.2	48.8	38.4	38.8	43.0	49.8
45	123.4	106.3	85.1	19.4	19.9	40.3	34.3	46.6	43.2	43.7	29.0	51.8	40.1
47	125.8	106.0	84.3	19.0	17.9	46.5	32.3	54.1	39.9	46.8	27.2	51.5	40.7
49	121.8	102.8	80.1	19.9	19.4	43.0	36.7	49.3	44.8	44.7	29.1	48.8	40.7
53	127.5	110.6	90.9	21.0	21.6	39.2	40.3	46.2	49.9	42.6	35.2	48.1	42.2
54	135.7	115.3	90.4	20.2	20.2	42.2	38.0	48.2	48.2	42.2	34.2	50.8	47.2
56	120.5	102.0	79.6	18.9	21.1	36.9	39.9	39.1	52.7	30.8	39.6	38.7	50.4
58	130.6	111.2	87.3	21.3	21.5	40.4	36.4	47.9	43.6	41.8	27.3	48.8	40.5
59	131.7	111.9	87.6	23.1	23.7	45.5	41.2	57.6	51.5	51.2	39.4	55.4	55.8
60	122.4	103.2	81.7	20.7	20.9	40.5	32.9	45.8	43.2	38.6	31.5	45.1	44.1
61	128.5	111.0	89.1	20.5	22.7	41.1	40.1	51.9	51.0	43.8	41.3	50.8	52.4
63	111.6	94.9	75.7	19.1	19.7	39.6	33.7	44.6	41.8	38.3	29.0	41.8	42.4
67	120.3	100.3	78.4	19.1	20.4	39.2	35.0	44.2	45.1	35.2	33.7	43.2	42.9
68	125.9	105.3	86.2	20.0	18.6	43.0	30.4	49.0	37.2	45.7	18.9	45.4	37.5
72	123.4	105.0	83.0	21.4	20.2	44.0	32.7	53.2	40.7	45.2	28.2	49.9	41.5
76	127.1	109.8	87.3	19.7	19.4	46.6	35.4	53.2	46.5	46.6	33.0	52.4	45.2
80	127.8	106.8	85.7	19.7	19.6	37.9	38.9	46.6	42.1	40.9	24.3	48.5	39.2
83	123.4	106.2	86.1	19.8	20.3	40.2	37.2	45.3	49.1	39.0	36.6	49.2	44.6

85	122.7	106.2	85.3	19.8	20.1	45.1	37.0	52.2	49.9	50.1	29.4	53.4	47.0
86	124.5	105.6	82.7	20.7	21.9	41.2	41.1	43.9	51.6	36.6	38.1	47.9	48.9
87	122.3	103.0	79.9	20.4	20.7	39.9	35.7	46.3	45.4	41.3	30.7	51.9	42.9
89	118	100.1	79.3	19.5	20.4	34.2	34.3	46.7	45.3	42.8	31.8	47.8	44.8
92	124.1	105.9	84.0	20.0	21.2	41.2	40.1	46.9	48.7	42.0	28.1	50.4	44.4
93	123.6	105.3	83.8	20.7	21.8	41.2	38.3	49.7	48.6	42.9	34.6	52.7	43.7
96	139.6	121.7	100.6	21.2	21.9	45.0	41.7	53.0	53.8	45.9	36.9	47.9	50.2
97	138.9	121.8	101.0	21.5	21.5	48.3	37.9	57.3	45.6	51.5	32.0	51.8	45.2
98	137.8	118.7	97.1	22.6	21.9	45.2	41.2	55.4	50.8	49.9	35.8	52.7	44.4
101	137.0	116.8	95.0	21.0	21.1	40.7	38.3	46.3	49.5	41.7	32.2	50.8	41.2
102	135.8	117.4	96.6	23.2	21.5	43.9	44.2	48.6	53.9	43.0	34.4	50.5	43.9
103	137.3	116.2	93.7	21.4	20.4	39.3	38.3	49.6	49.4	39.6	33.9	44.7	47.5
104	133.4	113.2	91.9	20.9	20.3	41.3	38.2	49.6	47.0	48.1	29.3	55.0	42.5
105	145.2	124.1	100.3	22.0	23.5	38.7	45.1	43.5	58.7	33.3	46.6	40.5	60.6
106	125.8	109.1	88	23.1	20.9	44.9	37.8	54.0	47.8	48.7	35.9	52.2	46.2
109	131.0	112.7	92.1	22.6	22.0	43.3	42.6	56.1	50.2	50.3	36.0	61.5	38.5
110	133.2	113.7	90.7	22.4	21.8	41.5	40.1	53.7	47.3	54.0	23.8	54.7	41.0
111	127.8	106.8	82.1	21.7	21.6	41.5	40.7	48.7	49.5	45.0	27.1	52.0	43.5
112	141.3	121.2	99.6	23.3	20.9	44.3	40.2	51.7	50.0	44.2	37.3	48.4	48.0
113	132.2	113.5	91.7	23.9	22.1	48.8	40.6	58.9	51.3	53.2	36.8	55.5	45.5
116	129.2	111.3	89.8	23.2	22.6	39.8	39.3	50.7	51.2	43.8	36.2	46.6	49.6
117	127.4	109.6	88.5	22.3	22.9	40.2	42.0	50.3	54.1	45.7	32.0	51.1	44.4
118	137.6	117.8	96.7	21.7	20.2	43.7	36.2	52.8	47.1	48.9	31.0	52.8	42.7
119	131.0	112.0	91.5	21.6	21.2	37.2	44.3	46.7	55.3	39.9	37.4	49.6	45.4
120	129.2	110.2	89.2	21.7	20.1	44.5	40.3	54.3	47.5	43.7	29.4	46.4	45.4
121	132.7	111.4	88.1	21.1	20.2	45.6	38.3	52.8	41.7	51.9	19.6	50.3	43.8
122	139.2	117.8	94.4	21.8	19.8	44.9	37.6	54.3	47.3	53.8	23.1	60.5	35.7
123	138.1	116.9	94.2	23.0	21.5	42.0	41.0	52.5	53.2	49.3	31.3	54.7	47.5
124	134.3	114.9	94.5	22.2	22.0	51.3	40.4	58.0	53.5	41.4	33.5	46.6	45.4
125	132.0	111.5	88.9	20.1	20.0	43.8	36.1	51.8	44.1	47.9	27.7	55.8	42.0
126	135.3	115.1	93.9	21.0	19.7	38.0	36.7	44.8	47.9	43.9	28.3	50.7	37.7
127	133.4	113.4	91.1	22.1	21.7	41.2	39.4	51.2	50.0	43.5	34.5	52.2	49.9
129	131.5	115.2	95.6	23.2	22.6	44.9	44.5	61.0	58.3	56.2	42.1	56.1	53.2
130	137.3	117.5	96.8	23.4	20.8	47.0	41.3	56.3	45.9	48.9	25.9	55.6	39.9
131	130.7	111.5	89.5	21.3	21.8	42.7	40.2	51.9	50.1	50.8	31.0	53.6	47.1
132	127.3	108.7	88.9	20.4	21.8	38.6	40.7	46.7	48.7	40.9	31.3	47.6	48.4
136	138.5	118.1	96.9	20.7	21.9	33.9	41.6	43.7	51.2	36.6	32.0	51.6	39.3
139	128.8	107.9	86.6	21.9	21.6	37.9	40.4	49.8	48.3	46.8	28.9	55.7	38.8
140	137.0	114.4	90.4	20.9	23.0	38.2	43.0	48.1	51.0	42.4	33.0	45.2	51.6
141	132.0	113.3	91.6	20.3	21.9	36.4	41.7	46.4	52.3	41.8	34.8	46.6	47.0
143	137.6	117.6	95.3	22.4	22.8	45.0	46.6	55.0	58.7	47.6	38.1	52.9	50.7
144	141.0	118.6	96.2	26.4	25.7	49.9	46.4	61.3	60.3	51.9	40.2	55.0	59.9
145	121.1	105.9	86.8	24.6	24.4	46.0	43.9	64.7	52.4	54.6	39.0	57.9	48.2
146	123.0	105.3	84.1	23.1	22.8	43.5	39.1	58.5	48.6	50.3	37.4	55.9	49.2
147	124.9	106.6	85.8	22.8	19.9	41.8	38.4	52.2	47.7	44.3	31.6	53.6	41.3
148	130.9	112.8	91.0	22.4	21.8	44.9	40.4	57.6	47.3	51.1	35.0	59.8	40.2
149	120.5	103.0	83.8	23.7	21.2	43.7	38.7	63.5	47.3	55.2	32.5	53.0	42.8
150	130.0	111.9	92.0	24.9	23.6	46.1	44.8	62.9	55.7	54.4	37.9	56.3	48.8
151	132.0	113.1	90.4	25.4	23.9	57.3	40.6	69.3	54.6	60.7	37.8	60.3	51.2
152	139.4	117.7	96.1	20.8	21.1	37.7	41.3	49.2	50.4	48.0	27.9	52.5	43.0
153	135.9	114.8	95.0	21.5	18.7	34.8	37.9	47.3	47.1	40.4	31.6	51.2	38.0
154	143.8	122.1	99.6	22.3	20.9	37.9	38.3	47.4	47.4	43.7	31.8	48.0	47.1
155	133.1	111.6	89.0	20.5	21.5	41.2	37.7	50.6	45.4	46.3	27.6	49.4	45.6

