THE HONGKONG POLYTECHNIC UNIVERSITY
INSTITUTE OF TEXTILES AND CLOTHING

CAD Technology for Clothing Biomechanical Engineering Design

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A thesis submitted in partial fulfillment of the
requirements for the Degree of Doctor of Philosophy

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the test.

______________________________(Signed)

___Ruomei Wang__________________(Name of student)

TO MY FAMILY

For their constant love, support and encouragement

ABSTRACT

The purpose of research is to establish a theoretical framework of integrated CAD system for clothing biomechanical engineering design by developing computer simulation and visualization platform. A mathematical model and visualization environment have been developed to simulate the dynamic mechanical interactions between clothing and human body during wear to reveal skin pressure distributions and distributions of stresses and strains in human body, as well as their impact to human psychological sensory perceptions. The CAD system is applied to establish scientific principles and framework for biomechanical engineering of biofunctional textile products to meet the requirements of biomedical and healthcare applications.

Clothing engineering design is a complex process, which generates and uses large volume of dynamic data with rich data structure and different categories of variables, such as specifications, engineering design orders, technical data, problem reports, design models and analysis files. An engineering design database management system for clothing biomechanical engineering design must provide powerful data management functions to support the design process. A flexible and multi-layer engineering database has been developed to meet the needs of clothing biomechanical engineering design.

Clothing biomechanical engineering design is a systematic and quantitative way of designing functional apparel products with 3D simulation of mechanical interactions of deformable human body and clothing, and prediction of clothing pressure sensory comfort performance. A hybrid simulation model has been developed by integrating mathematical models with computation algorithms to derive 3D garment data from a garment’s 2D pattern and to specify human body-garment contacting conditions for computational simulations.

Clothing biomechanical engineering design is a complex iterative-decision-making process. To increase efficiency in this complex process, an integration CAD system has been developed to provide an integrated environment from functional specification, data management, biomechanical computational simulation, design visualization and evaluation. To evaluate the pressure comfort performance of the design, a computational model has been developed to predict the mechanical sensory perception from skin pressure distributions, internal deformations, stresses and strains that are induced by the dynamic mechanical interactions between clothing and human body. To support designers and engineers to evaluate the biomechanical functional performances and sensory comfort of their design, visualization interfaces have been developed, which can not only present the quantitative data in scientific format, but also can transform the quantitative data to 3D color images to visually illustrate skin pressure distributions, deformations, stress and strain distributions

in internal structure of the body, also create 3D color map to visualize the pressure sensory perceptions at different parts of the body.

In summary, a theoretical framework for clothing biomechanical engineering design have been developed as an systematic CAD platform, which integrates engineering database, 3D geometric construction model, biomechanical simulation model, mechanical sensory perception simulation model, visualization interfaces of simulation results. This integrated CAD system provides a technology platform for design and engineering of textiles and apparel products on the basis of scientific data with effective visual illustrations.

RESEARCH OUTPUT

The research work so far has generated scientific publications, including：

1. **Ruomei Wang**, Yi Li, Fang You, Xiaonan Luo, Rational recurrence curves and recurrence surfaces in multivariate B-form on some regions, Journal of Computational and Applied Mathematics, 163(2004), 277-285 (SCI).
2. **Ruomei Wang**, Xiaonan Luo,Yi Li, Representation and Conversion of Bezier surfaces in multivariate B-form, Journal of Computational and Applied Mathematics, Vol. 195, Issues 1-2, 15 October 2006, 206-211(SCI).
3. **Ruomei Wang,** Yi Li, Xiaonan Luo, Xin Zhang, VISUALIZATION APPLICATION IN CLOTHING BIOMECHANICAL DESIGN, Lecture Notes4282, 2006, 522-529(SCI).
4. **Wang R.M**., Li Y., Zhang X., Luo X.N., Dai X.Q., 12 A CAD system for clothing biomechanical sensory engineering, Computational Textile, Ed by Xianyi Zeng, Li Yi, Da Ruan, Ludovic Koehl, Studies in Computational Intelligence, Springer Berlin / Heidelberg, 1860-949X (Print) 1860-9503 (Online), Volume 55/2007, DOI 10.1007/978-3-540-70658-8_18, 2007, 277-287, ISBN 978-3-540-70656-4
5. Yi Li, Zhong Wang, Zhong Wang, **Ruomei Wang**, Aihua Mao and Yubei Lin., FEAFUR: A computer software package for simulating human thermophysiological responses in dynamic thermal environment, Computational Textile, Ed by Xianyi Zeng, Li Yi, Da Ruan, Ludovic Koehl,

Studies in Computational Intelligence, Springer Berlin / Heidelberg, 1860-949X (Print) 1860-9503 (Online), Volume 55/2007, DOI 10.1007/978-3-540-70658-8_13, 2007, 223-233, ISBN 978-3-540-70656-4

6. **WANG Ruo-mei**, Luo Xiaonan and LI Yi, Database for biomechanical engineering design in “Biomechanical engineering of textiles and clothing”, Edited by Yi Li, and Xiaoqun Dai, Woodhead Publishing Ltd, 2006, 257-282.
7. **WANG, Ruo-mei**, Luo Xiaonan DAI Xiao-qun, ZHANG Xin and LI Yi, Preparing for the mechanical simulation in “Biomechanical engineering of textiles and clothing”, Edited by Yi Li, and Xiaoqun Dai, Woodhead Publishing Ltd, 2006,283-295.
8. LI Yi**, WANG Ruo-mei**, DAI Xiao-qun, ZHANG Xin and Luo Xiaonan, Visualization for the Mechanical Analysis in “Biomechanical engineering of textiles and clothing”, Edited by Yi Li, and Xiaoqun Dai, Woodhead Publishing Ltd, 2006,296-304.
9. **Wang Ruomei,** Li Yi, Luo Xiaonan, Lin Yubei, The research and implementation of Minimum Weight Triangulation Based on Improved Genetic Quantum, 7th World Congress on Computational Mechanics, Los Angeles, California, USA, July 16 - 22, 2006.
10. **Ruomei Wang**, Yi Li, Xiaoqun Dai, Xiaoning Zhou, A digital engineering design system for simulating clothing dynamical mechanical behavior, Proceedings of The Textile Institute 83rd World Conference, May 2004, Shanghai.