Table B.B – neck, shoulder and arm measurements of Y-type subjects

No.	H_{FNP}, cm	H_{SNP}, cm	H_{BNP}, cm	NW, cm	D_{FNP}, cm	D_{SNP}, cm	D_{BNP}, cm	NG_F, cm	NG_B, cm	SL, cm	SSN_F, cm	SSN_B, cm	UAG, cm	AL, cm	WRG, cm
1	141.3	145.3	145.6	13.7	35.3	28.5	25.3	23.4	16.0	13.2	20.0	20.1	27.4	56.8	15.4
3	140.2	146.7	147.6	12.5	39.5	33.1	29.7	27.5	15.6	15.1	20.8	22.2	29.1	62.3	16.2
4	135.5	140.7	141.5	12.6	34.9	28.1	25.2	24.8	15.5	11.7	19.0	18.4	23.4	58.7	15.7
6	141.0	145.5	146.2	12.6	40.7	33.5	29.4	25.9	15.5	14.3	20.8	21.3	30.2	59.8	16.5
7	139.5	145.1	145.8	13.2	39.4	33.0	28.9	25.0	17.2	14.6	21.0	22.2	29.6	58.1	15.3
8	137.0	142.8	143.5	12.1	37.0	30.8	27.0	24.3	14.8	14.2	20.2	20.6	28.4	60.2	16.6
9	155.4	161.1	161.9	13.0	36.5	30.7	27.8	23.9	15.6	15.2	21.4	22.3	26.4	68.1	16.5
10	156.8	162.5	163.1	13.1	38.8	32.7	28.9	24.3	15.8	15.3	21.3	22.4	30.4	67.2	15.5
11	163.3	168.9	169.3	13.1	37.4	30.3	27.0	26.4	15.0	15.1	21.1	22.0	30.7	69.6	16.9
12	155.0	159.9	160.7	12.7	37.0	30.7	26.9	24.5	16.0	15.3	20.7	23.0	30.9	64.6	16.5
13	156.5	164.4	165.0	12.6	37.1	30.9	27.9	26.1	15.8	15.6	22.0	22.5	30.2	66.6	16.6
14	154.3	161.0	161.7	12.9	40.8	34.0	30.3	26.2	16.1	14.4	21.2	21.3	26.9	68.7	16.8
15	157.6	163.7	164.4	12.7	38.4	31.4	28.3	26.0	15.1	14.2	21.3	21.2	27.1	69.7	17.2
16	153.9	159.1	159.7	12.2	38.7	31.5	28.5	26.6	14.9	13.9	20.6	20.5	29.0	67.3	17.4
17	152.1	157.6	158.5	14.1	37.6	31.0	27.6	25.4	17.0	15.5	21.8	23.4	33.2	66.1	16.7
18	154.3	161.0	161.4	12.3	38.9	32.8	30.1	24.5	14.8	15.8	22.1	22.5	28.7	63.4	15.3
19	152.5	159.4	159.9	13.0	38.1	31.5	28.5	26.8	15.2	13.8	20.6	20.9	28.2	65.3	16.0
20	158.6	164.7	165.1	13.2	41.9	34.9	31.8	26.6	15.1	14.7	21.5	21.6	33.0	66.2	17.1
21	156.5	163.7	165.3	13.8	38.3	32.1	28.9	28.5	17.1	14.5	21.9	22.4	31.5	69.9	16.4
25	135.9	140.7	140.8	14.2	39.4	31.1	27.7	26.9	16.1	13.4	19.8	20.8	29.0	56.7	15.4
28	153.9	160.0	161.0	11.7	35.8	28.9	27.0	25.2	13.4	13.4	20.9	19.7	24.5	65.0	15.9
29	140.9	147.5	148.3	12.5	37.4	30.8	27.3	26.3	15.2	15.0	20.7	22.0	28.6	58.7	15.1
34	137.0	143.2	144.2	12.6	38.2	32.6	29.0	24.8	15.3	13.6	19.6	20.5	27.8	56.3	14.9
37	137.3	141.1	142.2	13.6	39.0	31.2	27.7	26.3	16.6	11.9	19.7	19.3	28.2	54.7	14.8
38	130.5	135.3	135.7	13.3	38.7	31.7	28.2	24.2	15.8	14.6	20.3	21.9	29.6	53.4	15.9
45	139.9	143.8	144.4	12.7	36.5	29.2	26.0	24.2	15.7	13.1	19.4	19.9	30.3	57.3	15.6
47	141.0	146.0	146.2	12.5	37.9	29.9	27.4	25.9	15.1	11.6	19.0	17.9	29.0	55.4	15.5
49	137.3	140.5	141.1	11.7	37.1	29.4	25.9	23.8	14.7	12.8	19.9	19.4	28.8	57.1	15.2
53	141.3	149.0	149.5	13.7	36.9	30.6	27.3	26.5	16.6	14.4	21.0	21.6	28.0	64.3	15.7
54	152.9	156.6	157.0	14.2	41.6	33.4	30.1	25.4	16.9	12.9	20.2	20.2	29.9	65.8	16.6
56	135.9	140.7	141.7	12.7	38.8	32.0	29.0	23.2	16.0	13.7	18.9	21.1	27.1	57.5	15.7
58	146.4	151.0	152.3	12.0	36.9	29.8	26.8	24.0	15.4	14.6	21.3	21.5	26.0	59.7	14.9
59	149.6	153.3	153.9	13.5	41.2	33.6	28.8	25.6	16.9	16.4	23.1	23.7	33.7	62.1	17.3
60	135.9	141.4	142.2	13.2	37.0	29.7	27.3	26.1	15.5	13.8	20.7	20.9	28.3	59.2	15.4
61	146.4	151.1	152.0	13.3	38.5	31.0	26.8	25.7	16.9	14.8	20.5	22.7	31.3	64.2	17.0
63	125.4	129.4	129.9	12.3	38.6	31.6	28.1	22.9	14.9	12.9	19.1	19.7	26.2	50.9	13.2
67	133.0	137.3	137.9	12.7	35.4	28.9	25.4	23.5	15.4	13.1	19.1	20.4	27.6	52.7	14.0
68	137.5	143.1	143.4	11.9	37.8	30.3	28.1	23.6	13.8	12.7	20.0	18.6	28.0	57.5	15.1
72	139.1	144.5	144.7	13.6	38.3	30.3	27.0	25.6	15.0	13.7	21.4	20.2	29.6	55.2	16.4
76	142.4	147.5	147.9	13.1	38.0	31.3	27.5	25.5	15.6	12.5	19.7	19.4	29.2	57.9	16.1
80	139.1	145.3	145.7	12.0	34.8	28.2	25.5	25.4	14.4	13.0	19.7	19.6	24.6	57.7	15.0
83	139.9	145.2	145.5	12.9	39.1	32.0	28.8	24.3	15.3	13.6	19.8	20.3	29.8	57.4	15.9
85	141.0	145.5	146.2	12.6	40.4	33.1	29.4	25.7	15.1	13.3	19.8	20.1	30.9	59.8	16.5
86	139.5	145.0	145.8	13.2	39.2	32.5	28.9	25.5	16.4	14.2	20.7	21.9	29.9	58.1	15.3
87	137.0	142.7	143.5	12.1	37.0	30.1	27.0	24.6	14.5	14.3	20.4	20.7	28.5	60.2	16.6
89	132.2	137.7	138.2	12.8	38.8	31.7	28	24.6	15.7	13.5	19.5	20.4	27.4	53.1	14.0
92	140.2	145.3	145.8	12.4	35.7	28.9	25.5	23.3	15.2	14.3	20.0	21.2	29.9	58.1	15.8
93	138.3	143.1	143.1	13.3	36.9	28.9	25.8	25.8	14.4	14.7	20.7	21.8	31.5	58.4	17.3
96	155.7	162.4	162.8	12.9	38.6	32.2	28.9	26.9	14.9	15.1	21.2	21.9	31.1	66.3	18.1
97	156.4	162.5	163.1	12.2	48.5	40.1	37.9	28.1	13.8	15.0	21.5	21.5	31.3	65.6	18.1

98	152.8	159.4	159.8	12.9	38.6	29.9	28.0	29.1	14.1	15.2	22.6	21.9	32.1	64.6	17.0
101	150.6	158.3	158.8	12.6	38.5	31.3	29.3	28.1	14.8	14.1	21.0	21.1	27.4	65.4	17.4
102	150.7	156.9	156.6	14.9	38.0	30.1	27.8	29.0	15.1	14.2	23.2	21.5	29.7	62.3	18.9
103	149.9	157.2	157.2	12.7	40.3	33.5	31.0	28.1	13.9	14.0	21.4	20.4	31.7	60.0	17.6
104	147.4	153.2	152.7	13.0	36.7	27.9	25.6	28.0	13.7	13.9	20.9	20.3	31.4	57.2	18.4
105	158.9	168.0	168.1	13.6	42.4	35.6	33.3	29.8	14.3	16.2	22.0	23.5	29.8	69.1	19.8
106	141.9	147.8	147.6	12.9	41.8	31.4	29.2	31.2	13.5	15.1	23.1	20.9	32.0	59.7	19.2
109	145.3	152.8	152.7	13.4	39.7	32.3	30.0	27.9	13.9	15.6	22.6	22.0	31.4	61.6	17.8
110	147.8	154.8	154.8	13.4	40.0	32.7	29.6	28.1	15.3	15.4	22.4	21.8	34.1	63.7	17.9
111	141.3	148.2	148.7	12.9	36.2	29.6	27.3	25.9	14.1	15.0	21.7	21.6	31.1	59.5	17.4
112	156.1	163.4	163.5	12.6	41.2	32.9	31.4	30.3	13.3	14.7	23.3	20.9	30.1	69.3	17.9
113	147.8	154.5	154.5	14.3	40.4	31.1	28.2	32.5	15.7	14.9	23.9	22.1	34.1	62.8	19.0
116	143.8	152.0	152.3	14.2	42.3	34.9	32.1	31.3	15.9	15.4	23.2	22.6	34.5	61.8	18.0
117	141.7	149.9	150.1	14.5	39.3	30.9	28.8	30.3	16.1	15.7	22.3	22.9	34.6	59.7	17.6
118	152.1	158.9	158.8	12.7	39.4	30.5	28.7	13.5	29.2	13.9	21.7	20.2	32.4	65.5	17.8
119	143.8	153.2	153.3	11.8	41.1	34.8	32.7	29.0	13.3	15.1	21.6	21.2	28.2	64.7	16.6
120	144.2	149.8	149.8	12.3	38.6	30.9	28.5	27.4	13.4	13.8	21.7	20.1	28.2	59.6	17.2
121	147.4	151.6	151.9	12.3	37.3	29.9	27.5	25.2	14.2	13.9	21.1	20.2	27.6	58.5	17.6
122	153.9	161.1	161.3	12.1	38.1	30.7	28.6	27.3	13.6	13.8	21.8	19.8	30.7	63.3	17.0
123	152.5	161.9	162.1	12.0	42.6	35.8	33.8	29.6	13.6	15.2	23.0	21.5	29.8	64.5	19.5
124	150.7	155.5	155.9	12.8	39.7	31.8	29.3	27.1	14.3	15.5	22.2	22.0	32.3	63.1	18.8
125	147.1	152.3	152.7	12.2	37.9	30.8	27.9	24.9	14.8	13.4	20.1	20.0	26.5	63.2	17.9
126	145.2	154.0	154.5	11.5	38.4	33.0	30.8	26.0	13.2	13.6	21.0	19.7	25.0	65.4	16.5
127	147.8	156.2	156.3	13.9	40.9	34.1	31.5	30.0	14.6	14.9	22.1	21.7	31.4	65.6	17.6
129	147.8	155.7	155.9	13.8	42.3	33.9	30.6	30.8	15.6	15.5	23.2	22.6	41.2	67.9	19.3
130	150.3	159.3	159.5	11.5	39.3	30.7	28.9	30.7	12.8	14.9	23.4	20.8	27.7	66.1	18.1
131	146.0	153.2	153.7	12.7	38.7	31.1	28.5	28.1	14.4	15.1	21.3	21.8	31.4	62.9	19.0
132	139.7	147.2	147.5	12.1	37.5	29.9	27.7	28.2	13.6	15.1	20.4	21.8	29.2	58.1	17.5
136	150.9	158.6	158.7	11.6	37.7	31.6	29.3	26.4	13.4	15.7	20.7	21.9	29.1	63.0	15.2
139	140.5	147.6	147.6	12.7	36.4	28.9	27.3	30.0	14.5	14.9	21.9	21.6	32.8	58.3	17.6
140	150.9	157.6	157.8	13.1	38.7	31.8	29.3	26.7	14.6	16.0	20.9	23.0	29.8	63.2	18.0
141	146.6	154.2	154.7	11.9	39.1	30.9	29.5	28.6	15.0	14.7	20.3	21.9	31.3	62.1	16.7
143	152.4	160.5	160.2	14.2	40.7	31.8	29.6	33.0	15.4	15.6	22.4	22.8	34.3	64.3	19.0
144	153.8	164.4	164.7	14.8	44.8	35.0	33.1	37.6	16.8	17.4	26.4	25.7	43.1	65.2	20.4
145	138.6	146.5	146.8	13.4	41.7	31.7	29.5	34.2	15.4	17.4	24.6	24.4	38.7	57.2	18.1
146	138.3	146.2	146.4	13.6	42.1	32.7	30.9	33.5	15.2	15.5	23.1	22.8	34.1	57.3	18.2
147	134.3	145.5	145.7	12.0	39.2	31.6	30.2	33.9	13.7	13.4	22.8	19.9	32.7	56.9	17.1
148	146.9	154.5	154.5	12.8	39.2	29.5	27.1	31.1	13.9	15.3	22.4	21.8	35.1	60.9	17.4
149	133.6	142.2	142.4	13.5	42.1	32.6	30.7	34.1	14.9	14.6	23.7	21.2	37.8	50.1	17.5
150	144.1	153.4	153.3	12.6	42.7	32.4	30.5	35.5	14.1	16.7	24.9	23.6	42.5	58.6	19.1
151	149.5	157.0	157.2	14.0	42.5	32.8	30.6	33.3	16.0	16.6	25.4	23.9	44.8	62.5	19.0
152	152.4	160.5	160.5	12.1	42.3	33.6	32.0	30.4	12.9	14.8	20.8	21.1	29.8	59.3	18.3
153	145.1	153.4	154.0	10.2	40.8	32.5	31.6	30.7	11.3	13.2	21.5	18.7	28.6	62.4	16.2
154	155.6	164.5	164.1	11.8	41.0	33.0	31.8	29.0	12.3	15.2	22.3	20.9	30.8	61.9	16.2
155	147.3	153.1	153.3	12.6	37.3	28.0	26.3	28.5	14.6	14.4	20.5	21.5	29.4	60.1	17.7

Body measurements of ninety-five A-type male body subjects are shown in Table B.C, B.D.

Table B.C – Torso measurements of A-type subjects

No.	H_C, cm	H_W, cm	H_H, cm	SNW_F, cm	SNW_B, cm	AW_F, cm	AW_B, cm	CG_F, cm	CG_B, cm	WG_F, cm	WG_B, cm	HG_F, cm	HG_B, cm
2	121.2	102.1	82.5	42.4	41.4	38.9	37.8	46.2	50.1	40.9	42.2	45.9	50.9
5	129.5	109.1	87.4	42.7	43.0	40.8	30.3	47.0	40.2	44.1	27.0	51.8	42.0
22	131.1	112.1	91.0	44.5	44.0	42.5	43.0	46.7	52.4	45.3	37.2	52.9	46.5
23	127.6	107.2	84.1	42.5	42.7	40.7	37.6	48.4	47.0	39.9	38.2	40.8	59.3
24	120.5	101.6	80.1	44.1	43.8	40.6	39.8	48.5	54.3	41.6	44.8	43.8	57.1
26	127.2	105.8	84.7	43.8	45.6	39.2	36.2	43.7	42.9	41.9	27.1	54.9	36.3
27	131.5	111.1	89.1	43.6	43.4	36.6	36.7	43.6	43.6	37.4	30.3	51.5	42.0
30	120.4	102.7	81.6	44.6	44.0	39.6	37.5	50.0	50.1	44.7	39.3	48.9	49.2
32	120.2	101.5	79.8	42.7	41.7	41.5	35.8	44.6	42.3	39.4	30.0	50.2	42.6
33	123.5	103.7	85.0	40.5	40.7	37.0	32.8	41.4	40.1	35.2	29.2	39.7	43.6
35	131.5	111.4	88.2	47.0	46.8	40.1	38.6	52.6	53.2	48.5	44.3	61.0	51.7
36	124.0	105.9	85.1	45.1	43.0	39.3	40.2	48.1	51.5	43.2	41.3	49.6	52.7
40	131.0	111.5	90.9	43.2	44.2	40.0	36.4	45.8	42.4	44.8	25.2	47.1	40.0
41	123.4	105.1	82.9	42.9	42.6	40.6	36.0	43.8	45.4	42.2	31.3	49.8	42.9
42	123.8	105.3	84.3	42.3	42.0	37.6	34.2	43.1	41.2	43.4	25.5	52.5	31.7
43	122.1	103.9	83.5	42.1	41.8	35.9	34.5	41.9	41.7	36.8	30.3	40.2	45.5
48	125.5	106.3	86.9	45.9	45.3	40.9	32.2	45.6	41.1	43.4	27.3	46.3	41.6
50	122.8	104.1	82.9	45.6	43.4	42.0	36.0	52.7	40.8	48.8	27.7	53.6	40.7
51	129.2	110.5	89.3	44.7	43.4	44.2	36.6	50.4	46.5	45.2	37.8	52.7	49.0
52	140.7	117.6	93.7	45.5	46.7	34.3	37.4	39.2	47.6	36.4	33.4	45.6	44.7
55	125.2	106.9	83.9	43.4	42.6	39.9	37.7	45.0	47.7	43.7	34.2	48.3	45.5
57	131.2	111.5	90.1	44.9	43.1	44.0	35.7	48.8	47.0	41.8	35.0	48.0	48.1
62	127.9	107.8	86.6	44.7	45.5	41.8	35.6	52.1	46.4	48.1	36.2	60.9	42.9
64	127.5	108.5	86.9	44.6	44.2	41.1	35.4	47.1	41.2	46.1	24.1	52.7	39.1
65	119.3	102.2	83.0	43.6	41.9	41.1	38.9	49.6	52.0	46.6	41.5	46.1	50.6
66	121.2	105.0	85.3	41.2	39.3	41.9	32.0	48.1	40.8	45.4	30.9	51.1	42.2
69	119.3	101.1	80.9	43.5	42.5	39.8	36.1	45.6	42.4	43.6	28.4	49.2	42.7
70	132.7	111.1	89.5	48.9	43.6	50.6	33.1	57.8	37.8	57.3	19.7	59.7	36.6
71	118.7	101.2	80.6	44.2	41.6	44.2	36.7	55.1	44.1	51.5	33.9	52.6	45.8
73	126.8	105.8	82.9	47.5	46.1	40.8	39.1	51.0	41.8	46.9	31.8	50.5	49.1
74	120.5	103.1	82.1	39.6	40.7	32.9	35.4	36.1	40.3	34.0	27.8	49.0	31.4
75	122.3	104.0	82.3	43.8	40.9	45.5	37.6	51.4	47.1	43.5	37.2	45.6	50.4
77	126.8	107.4	86.8	43.3	43.0	38.4	36.9	46.1	43.1	41.4	28.6	46.3	45.9
78	129.8	108.6	86.4	46.9	45.4	43.3	33.9	52.6	40.8	47.5	26.4	56.5	35.7
79	123.7	103.3	81.4	46.3	45.5	40.6	40.7	48.6	52.4	44.3	42.4	49.6	50.9
81	124.7	104.4	82.9	46.6	42.7	45.2	33.1	51.2	38.5	48.1	28.1	52.1	37.8
82	115.1	99.3	79.3	44.7	41.4	42.7	37.7	50.1	47.9	40.8	42.4	47.7	49.1
84	123.0	104.1	83.9	43.1	43.2	38.1	37.1	43.2	46.1	38.9	31.9	53.4	37.1
88	125.6	107.4	84.1	47.6	46.1	48.2	33.7	49.6	41.6	52.3	26.0	57.2	42.8
90	124.7	106.2	83.9	45.6	43.5	42.2	39.9	51.2	49.7	48.0	38.7	58.2	40.8
91	124.5	107.6	86.6	44.5	44.0	41.6	36.6	47.1	47.3	43.2	35.0	53.6	43.9
94	118.9	101.7	81.2	44.0	39.6	42.2	33.0	51.7	42.3	48.3	30.2	47.7	43.2
95	131.7	112.1	92.2	43.9	45.9	36.8	35.4	44.4	45.4	41.2	29.0	48.7	37.8
99	127.1	110.8	90.6	46.6	43.4	44.5	39.5	54.1	55.4	49.5	44.8	49.9	47.9
107	127.0	107.7	88.5	46.4	44.9	42.2	46.4	51.6	54.4	47.8	40.8	54.4	46.7
108	138.4	117.3	96.6	44.7	46.6	36.8	36.6	47.9	47.4	42.6	36.8	49.7	48.9
114	132.8	111.6	91.0	45.6	44.5	38.2	37.0	47.2	47.9	42.7	32.4	45.4	49.0
115	132.3	113.9	94.1	45.0	44.4	42.3	39.7	54.3	51.0	51.4	36.5	54.7	42.3
128	137.6	116.3	93.5	46.4	45.2	45.6	35.8	52.0	40.4	48.3	26.2	54.0	38.8
133	130.5	110.2	87.8	46.9	42.6	39.6	41.4	51.3	50.0	43.6	38.7	48.3	51.9