11. **Ruomei Wang**, Yi Li , Xin Zhang ,Xiaonan Luo , Xiaoqun Dai, A CAD for clothing biomechanical sensory engineering, 17th IMACS World Congress Scientific Computation, Applied Mathematics and Simulation, Paris, France, July 11 - 15, 2005, Computational Textile.

12. Li Yi, **Wang Ruomei,** Software copyright: 3D-Apparel CAD system (2005SR01691).

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Table of contents

List of figures

List of tables

CHAPTER 1 INTRODUCTION

1.1 INTRODUCTION

1.1.1 Clothing Biomechanical Performance

Since human civilization began, clothing has played a most important role, not only to provide warmth, comfort, and physical protection, but also to beautify the body and life. With the development of technology and progress of social culture, modern consumers demand that clothing products have superior multi-functional performance and greater comfort. They are interested in clothing that not only looks good but also feels good [55].

In the new century, the textile and clothing markets are highly competitive. To meet and even exceed customer expectation is the key to success in the market place for any enterprise. Research on clothing comfort has substantial financial implications for the business management of textile enterprises in the effort to satisfy the needs and wants of consumers in order to obtain sustainable competitive advantages in modern consumer markets.

The comfort and functional performance of clothing involves a number of aspects [55]:

- The thermo-physiological performance: attainment of comfortable thermal and wetness states, it involves transport of heat and moisture through the fabric.

- Sensorial performance: the effect of various neural sensations when a textile comes into contact with the skin.
- Body movement performance: ability of a textile to allow freedom of movement, reduced burden, add/or shape the body.
- Aesthetic appeal: subjective perception of clothing to the eye, hand, ears and nose, which contributes to the overall well-being of the wearer [30].

Clothing mechanical performance has been identified as one of the important attributes. During wear, clothing contacts with the skin at most parts of the body. The moving body will induce mechanical stimuli from the contact between the body parts and clothing, and these, in turn, induce responses from various sensory receptors to formulate various perceptions, e.g. touch, pressure, prickle, itch and inflammation, which affect the mechanical comfort of the wearer [33].

The study of clothing biomechanical performance deals with the relationship between clothing mechanical performance and human factors: (1) physical (such as the body size and shape); (2) biomechanics of the human body (such as the deformation of the muscles); (3) neurophysiology (formulating sensory signals from the interactions of the body with the clothing); and (4) psychology (subjective perception of sensory sensation from the neurophysiological sensory signals and then formulating subjective overall perception and preferences). The study of clothing mechanical behavior can create new clothing by enhancing existing designs or by altering existing ones to perform new functions.

Figure 1.1 shows the main components of clothing biomechanical engineering design.

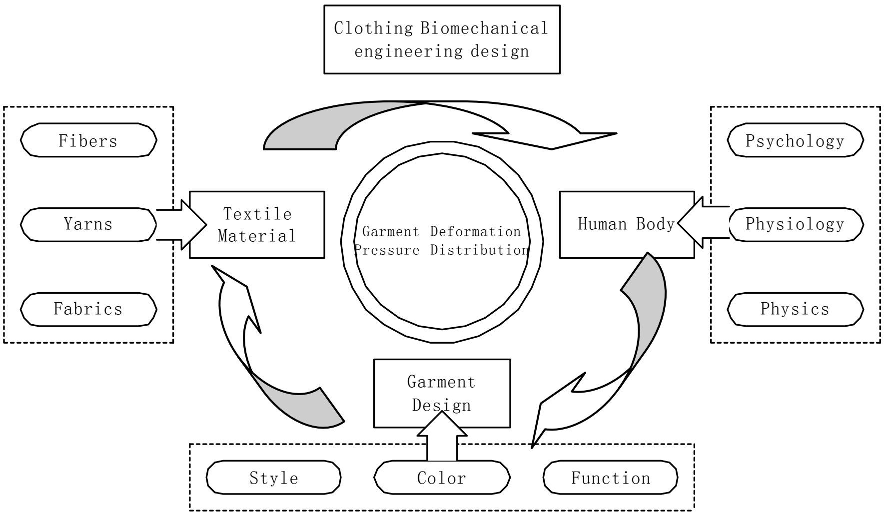


Figure 1.1 The components of clothing biomechanical engineering design

According to the Figure 1.1, clothing biomechanical engineering design is a systematic and quantitative way of designing functional apparel products; it involves physical, chemical, mathematical and computational sciences, and engineering. The studies of clothing biomechanical performance will create the knowledge at the body-clothing system level.

1.1.2 CAD Technology

The task of clothing biomechanical engineering design consists of selecting the garment (style, color), materials, and human model to meet specified functional requirements for the clothing. This design phase is a complex iterative-decision –making competitive process with analysis and synthesis based on knowledge of the basic sciences, mathematics, and engineering principles. It uses and generates a large number of dynamic data during the design process. Engineering design deals with a number of value types (text, numbers, equations, diagrams, graphical, photographic images etc.). When the design phase has determined a feasible style and appropriate materials parameters, the analysis phase is used to calculate the mechanical performance of the dynamic contact system, such as distributions of stresses and strains in the garment, the deformation of the skin and the soft tissues, the garment pressure distributions on the skin. The analysis is concerned with the mathematical testing of the design to check whether it meets the functional criteria of clothing.

To make the concept a realistic possibility, computer graphics, computer display technology, computer databases, and mathematical models need to be used to provide a visual environment for design, analysis, evaluation, and visualization for all the knowledge needed to predict the performance of clothing during wear. Hearle [31] presented the concept of textile product design with fabric mechanics as a design tool. He discussed the different approaches available to tackle fabric mechanics in a hierarchical way and developed a concept of a computer aided total design system based on three frameworks: 1) a database about fiber and fabric properties; 2) a knowledge based system using the pool of available expertise and historical data; 3) a deterministic suite of programs in structural mechanics.

In 2000, Kawabata [47] pointed out that the engineering design of textiles with a focus on the design of textiles' quality and performance is now moving to an important stage. The goal is the engineering design of the ideal quality of clothing on the basis of fiber science, textile mechanics and the objective measurement technology that has been developed.

Obviously, the development of a generalized knowledge based CAD system for the engineering of textiles and clothing, to meet the requirements for analyzing, simulating, and evaluating fabric mechanical behavior, has great importance both economically and in its applications.

To develop a clothing biomechanical engineering design system with the required functions, a serious of fundamental works has been undertaken, combining science, engineering and information technologies. The works mainly focus on research aspects: 3D garments; mechanical models for the human-clothing contact system; clothing engineering database; modeling psychophysical relationships between mechanical stimulation and subjective comfort perception.

1.1.3 Applications

Clothing biomechanical performance is an important factor to be considered during functional clothing design. The knowledge and methodology of clothing biomechanical engineering design can be applied in number of ways [55]:

- To conduct consumer research by utilizing the research techniques developed to understand what consumers want and need, and to identify a market gap for new product development;
- To develop textile products that have unique functional features and are sure to satisfy targeted customers;
- To use consumer sensory evaluation as a way for new product evaluation to reduce the risk of market failure;
- To develop technical information and specifications for promotional and marketing purposes;
- To formulate quality control tools by developing test methods, instruments, and standards.

Creig [14] pointed out the importance of systematically studying product attributes, and their relative importance in motivating buyers, by inferential procedures. A set of functional and emotional product attributes needs to be identified to explain a buyer’s brand preferences among all brands or choices. During the process of purchase decision-making, consumers evaluate the apparel with many factors: physical properties of the clothing, physiological characteristics of the buyer, the wear environment, economics of the clothing, and background. Li [55] reported the methods and aims for consumer research.

By identifying the major factors of textile materials and clothing structural characteristics that influence the mechanical behavior during wear, the outcome of the research will be valuable in aiding the development of integration design procedures to guide designers in producing clothing mechanical performance based on human factors. The research outcome of this study may also contribute significantly to the physiological health and comfort of the wearer and to pressure therapy in medical clinical practices.

1.2 LITERATURE REVIEW

1.2.1 Integrated Technology

The word integration means ‘whole’ [27]. An integration system is composed of related components.

There are many software tools available from different suppliers or, in some organizations, produced locally for internal use. In fact, the number of tools which may be of benefit to a specific project is overwhelming for these reasons [16]:

- They come from different vendors;
- They originate on different platforms and operating systems;
- They are based on different philosophies and employ different styles;
- They treat data as proprietary to the tool;
- They have their own priorities and timetables for enhancement of their functionality.

The issue faced is how to use the available tools in a consistent and applicable fashion.

Effective tools are expected to: present a uniform user interface; share data between tools; conform to our view of the software engineering process; be controlled in a uniform manner, allowing portability across platforms.

Providing an integration framework in which different tools can be incorporated requires a model like the one below which identifies the different services required to support integration, and shows an integration framework [16](see Figure 1.2).

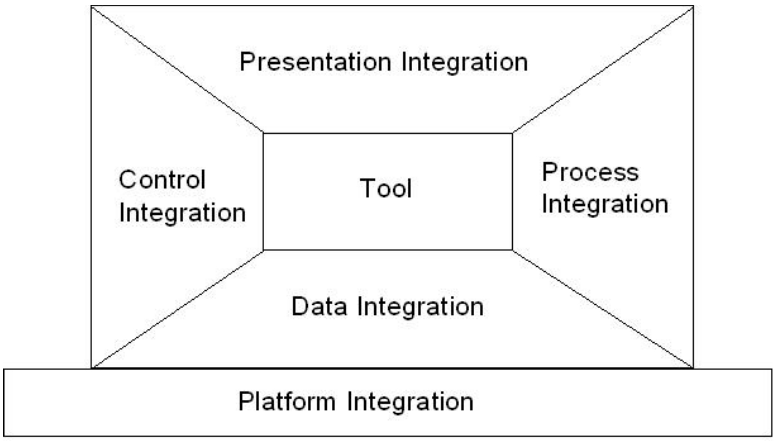


Figure 1.2 Integration framework

Presentation integration refers to the interface with the user of the tool. The interface may be for the purpose of invoking the tool or communicating with the tool as it performs its job. That means the user can use this interface to describe their problem and then use different tools.

Critical to tools working together is their ability to share data. Simple scenarios are that one tool generates output that is held as a file that is then read by another. In order to achieve data integration, a database is required.

Combining tools together to make a viable software development environment requires mechanisms to control tools by offering facilities to register tools, invoke individual tools, perform tool composition and allow messages to be passed between tools or from tools to users. This is called control integration.