134	127.8	108.0	87.5	46.0	45.4	35.8	41.8	42.3	53.3	36.2	42.3	41.8	57.0
135	141.5	122.1	100.9	44.5	43.8	37.5	43.6	45.7	51.1	40.4	30.7	48.4	41.0
138	127.9	108.5	86.3	46.6	44.3	39.1	39.3	47.2	49.3	43.3	37.1	48.0	48.4
142	134.6	114.5	94.2	49.7	49.0	45.4	39.4	63.9	52.6	58.3	41.5	56.3	51.9
156	146.2	123.7	102.8	47.0	48.0	38.6	39.1	44.3	50.2	43.9	33.8	51.6	46.2

Table B.D – neck, shoulder and arm measurements of A-type subjects

No.	H_{FNP}, cm	H_{SNP}, cm	H_{BNP}, cm	NW, cm	D_{FNP}, cm	D_{SNP}, cm	D_{BNP}, cm	NG_F, cm	NG_B, cm	SL, cm	SSN_F, cm	SSN_B, cm	UAG, cm	AL, cm	WRG, cm
2	132.5	139.7	140.3	13.6	38.8	31.2	28.1	27.5	15.6	132.5	139.7	140.3	13.6	38.8	31.2
5	140.9	147.2	147.8	11.2	38.5	32.1	29.8	25.3	12.6	140.9	147.2	147.8	11.2	38.5	32.1
22	147.1	151.8	152.3	13.3	37.2	30.6	26.6	26.8	15.8	147.1	151.8	152.3	13.3	37.2	30.6
23	141.7	148.8	149.2	14.1	45.8	38.4	34.3	29.2	16.1	141.7	148.8	149.2	14.1	45.8	38.4
24	136.2	142.1	142.6	14.0	44.6	36.0	31.9	29.8	16.4	136.2	142.1	142.6	14.0	44.6	36.0
26	139.5	146.3	147.3	12.3	37.2	30.8	28.2	25.3	14.4	139.5	146.3	147.3	12.3	37.2	30.8
27	144.9	150.4	151.2	11.8	35.7	29.0	25.5	24.0	14.9	144.9	150.4	151.2	11.8	35.7	29.0
30	135.8	141.7	142.1	14.4	39.3	30.9	26.8	28.4	17.5	135.8	141.7	142.1	14.4	39.3	30.9
32	134.8	139.6	140.6	11.7	39.7	32.6	29.5	24.7	14.1	134.8	139.6	140.6	11.7	39.7	32.6
33	133.2	140.3	141.0	11.5	39.1	32.4	30.4	25.2	13.0	133.2	140.3	141.0	11.5	39.1	32.4
35	147.5	152.7	153.4	14.0	39.9	33.0	28.2	26.1	17.0	147.5	152.7	153.4	14.0	39.9	33.0
36	140.6	145.0	145.4	14.6	38.2	30.7	26.0	26.2	18.2	140.6	145.0	145.4	14.6	38.2	30.7
40	144.2	151.0	152.0	11.8	36.6	30.8	28.4	24.9	14.2	144.2	151.0	152.0	11.8	36.6	30.8
41	138.4	143.7	144.4	11.5	40.1	33.6	30.8	24.4	13.6	138.4	143.7	144.4	11.5	40.1	33.6
42	137.3	142.8	143.1	11.8	35.9	29.2	26.4	23.5	13.4	137.3	142.8	143.1	11.8	35.9	29.2
43	136.3	142.0	142.6	12.9	38.9	32.8	29.2	24.3	15.2	136.3	142.0	142.6	12.9	38.9	32.8
48	137.3	144.5	145.1	11.1	39.1	31.8	29.6	28.2	12.5	137.3	144.5	145.1	11.1	39.1	31.8
50	138.3	143.5	144.2	12.5	35.5	28.2	24.8	24.9	15.8	138.3	143.5	144.2	12.5	35.5	28.2
51	146.0	150.6	151.1	13.9	38.7	32.0	28.4	25.5	15.9	146.0	150.6	151.1	13.9	38.7	32.0
52	152.5	159.9	160.3	12.2	40.3	34.7	31.4	26.1	14.6	152.5	159.9	160.3	12.2	40.3	34.7
55	139.9	145.4	146.0	12.9	38.4	31.9	28.2	24.3	15.4	139.9	145.4	146.0	12.9	38.4	31.9
57	145.3	150.6	151.2	12.1	39.2	31.8	28.6	25.8	14.1	145.3	150.6	151.2	12.1	39.2	31.8
62	139.5	147.8	148.3	12.3	39.3	31.5	28.6	28.0	14.5	139.5	147.8	148.3	12.3	39.3	31.5
64	143.5	148.2	148.9	12.7	36.8	30.1	26.2	25.4	15.1	143.5	148.2	148.9	12.7	36.8	30.1
65	135.2	139.5	139.8	13.7	40.4	32.7	28.4	25.7	16.3	135.2	139.5	139.8	13.7	40.4	32.7
66	135.5	140.5	141.3	13.0	37.2	29.4	26.7	24.7	15.3	135.5	140.5	141.3	13.0	37.2	29.4
69	134.0	139.4	139.8	13.1	36.1	30.0	26.6	24.1	15.6	134.0	139.4	139.8	13.1	36.1	30.0
70	146.3	151.6	151.4	13.7	35.2	28.7	26.1	29.4	14.1	146.3	151.6	151.4	13.7	35.2	28.7
71	133.7	138.8	138.9	12.0	40.4	31.2	28.5	26.9	13.9	133.7	138.8	138.9	12.0	40.4	31.2
73	140.9	147.6	147.9	12.2	41.7	34.3	31.3	28.3	14.1	140.9	147.6	147.9	12.2	41.7	34.3
74	133.3	139.8	140.4	11.0	35.9	30.4	27.3	22.4	13.4	133.3	139.8	140.4	11.0	35.9	30.4
75	136.6	141.1	141.5	13.6	39.7	32.2	29.2	24.3	15.5	136.6	141.1	141.5	13.6	39.7	32.2
77	140.2	146.2	146.5	11.8	40.4	33.3	30.2	24.9	13.7	140.2	146.2	146.5	11.8	40.4	33.3
78	143.7	149.6	149.6	12.5	39.3	31.7	29.1	27.6	13.8	143.7	149.6	149.6	12.5	39.3	31.7
79	138.4	143.9	144.4	13.5	41.2	33.2	29.3	27.8	15.9	138.4	143.9	144.4	13.5	41.2	33.2
81	136.8	144.4	144.7	11.8	39.1	31.3	28.4	29.8	13.8	136.8	144.4	144.7	11.8	39.1	31.3
82	131.9	137.2	137.7	12.5	39.2	31.5	27.7	25.5	15.6	131.9	137.2	137.7	12.5	39.2	31.5
84	136.6	142.7	143.1	12.6	38.0	31.6	27.9	24.8	14.8	136.6	142.7	143.1	12.6	38.0	31.6
88	143.1	149.5	149.5	12.7	40.1	31.7	28.6	27.4	15.6	143.1	149.5	149.5	12.7	40.1	31.7
90	140.2	145.7	145.6	13.0	37.6	29.6	26.5	25.7	15.6	140.2	145.7	145.6	13.0	37.6	29.6
91	140.9	146.6	146.6	12.3	38.6	31.4	27.6	25.8	14.9	140.9	146.6	146.6	12.3	38.6	31.4
94	133.9	138.4	138.2	11.7	38.8	29.9	27.6	26.8	11.8	133.9	138.4	138.2	11.7	38.8	29.9
95	143.8	150.5	152.7	11.9	39.8	33.9	31.6	26.1	13.2	143.8	150.5	152.7	11.9	39.8	33.9

99	143.8	150.1	149.7	14.2	38.4	29.7	27.1	27.9	15.5	143.8	150.1	149.7	14.2	38.4	29.7
107	140.9	148.1	148.0	13.7	38.6	31.1	28.7	29.5	13.7	140.9	148.1	148.0	13.7	38.6	31.1
108	149.2	158.8	159.2	13.2	40.8	34.3	31.8	28.5	14.9	149.2	158.8	159.2	13.2	40.8	34.3
114	143.8	152.1	152.3	11.5	41.9	34.2	32.6	28.8	12.4	143.8	152.1	152.3	11.5	41.9	34.2
115	145.6	153.6	153.7	11.9	39.3	32.0	29.2	29.6	13.2	145.6	153.6	153.7	11.9	39.3	32.0
128	150.3	157.6	157.5	12.2	41.2	33.8	31.4	28.2	13.2	150.3	157.6	157.5	12.2	41.2	33.8
133	144.8	149.8	150.4	12.7	41.2	31.3	28.7	29.2	15.3	144.8	149.8	150.4	12.7	41.2	31.3
134	140.5	149.1	149.3	12.5	40.9	33.2	30.7	28.7	14.9	140.5	149.1	149.3	12.5	40.9	33.2
135	154.9	161.8	161.9	12.7	36.1	29.0	26.9	27.5	14.4	154.9	161.8	161.9	12.7	36.1	29.0
138	142.6	149.2	149.5	12.0	40.9	31.6	29.5	29.4	13.0	142.6	149.2	149.5	12.0	40.9	31.6
142	149.1	157.5	157.6	12.3	42.5	33.0	31.4	32.5	13.3	149.1	157.5	157.6	12.3	42.5	33.0
156	157.8	166.6	166.6	12.7	40.3	32.1	30.7	29.0	13.5	157.8	166.6	166.6	12.7	40.3	32.1

Body measurements of ninety-five B-type male body subjects are shown in Table B.E, B.F.

Table B.E – Torso measurements of B-type subjects

No.	H_C, cm	H_W, cm	H_H, cm	SNW_F, cm	SNW_B, cm	AW_F, cm	AW_B, cm	CG_F, cm	CG_B, cm	WG_F, cm	WG_B, cm	HG_F, cm	HG_B, cm
31	121.4	105.3	87.5	41.6	40.6	40.4	39.4	46.3	47.2	41.0	39.9	47.5	46.8
39	125.0	106.6	86.9	41.9	43.7	36.3	34.5	38.6	46.0	35.8	35.0	41.2	49.4
44	125.4	105.9	83.6	46.2	44.4	41.9	38.4	52.5	46.9	48.9	36.7	55.9	47.0
46	132.5	113.0	93.9	44.4	43.5	40.8	36.3	49.3	44.4	49.1	32.1	56.0	35.9
100	124.7	105.9	84.1	47.1	44.8	41.8	39.4	55.6	48.7	54.2	39.7	51.0	48.4
137	143.7	120.7	98.0	48.2	49.2	36.3	35.8	41.0	46.1	43.0	31.8	47.2	48.3

Table B.F – neck, shoulder and arm measurements of B-type subjects

No.	H_{FNP}, cm	H_{SNP}, cm	H_{BNP}, cm	NW, cm	D_{FNP}, cm	D_{SNP}, cm	D_{BNP}, cm	NG_F, cm	NG_B, cm	SL, cm	SSN_F, cm	SSN_B, cm	UAG, cm	AL, cm	WRG, cm
31	135.9	142.5	143.3	12.9	38.6	31.4	28.4	27.1	15.5	13.7	20.2	21.0	27.8	58.6	15.7
39	138.8	145.0	145.9	12.6	39.9	34.5	31.7	24.6	14.7	13.0	19.2	19.8	28.0	57.2	15.6
44	139.9	146.5	146.7	14.3	39.7	30.9	27.3	29.4	15.7	13.1	20.9	20.0	29.9	56.7	16.7
46	146.7	152.1	152.7	13.3	38.4	31.1	27.9	26.2	13.0	13.1	20.2	20.0	26.7	59.0	14.2
100	139.0	146.0	146.0	14.6	41.0	31.0	28.2	31.0	16.8	14.0	22.0	21.8	35.8	58.4	19.2
137	157.8	164.7	164.8	12.7	42.4	34.3	32.3	29.0	14.4	13.5	20.7	20.2	30.9	65.1	17.3

APPENDIX C

Consumers'opinions

5,146 pieces of consumers' opinions towards eighty-one men's shirts from thirty brands sold on online platform TMall were shown in Table C.A.

Table C.A – Consumers' opinion towards men's shirts

Brand	Shirt No.	Number of opinions				
		Positive and neutral opinions	Negative opinions about			
			Size and shape	Material	Quality	Service
Uniqlo	1	150	15	16	3	5
	2	40	7	0	0	3
	3	37	2	4	0	0
	4	120	12	13	2	3
	5	45	6	0	1	3
Peacebird	6	90	11	5	6	2
	7	5	1	2	0	0
	8	87	4	3	0	1
	9	80	14	4	10	4
GXG	10	37	2	7	1	1
	11	67	7	0	5	2
	12	24	9	0	0	1
	13	19	2	13	2	0
	14	133	24	11	2	5
H&M	15	6	2	0	0	1
	16	36	11	0	1	0
	17	86	33	1	0	2
	18	43	7	0	0	0
Levi's	19	18	3	0	1	0
Metersbonwe	20	90	9	6	9	0
MUJI	21	51	3	0	0	2
	22	51	5	1	0	0
	23	52	10	0	0	2
Seven	24	75	6	5	1	0
Vancl	26	150	10	2	1	0
Zara	27	27	5	0	0	0
	28	22	6	1	0	1
	29	17	3	0	1	0
	30	31	1	0	3	0
Giodano	31	15	1	0	0	0

	32	100	11	1	0	1
	33	59	12	1	0	0
Goldlion	34	20	2	3	0	0
Selected	35	24	12	1	2	0
	36	42	0	0	1	0
G2000	37	22	1	1	3	2
	38	120	12	9	6	0
	39	53	13	9	3	1
	40	54	6	1	5	5
JackJones	41	35	2	0	4	1
	42	94	7	0	5	2
	43	155	9	5	2	4
Gap	44	110	26	2	1	11
	45	91	14	2	1	5
	46	83	1	0	4	0
Baleno	47	155	44	3	4	0
	48	160	11	0	1	4
	49	30	4	0	4	3
Jeanswest	50	73	6	2	1	2
GU	51	59	3	0	0	0
	52	93	10	1	6	0
	53	46	10	0	1	1
C&A	54	3	2	0	0	0
	55	50	6	0	0	0
	56	37	4	0	0	0
	57	54	3	0	0	0
Bershka	58	15	1	0	1	0
	59	7	2	0	0	0
	60	5	2	1	0	0
Pull&Bear	61	66	11	2	0	1
American Eagle	62	116	22	0	0	5
	63	34	2	0	0	0
Trendiano	64	47	2	0	0	7
	65	30	10	1	1	1
	66	16	1	1	1	0
	67	42	2	2	4	1
Me&city	68	48	4	0	2	2
	69	41	0	0	1	0
Hollister	70	17	2	0	0	0
	71	10	2	0	0	0
Tommy Hilfiger	72	38	7	0	3	1
	73	10	3	0	1	1
	74	15	4	0	1	0

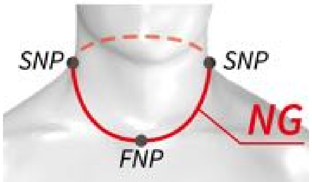
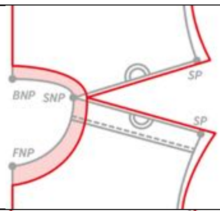
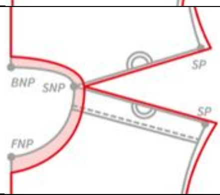
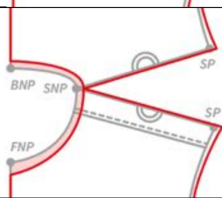
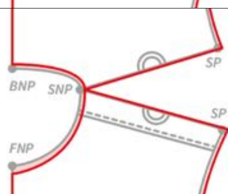
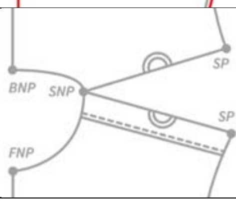
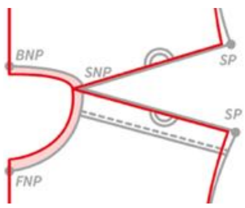
TeenieWeenie	75	17	3	0	1	0
	76	21	2	0	0	0
	77	31	7	1	2	2
Massimo Dutti	78	22	1	0	0	1
	79	16	3	1	0	0
Hugo Boss	80	6	3	0	1	0
	81	21	3	0	0	0
Sumnumber	81	4217	561	144	122	102
Ratio		81.9%	10.9%	2.8%	2.4%	2.0%

APPENDIX D

Indicators of shirt misfit

Table D.A – D.D shows the fit criteria of neckline and collar, shoulder seam, sleeve and bodice, respectively.