Process integration will offer facilities to model the process, manage the work-flows, identify the deliverables, and manage, in a sensitive manner, those involved in the development process.

Platform integration is the provision of a layer which sits between the individual tools and the operating system. It provides a consistent interface so that the tools developed to use that interface do not need to be modified when moved to a different platform that has the same platform integration layer.

Integration technology will certainly evolve and become more accessible. It will mean simplifying the process of tools integration, educating users and helping them become more productive by producing higher quality systems than are available today [24].

Integration technology has been applied in different areas because an integrated technology can support all steps from problem formulation to problem solution.

The task of design, production planning and manufacturing of new and more sophisticated products aimed at qualitatively improving products, reducing time and costs and simultaneously increasing productivity is only mastered when data processing and automation are incorporated. Kochan [49] reported an integration application in manufacture, while Zdenek Kozar [50] reported an integrated CAD/CAM systems production automation process.

Usowicz [85] reported that integration should provide the following advanced functions as minimum requirements: integration should support user specified customization of the environment’s tools and/or the addition of new tools; it should provide mechanisms for monitoring and determining the degree of process toward completion of system development.

Wang papers [25], [102], [19], [68], [52] have reported the integration technology applied in different areas.

1.2.2 Engineering database

"Database" is one of the most important terms in computer technology. As it is commonly known today, a database management system carries out the organization of data storage and data management for a whole application area. This provides three major advantages: the organization of data does not necessitate specific programming for the application systems; the application is easier to extend, and the application data can also be made accessible to other application systems [43]. The database management systems can be regarded as being the realization of the idea behind integrated data processing.

Great progress has been made in the development of business database management systems. Their significance is steadily increasing due to their powerful query and operating languages, and their simplicity with regard to data representation. With the development of computer applications in the engineering process, the engineering database assumer an important role. However, an engineering database is different from a business database.

Engineering design is based not only on mathematics and physics, but also on production technology, materials science, machine elements, industrial management and cost accounting. Such activity includes not only semantic information, as in the case of business databases, but also information details of the engineering design, whereas a business database is a mere collection of related information.

Engineering design needs to receive rich information to create an elaboration of a design specification. The information can be received in different ways, from market analyses, trend studies, patents, technical journals, questions from customers, concrete assignments, design catalogues, analyses of natural and artificial systems, calculations, experiments, analogies, general and in-house standards and regulations, stock sheets, delivery instructions, computer data, test reports, accident reports, and through asking questions [22]. Information can be processed by analysis and synthesis, calculation, experiment, the elaboration of layout drawings and also the evaluation of solutions. It can be transmitted by means of drawings, reports, production documents etc.

It must be noticed, however, that the engineering process contains many loops in which activities with a routine character; such analysis is followed by activities with a creative character such as selection. The DBMS should support this process [60].

Data flow in engineering design is very dynamic in the sense that they are not known a priori but defined during the design process. So the DBMS should not only deal with a component for the storage of standardized parts, design procedures and material properties, but also with structures, machines and installations composed from these elements.

Furthermore, the DBMS should be used for storage and retrieval of measured and calculated data in such a way that the origin of these data can be traced. The DBMS should support typical engineering activities such as the analysis and modification of complex structures. Various way of presenting the database contents must be possible, including graphical, representation of objects and measurement data [60].

Therefore, the fundamental difference between an engineering design database and a business database is the stability of the administrative environment as compared to the dynamic engineering environment. The development of the engineering design database management system (EDDBMS) must carefully consider the characteristics of the engineering design processes.

A conceptual scheme is a formal description of the conceptual database. There are three major data models that are used in database systems: the relational data model, the hierarchical data model and the network data model [84]. The relational data models, in which all entities and dependencies between entities of the reality are stored in a database, are described by using the concept of ‘relation’. A relation is defined as a set of structural k-tuples. These k-tuples are composed of data elements. A relation description consists of a description of its domains (names and kind of values). The hierarchical data model represents entities and hierarchical relationships among different entities. In this model, each entity is represented as a record and hierarchical relationships by a tree structure. The network data model allows the representation of arbitrary relationship between entities. Each entity is represented as a record, and it may be owned by more than one record, leading to a network structure. According to the characteristics of the engineering design, the hierarchical model is used to describe the database [99].

Dittrich [43] and Rasdorf [89]have presented an engineering database case study for VLSI and an engineering database applied to CAD/CAM.

1.2.3 Clothing biomechanics

1.2.3.1 Material properties

Fabrics are the fundamental materials constituting garments and textiles. The mechanical properties of a fabric will affect the performance of the clothing mechanics during wear and simulation of wear, such as the deformations, constraints or force patterns. While any number of parameters may be defined for modeling the behavior that may occur in some applications, a standard set of parameters is used for describing the most important mechanical characteristics of fabric materials [80].

The biomechanical functional performance of garments and devices is very much dependent on the fabric mechanical and surface properties, which are largely determined by the constituent fibers and yarns, internal structural features and the surface morphological characteristics of individual fabrics. Scientific understanding and knowledge of fabric mechanical properties and modeling of their mechanical behavior are essential for biomechanical engineering of clothing and textile products.

Woven fabric is one of the major materials for apparel use. In normal garment wear, cloth deformation is a mixture of tension, bending shearing and twisting. They are usually measured using the Kawabata Evaluation System(KES).

Kawabata and his co-workers developed the KES-F (Kawabata Evaluation Systems for Fabrics) with the aim to measure objectively the appropriate fabric properties and then to correlate these measurements with the subjective assessment of handle [46]. The Kawabata Evaluation System for fabric is a reference methodology for the experimental observation of the properties of a fabric material.

The system consists of four specialized instruments: 1) FB1: tensile and shearing; 2) FB2: bending; 3) FB3: compression; and 4) FB4: surface friction and variation. The system investigates the responses of various mechanical behaviors under low-loads. As is well known, fabric mechanical properties in a low-load region possess a peculiar non-linearity. One example of the non-linearity is the hysteresis behavior in the load deformation relation. These properties of cloth have significant influences on the aesthetic shape and wear comfort in garment end use. They must be measured exactly and expressed by parameters.

Tensile property

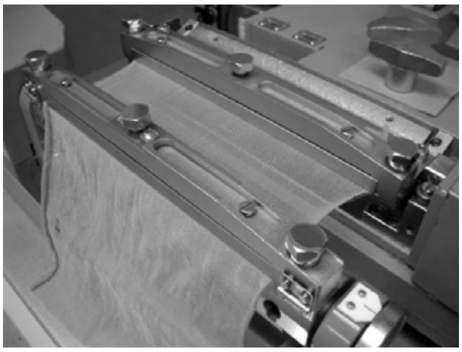
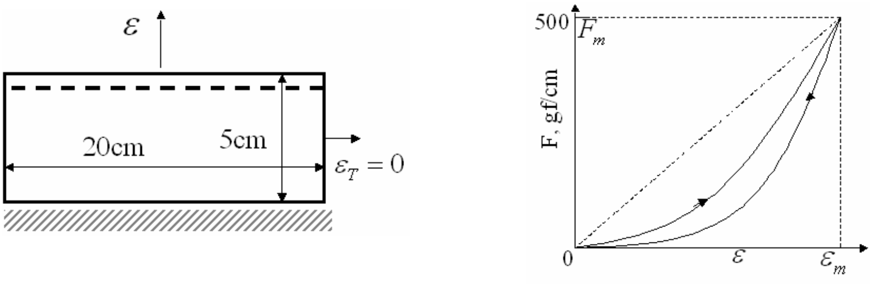


Figure 1.3 KES-FB1 tester adopted from Y. Li,X-Q. Dai, Biomechanical engineering of textiles and clothing, Woodhead publishing limited, Cambridge CB1 6AH, England, 2006



(a) Specimen extension (b) Load-elongation curve

Figure 1.4 KES tensile test

Figure 1.3 shows the KES-FB1 tester. The tensile test is illustrated in Figure 1.4 (a), where extension is applied along the 5cm direction of the specimen up to 500gf/cm. The transverse contract is not limited. Figure 1.4 (b) shows a typical load-extension hysteresis curve. From this curve, several parameters are derived:

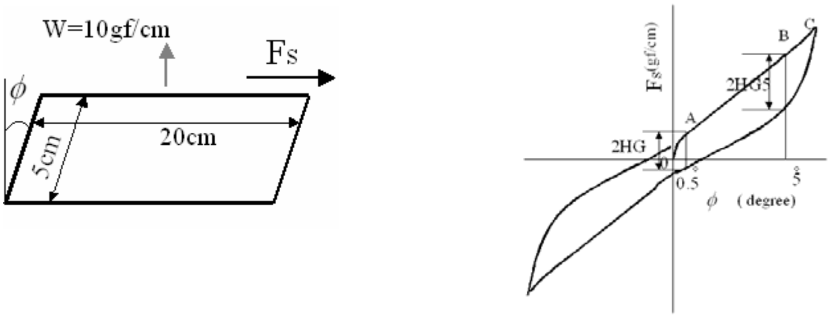
Tensile energy, $WT = \int_0^{\varepsilon_m} F d\varepsilon$, (gf×cm/cm^2);

Linearity of load-extension curve, *LT=WT/WOT*, where $WOT = F_m \cdot \varepsilon_m / 2$;

Tensile resilience, $RT = (WT'/WT) \times 100$, (%), where $WT' = \int_0^{\varepsilon_m} F'd\varepsilon$;

Extensibility, EM, the strain(ε_m) at 500gf/cm.

Shearing property



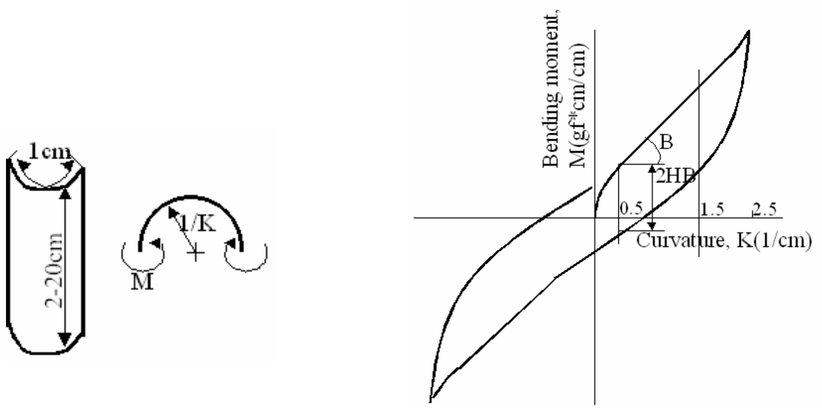
(a) Specimen shearing (b) KES shearing curve

Figure 1.5 KES shear test

The shear test is carried out using the same tensile tester with tensile test (KES-FB1). The test is illustrated in Figure 1.5 (a). A rate of shear strain of 8.34×10^{-3}/sec. is applied to the specimen under a constant extension load 10gf/cm up to a maximum shear angle of 8°. Figure 1.5 (b) is the shear-force-shear-angle hysteresis curve typically obtained. From it, the following parameters are derived: i) *G*, the shear rigidity, is the mean slope of the curve in the region ϕ=0.5°~5°; ii) *2HG* is the hysteresis of shear force at a shear angle of 0.5°; iii) *2HG5* is the hysteresis of the shear force at a shearing angle of 5°.