Table D.A – Fit criteria of neckline and collar

Fit level	Description	Photo	Scheme of pattern block
	FNP: front neck point; SNP: side neck point.	Responsible BM: Neck girth (NG)	
a. When the neckline and collar are too large.			
1	Obvious large gap between neck and collar		
2	Obvious gap between neck and collar		
3	Observable gap between neck and collar		
4	Tiny gap between neck and collar		
5	Fit without gap		
b. When the neckline and collar are too small.			
1	1. Many stressed folds around neck 2. Front placket is deformed 3. The buttons cannot be tied		

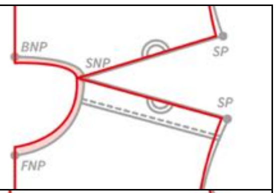
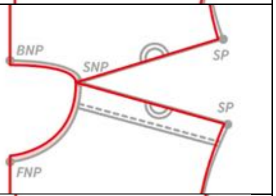
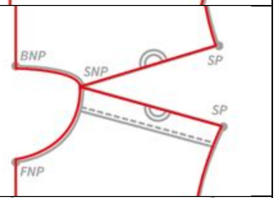
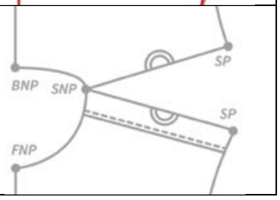
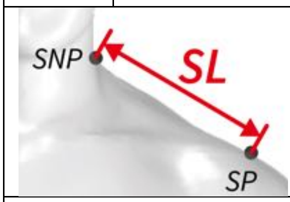
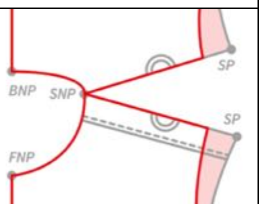
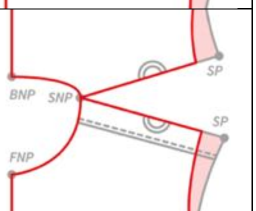
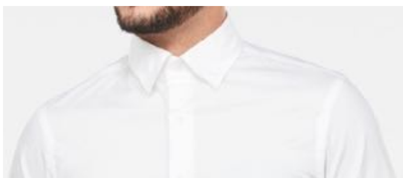
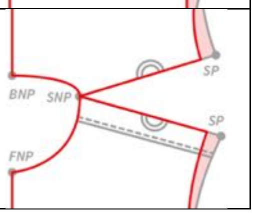
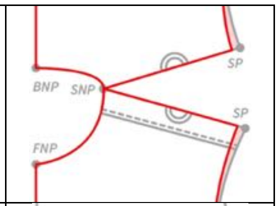
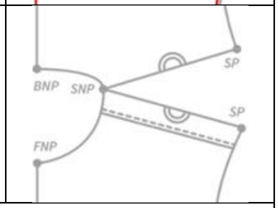
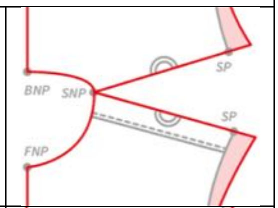
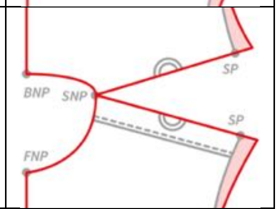
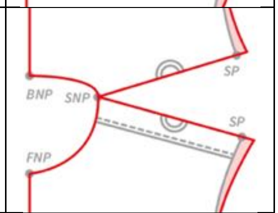
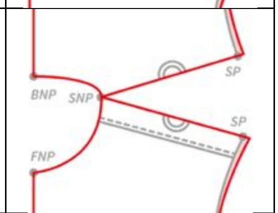
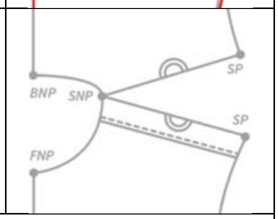
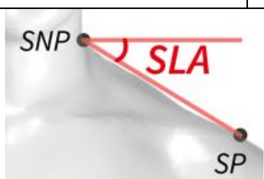
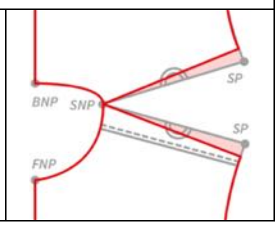
2	1. Many stressed folds around neck 2. Front placket deformed		
3	some stressed folds around neck		
4	several folds around neck		
5	Fit without fold		

Table D.B–Fit Criteria of shoulder seam

Fit level	Description	Photo	Scheme of pattern block
	SP: shoulder point.	Responsible BM: Shoulder length (SL)	
a.When the shoulder seams are too short.			
1	Protrudingbulgeand many folds around SP		
2	Some folds around SP		
3	A few folds around SP		

4	Nearly no folds around SP		
5	No fold around SP		
b. When the shoulder seams are too long			
1	Big protrudingbulges around SP		
2	Small protrudingbulges around SP		
3	A few folds around SPs		
4	Nearly no folds around SPs		
5	No fold around SPs		
	Responsible BM: Shoulder sloping angle (SLA)		
c. When the shoulder seams are too down			
1	Many big bulges and folds around SNP		