Bending

Figure 1.6 KES-FB2 bending tester adopted from Y. Li,X-Q. Dai, Biomechanical engineering of textiles and clothing, Woodhead publishing limited, Cambridge CB1 6AH, England, 2006



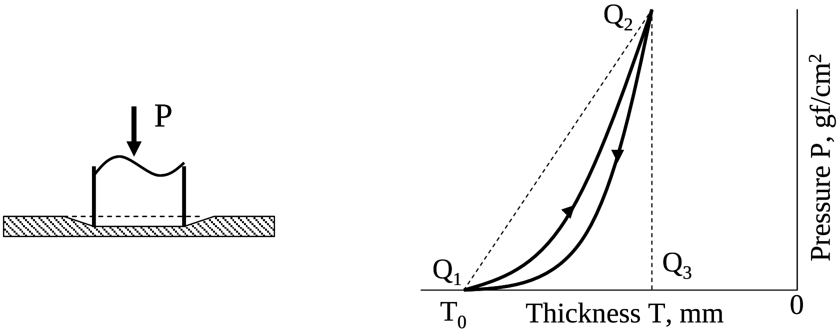
(a) Specimen bending (b) KES bending curve

Figure 1.7 KES bending test

Figure 1.6 shows the KES-FB2 bending tester. In the KES bending test, a specimen is bent between the curvatures –2.5 and 2.5 cm^{-1} as illustrated in Figure 1.7 (a). Figure 1.7 (b) is a typical bending curve, from which two parameters are derived: *B*, the bending rigidity, the mean slope of the curve in the region K=0.5~1.5 cm^{-1}; and *2HB*, hysteresis of the bending moment, measured at K=0.5cm^{-1}.

Compression

Figure 1.8 KES-FB3 tester adopted from Y. Li,X-Q. Dai, Biomechanical engineering of textiles and clothing, Woodhead publishing limited, Cambridge CB1 6AH, England, 2006



(a) Compression deformation (b) KES compression curve

Figure 1.9 Compression test

Figure 1.8 shows the KES compression tester FB3. The specimen used for compression test is of size 2.5cm×2.0cm, and the effective pressure region is a circular area of 2cm^2. The specimen is compressed in the direction of its thickness to a maximum pressure of 50gf/cm^2 as illustrated in Figure 1.9 (a). The shape of the resulting pressure-thickness curve (Figure 1.9 (b)) is similar to that of the load-extension curve, and the parameters defined are the same as those for the tensile property: *LC*, linearity of compression curve; *WC*, compression energy; and *RC*, compression resilience. The fabric thickness at 50Pa pressure, T_0 and that at 200Pa pressure, T_m, can also be obtained from the thickness-pressure curve, that the compression tester can also be used for fabric thickness measurement.

Surface property

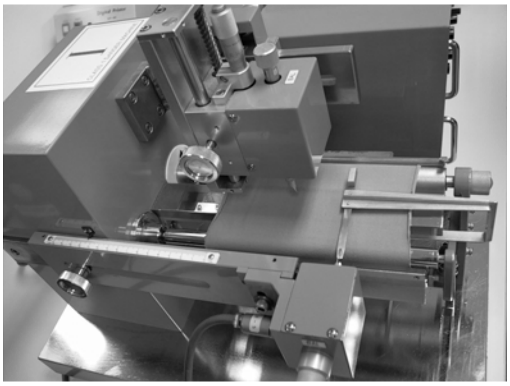
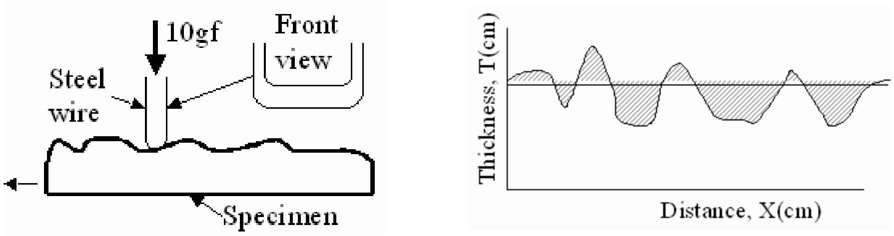


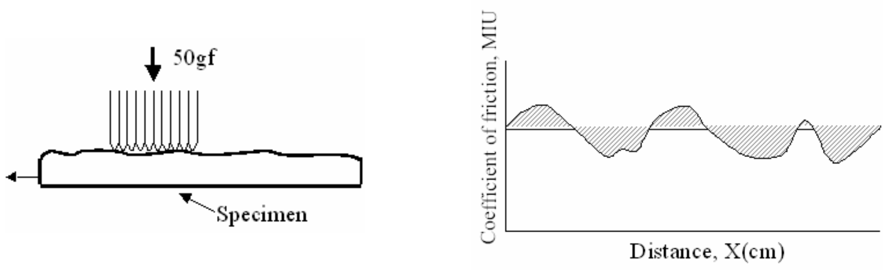
Figure 1.10 KES-FB4 tester



(a) Roughness measurement (b) Surface thickness variation

Figure 1.11 KES surface roughness test

Figure 1.10 is the KES-FB4 tester for surface properties. The surface roughness is measured by pulling across the surface a steel wire of 0.5mm diameter that is bent into a U shape as illustrated in Figure 1.11 (a). Figure 1.11 (b) shows a plot of the height variation along the distance. The mean deviation of surface contour, *SMD* is calculated from the plot, since *SMD=hatched area/X*.



(a) Friction measurement (b) Surface friction variation

Figure 1.12 KES surface friction test

The surface friction is measured in a similar way by using a contactor consisting of 10 pieces of the same wire used in the roughness test, as shown in Figure 1.12 (a). The force required to pull the fabric past the contactor is measured. Figure 1.12 (b) shows a typical plot of friction versus distance travelled, from which two parameters are calculated: coefficient of friction, *MIU*, the mean value of the curve; and the mean deviation of the coefficient of friction, *MMD*.

1.2.3.2 Clothing modeling in CAD

In order to achieve clothing biomechanical engineering design using CAD technology, it is necessary to describe the available models of clothing. There are four types of model.

Geometrical models

A simple approach for cloth modeling is to geometrically characterize the shape of the clothing surface. In 1986, Weil [91] specified geometrical constraints in order to generate the images of cloth objects, and produced three-dimensional drape images by modeling the cloth as a constrained system of grid points. His research can be applied in specific application areas and can generate a static shape quickly. Coquillart [13] presented a new geometrical deformation technique for cloth-like surfaces. Hinds [42] et al used a technique to define 3D garment panels as surfaces with respect to an underlying body and applied this method to interactive garment design. They represented a static mannequin’s body as bicubic B-Spline surfaces, designed the garment panels around the body, and then reduced the panels to 2D cutting patterns. Dai et al [97] proposed a geometrical method to model cloth drape, using a few shape parameters predicted according to the pattern structure and mechanical properties of cloth. This method was used to visualize the 3D drape ability of cloth, and then it was extended to flared skirt modeling.

Turquin et al [83] presented a method for simply and interactively creating basic garments for dressing virtual characters. The user draws the outline of the front or back of the garment, and the system makes reasonable geometric inferences about the overall shape of the garment. This method can be used to create the 3D garment.

Wang et al [8], [9] presented a promising solution technique for a three dimensional automatic made-to-measure scheme for apparel products. The latter are essentially designed with reference to human body features, and thus share a common set of features with the human model. The parametric feature-based modeling enables the automatic generation of fitted garments on different body shapes. The major advantage of this method is that the design process could be performed automatically in 3D and the freeform surfaces adopted to represent the complex geometry models of apparel products.

The main deficiency of the geometric model is the narrow range of application, but it has other disadvantages. The first, in the geometric model, a variety of mathematical surfaces is used to model the clothing surface in that various kinds of Bezier or spline surfaces model curved surfaces in a continuous way. This requires the designer to have a good knowledge for geometric modeling. Secondly, discrete surface representations may also be considered, such as polygonal meshes, triangle meshes and so on. Thirdly, this method does not consider the physical properties of clothing. Therefore, the most important use of geometrical models is applications in very specific contexts, where the expected behavior and evolution is well known and well integrated into the model. The main interest of geometrical simulation models for clothing simulation application is to have a computationally efficient and high controllable model, which can perform the simulation well in certain predefined contexts.

Continuous models

A continuum mechanics model describes the mechanical state of clothing using continuous expressions defining on the geometry. For deformable surfaces, such expressions are usually the surface deformation energy related to the local surface deformation. Mechanical laws are directly derived from them, providing the strains are exerted on infinitesimal surface elements.

Imaoka et al. [39], [38] developed a continuum mechanics model of a fabric for their 3D apparel CAD system. Many dynamic finite element and finite difference approaches have been developed [81], [82] [7] [88].

In 1991 Collier et al. [12] used a geometric non-linear finite-element method based on a simple shell theory to predict fabric drape behavior in which fabric deformation is characterized as a non-linear small-strain/large-displacement problem. Chen et al [10] proposed geometric constraints to a thin plate element model, assuming that the lengths of the threads in a fabric remain unchanged after deformation. Hu et al [40], [75] provided a new computational fabric mechanics models using finite volume method, which proved to be an efficient model.

Continuous models treat deformable objects as a continuum, i.e. solid bodies with mass and energies distributed throughout. While the models are continuous, but the computational methods used for solving the model equations in computer simulations are ultimately discrete. Commonly, finite element models are generally mode accurate, and computationally more expensive, than other clothing models.

Discrete models

Continuum models involve solving large systems of simultaneous ordinary differential equations. However, the computational cost is often very expensive. Another approach is to discretize the fabric into a set of point masses, or particles, which interact through energy constraints or forces, and thus model approximately the behavior of the material.

In 1995, Provot [70] proposed a mass-spring system to model clothing. Breen and House [4, 5] developed a non-continuum particle model for fabric drape that explicitly represents the micro-mechanical structure of a fabric via a particle system. Their model is based on the observation that a fabric is best described as a mechanism of interacting mechanical parts rather than a continuous substance, and derives its macro-scale dynamic properties from the micro-mechanical interaction between threads.

Particle system models are widely used to simulate clothing mechanical behavior during wear. The biggest advantage of this type of model is their simplicity. It is easy to implement a spring-mass system which effectively simulates the deformation of a polygonal mesh that represents an elastic surface. Breen et al [4] described woven fabrics as a set of particles falling in a gravitational field according to physical laws. The clothing surface was discretised using a uniform grid where each node is a particle of the mechanical system. Ng et al [28] presented a rectangular grid and minimization techniques to obtain the shape of the cloth. The material is modeled by a set of energy equations, which takes the bending rigidity, density, elasticity, diagonal-to-axial strength ratio, and rigidity into account. As the positions, velocities, and forces of each particle appear explicitly in the equations, any kind of nonlinear effect or time-varying geometrical constraint may be implemented [86]. Dai et al [98], Oshita et al [61] et al has done similar work.