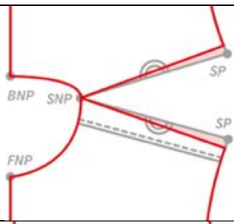
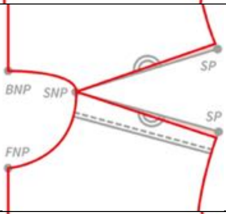
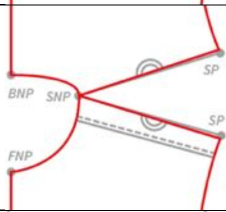
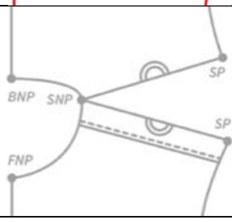
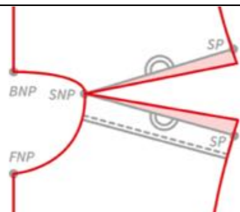
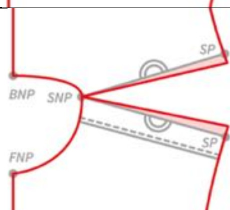
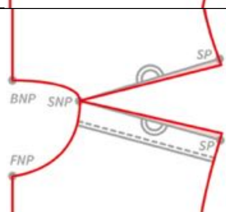
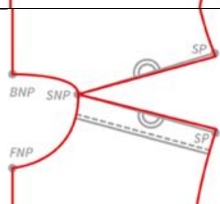
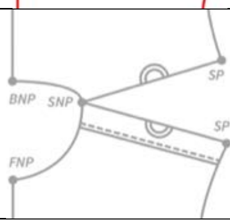
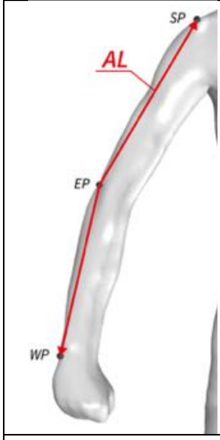
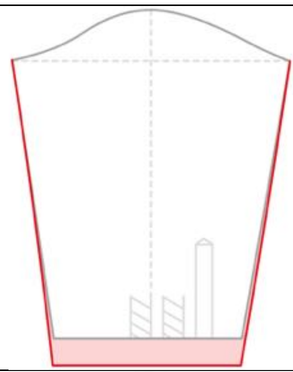
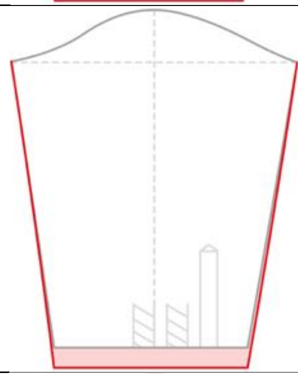
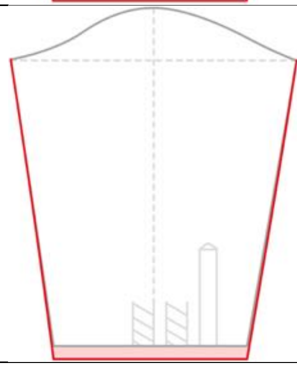
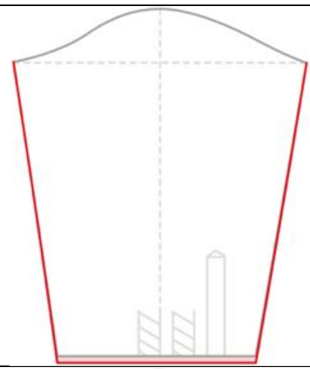
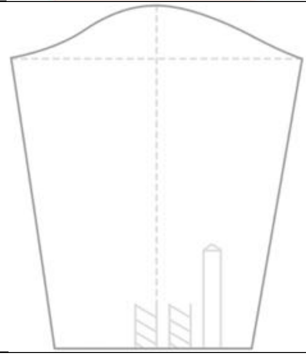
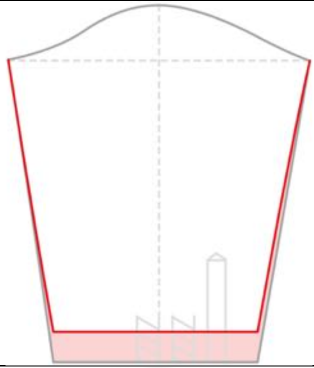
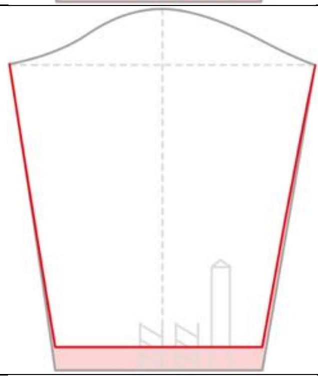
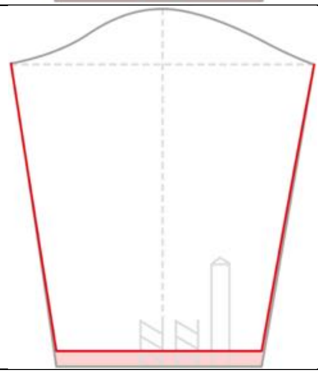
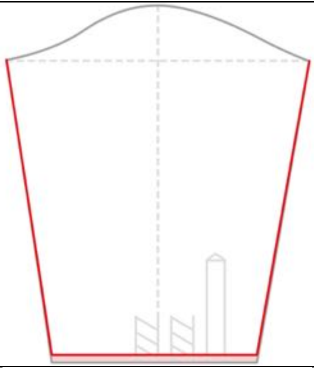
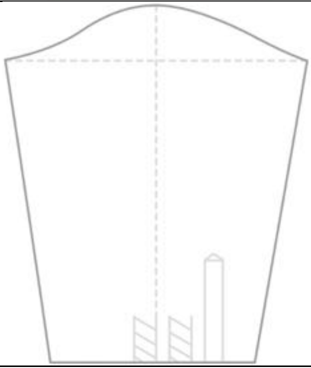
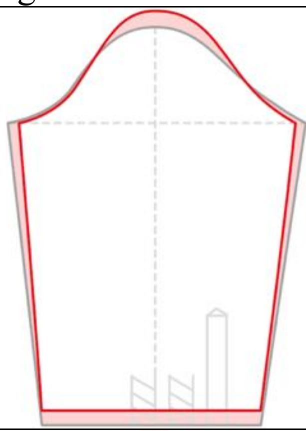
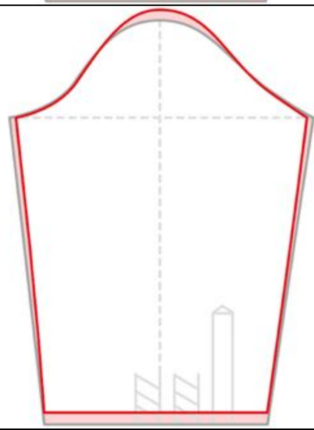
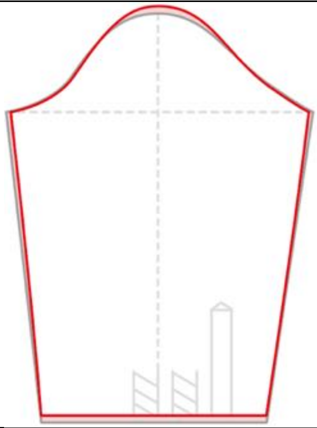
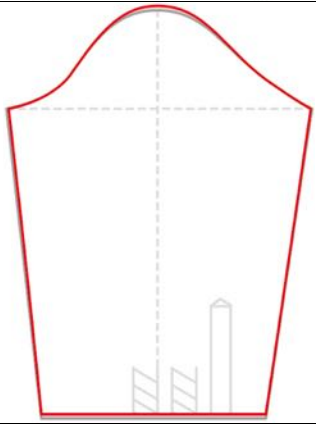
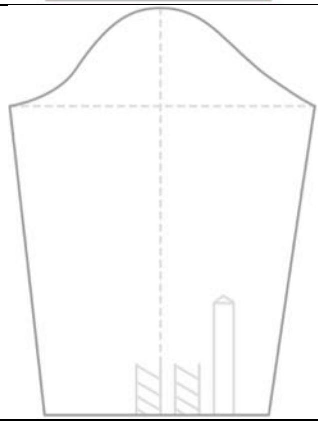
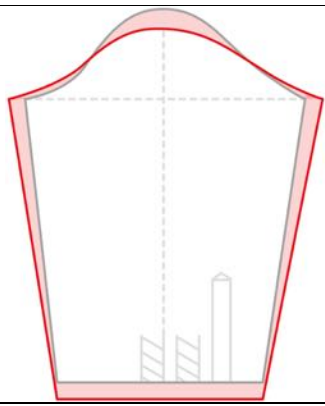
2	Some bulges and folds around SNP		
3	Small circular bulges around SNP		
4	A few tiny circular bulges around SNP		
5	Smooth seams without fold		
d. When the shoulder seams are too up			
1	Big bulges around SP		
2	Small bulges around SP		
3	Big folds from front center towards SP		
4	Tiny folds from front center towards SP		
5	Smooth seams without fold		

Table D.C–Fit criteria of sleeve

Fit level	Description	Photo	Scheme of pattern block
		EP: elbow point; WP: wrist point.	Responsible BM: Arm length (AL)
a. When the sleeves are too long.			
1	Almost the whole hands are covered		
2	Whole palms are covered		
3	Half palms are covered		

4	Small parts of palms are covered		
5	Cuffs around the wrists		
b. When the sleeves are too short.			
1	Cuffs are too higher than the wrists.		
2	Cuffs are higher than the wrists.		
3	Cuffs are a little higher than the wrists.		

4	Cuffs almost cover the wrists.		
5	Cuffs around the wrists.		
		Responsible BM: Armhole depth (AD)	
c. When the sleeve cap height is too large			
1	Big bulges and waves around upper arm area		
2	Bulges and waves around upper arm area		

3	Bulges around upper arm area		
4	Small bulges around upper arm area		
5	Smooth upper arm without bulge and fold		
b. When the sleeve cap height is too small.			
1	Lots of stressed folds arounddeltoid		

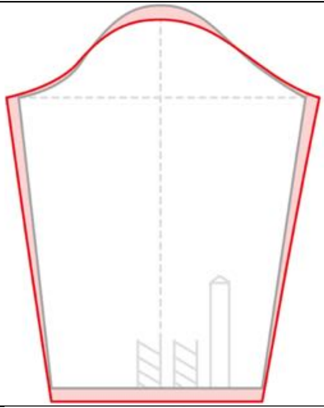
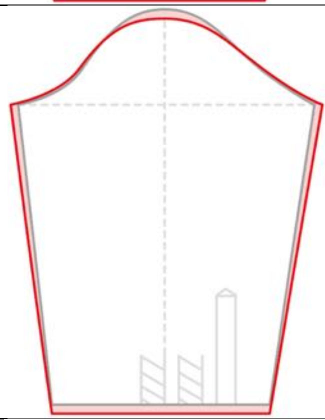
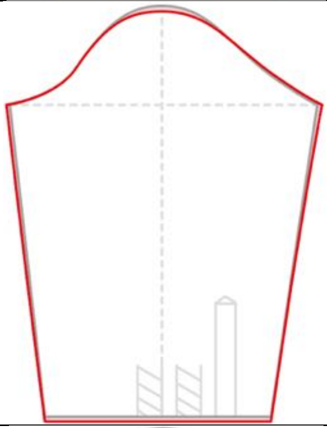
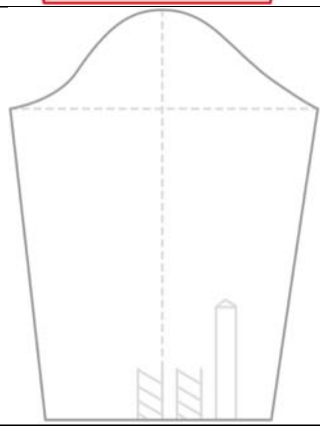
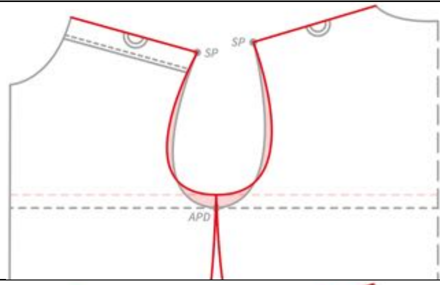
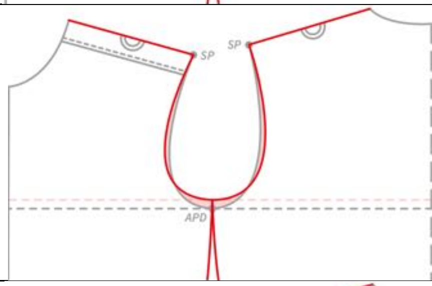
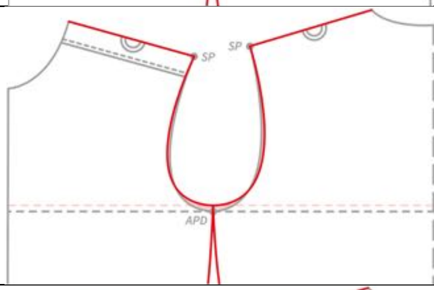
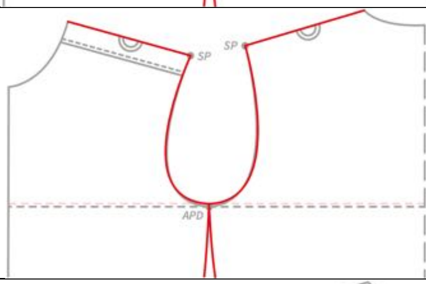
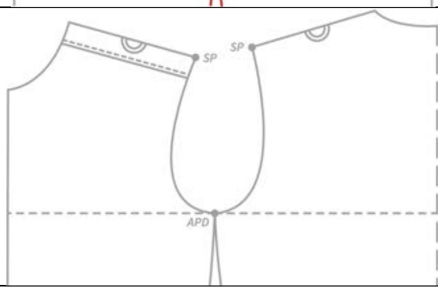
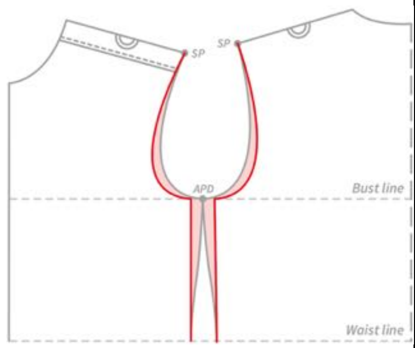
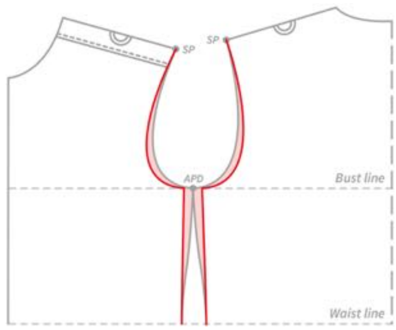
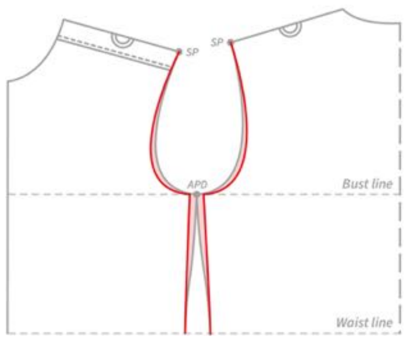
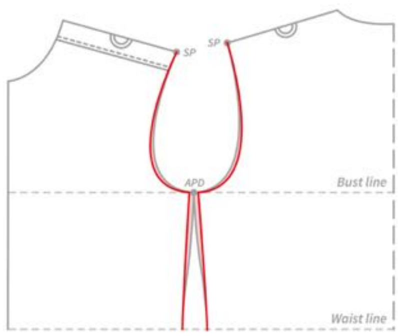
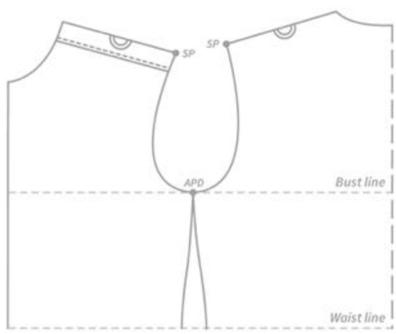
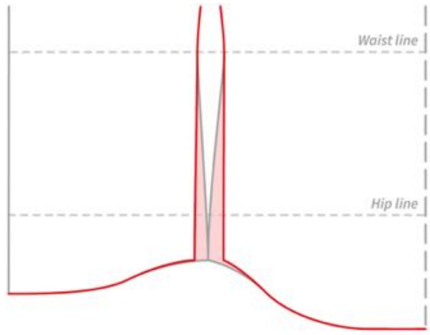
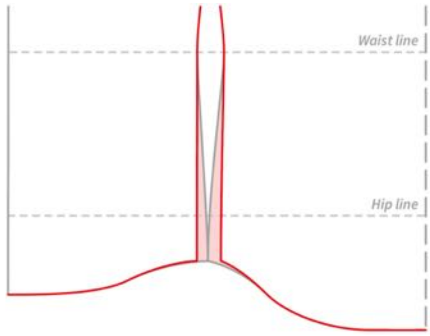
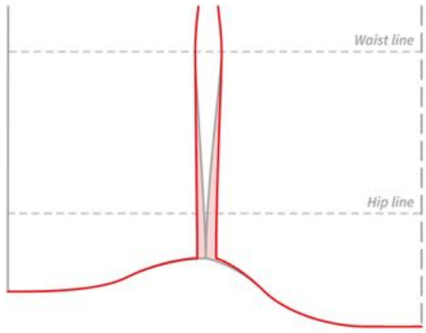
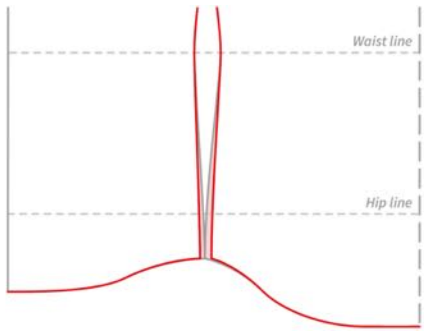
2	Many stressed folds arounddeltoid		
3	A few stressed folds arounddeltoid		
4	Almost no stressed folds arounddeltoid		
5	Smooth upper arm without bulge and fold		

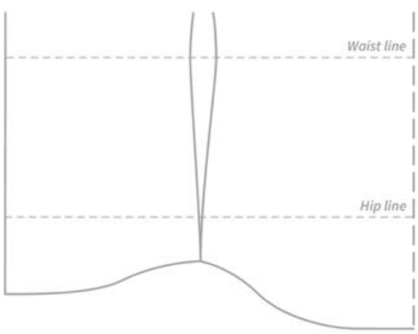
Table D.D–Fit criteria of bodice

Fit leve l	Descriptio n	Photo	Scheme of pattern block

	APD: armpit depth (axilla)	Responsible BM: Armhole depth (AD)	
1	Many stressed folds around axilla		
2	Some stressed folds around axilla		
3	A few stressed folds around axilla		
4	Almost no stressed folds around axilla		
5	Smooth armholes without stressed fold		
	Responsible BM: Chest girth (CG).		

1	1.Deformed front placket 2. Many stressed folds around chest		
2	Some stressed folds around chest		
3	A few stressed folds around chest		
4	tight shape without observable fold		
5	Smooth front piece without folds.		

	Responsible BM: hip girth (HG).		
1	Badly deformed back piece with big stressed folds from chest to bottom		
2	Many stressed folds around chest and hip		
3	Several folds around hip		
4	A few folds around hip		

5	Smooth back piece nearly without folds		

APPENDIXE

Results of technology validation

УТВЕРЖДАЮ
Генеральный директор ООО «Тексел»,
к.ф.-м.н.

М.А. Федюков
121205, Сколково
Большой бульвар, 42, стр. 1
«16 » ноября 2020 г.

М.П.

УТВЕРЖДАЮ
Ректор ФГБОУ ВО «Ивановский
государственный политехнический
университет», д.т.н.
Е.В. Румянцев
Иваново, 153000,
Шереметевский пр., 21
«16 » ноября 2020 г.

М.П.

АКТ испытаний
технологии дистанционного проектирования мужских сорочек

Мы, нижеподписавшиеся, В.Е.Кузьмичев, заведующий кафедрой конструирования швейных изделий, профессор, Янь Цзяци, аспирант, от Ивановского государственного политехнического университета, и М.А. Федюков, генеральный директор ООО «Тексел», составили настоящий акт о том, что нами проведена проверка дистанционной технологии виртуального проектирования мужских сорочек на фигуры индивидуальных потребителей e-bespoke.

Время проведения испытаний: декабрь 2019 года – ноябрь 2020 г.

Технология реализована с помощью аппаратно-программного комплекса, в который вошли следующие компоненты: (1) бодисканер Texel Portal MX; (2) программа для построения чертежей одежды (BUYI Technology, Китай); (3) программа для генерирования виртуальных двойников фигур и одежды CLO 3D, версия 5.0.156.38765 (CLO Virtual Fashion, Республика Корея).

Проверка технологии была проведена в следующей последовательности.

1. ООО «Тексел» передала файлы со сканированными 3D-изображениями девяти мужчин разных морфологических типов.

2. В ИВГПУ все 3D-изображения были обработаны для выявления морфологических особенностей и параметризованы с помощью традиционных и вновь предложенных размерных признаков.

3. В ИВГПУ были построены чертежи деталей сорочки полуприлегающего силуэта для всех девяти фигур, на основе которых разработаны лекала.

4. В ИВГПУ была проведена проверка правильности разработанных чертежей путем выполнения виртуальных примерок всех сорочек.

5. В ООО «Тексел» по разработанным лекалам были изготовлены сорочки.

После изготовления сорочек была проведена их примерка на ранее выбранных фигурах для оценки внешнего вида и соразмерности.

В результате оценки установлено, что большинство сорочек имели хорошую посадку в соответствии с морфологическими особенностями фигур. Использованное количество новых размерных признаков достаточно для проектирования сорочек.

Были выявлены некоторые несоответствия между размерами воротника и шеи, руки и рукава, которые устранены путем перестроения лекал.

ЗАКЛЮЧЕНИЕ

Разработанная технология, включающая новую антропометрическую базу данных о строении торса мужских фигур в виде совокупности размерных признаков и алгоритм их использования для построения чертежей деталей, может быть использована для дистанционного проектирования и изготовления мужских сорочек категории e-bespoke.

От ООО «Тексел»
М.А. Федюков
«16 » ноября 2020 г.

От ИВГПУ
В.Е.Кузьмичев
Янь Цзяци
«12 » ноября 2020 г.