However, as well as problems of instability and high cost resulting from numerical calculation in solving ordinary differential equation systems, the resulting accuracy is also a problem.

Hybrid models

Hybrid models combine particle models and geometrical models to mutual benefit. They usually employ a geometrical technique to determine a rough shape for the simulated cloth and then use a particle technique to refine the structure.

Taillefer [79] reported the mixed modeling of a hybrid. Kunii et al [51] first used particle systems in their hybrid cloth model for the animation of a sleeve on a bending arm. Other hybrid techniques have been summarized in [67] [77].

Hybrid techniques exploit the advantages of both underlying techniques. However, current hybrid models are limited to simulate specified or well-defined shapes and they seem to be difficult to apply in more general situations in clothing simulation.

1.2.3.3 Numerical simulation System

A human-clothing biomechanical numerical simulation system can be used to generate a quantitative description of the mechanical behaviors such as the garment deformation process, the garment pressure distribution, the human body deformation and the inner stress in the skin.

Commercial Finite Element (FE) software packages are convenient tools to carry out mechanical analysis. Integrating FE software such as LS-DYNA (Livermore Software Technology Corporation), ANSYS (Ansys Inc., USA), ABAQUS (Hibbitt, Karlsson & Sorensen Inc., USA), into the clothing biomechanical engineering system is an effective way to construct the mechanical simulation system. Li [99] and Zhang [104] presented some applications of mechanical design using the LS-DYNA software package.

Since the generalized tools for mechanical analysis may sometimes be insufficient to solve the complicated problems involved in textile products, they can not integrate the whole design process. There are also many specific systems and models that have been developed for clothing biomechanical engineering design. Dai et al [95] presented a simulation system using a new particle model to describe the deformation during wear.

To implement mechanical simulation, the behavioral laws of the material have to be combined with mechanical laws in a single framework that works on an appropriate geometrical representation of the objects to be simulated. The simulation will involve complex equations, usually ordinary or partial differential equations, and the system needs to be solved under the boundary conditions expressing various constraints. Mathematics only provides analytical solutions for a limited class of simple equations. For the more complex mechanical simulations, such analytical solutions are often not available, and numerical methods are the only practical solution.

Since the problem is often nonlinear due to the large deformations involved, complicated contact boundaries, or material nonlinearity, the solution cannot be obtained by solving a single system of equations, as would be done in a linear problem. Instead, the solution is reached by applying the specified loads gradually and incrementally working towards the final solution. Usually, an approach combining incremental and iterative procedures is used for solving nonlinear problems.

The differential equations of a dynamic system need to be solved numerically along a time evolution. To perform such a simulation, discretization of the time domain is necessary. This results is the numerical computation of a sequence of states during the time period. Interpolation of the successive states provides an approximation of the entire trajectory.

The description for a dynamic system is often a second order ordinary differential equation system in which the variables are positions of the nodes or particles along the evolving time. To solve a second order differential equation, for example, a motion equation: $f(X(t), X'(t)) = X''(t)$, a common solution is to convert it to a first-order differential equation by employing a new variable: $v(t) = X'(t)$. Then the equation can be rewritten as:

$$\frac{d}{dt}\begin{pmatrix} X(t) \\ v(t) \end{pmatrix} = \begin{pmatrix} v(t) \\ f(X(t), v(t)) \end{pmatrix}.$$

To solve a first order differential equation, there are two families of methods: explicit integration and implicit integration. Simulation accuracy, time-step, calculation stability, and computational cost are the main factors to be considered in choosing a numerical integration method.

Explicit approach:

The simplest numerical method to solve a differential equation is Euler's method, which can be formulated as: $X(t + \Delta t) = X(t) + \Delta t X'(t)$. Though Euler's method is simple, it may be in accurate and unstable. The most widely used explicit methods are the Runge-Kutta family method. The fourth order Runge-Kutta method can be formulated as follows.

$$k_1 = \Delta t f(X(t), t),$$

$$k_2 = \Delta t f(X(t) + k_1 / 2), t + \Delta t / 2),$$

$$k_3 = \Delta t f(X(t) + k_2 / 2), t + \Delta t / 2),$$

$$k_4 = \Delta t f(X(t) + k_3 / 2), t + \Delta t),$$

$$X(t + \Delta t) = X(t) + k_1 / 6 + k_2 / 3 + k_3 / 3 + k_4 / 6.$$

Inaccuracy and instability are major problems in explicit methods.

Implicit integration approach:

Instead of proceeding the evolution forward, the implicit integration predicts $X'(t+\Delta t)$ and computes $X(t+\Delta t)$ backwards [3]. The backward Euler method can be formulated as: $X(t+\Delta t) = X(t) + \Delta t X'(t+\Delta t)$. Applying the method to the motion equation yields:

$$\begin{pmatrix} \Delta X \\ \Delta v \end{pmatrix} = \Delta t \begin{pmatrix} v(t) + \Delta v \\ f(X(t) + \Delta X, v(t) + \Delta v) \end{pmatrix},$$

where, $\Delta X = X(t+\Delta t) - X(t),$ and $\Delta v = v(t+\Delta t) - v(t)$. Applying a Taylor series expansion to the function $f(X(t), v(t))$ yields the first order approximation:

$$f(X(t) + \Delta X, v(t) + \Delta v) = f(X(t)) + \frac{\partial f}{\partial X}\Delta X + \frac{\partial F}{\partial v}\Delta v.$$

Substituting this into the above equation and substituting $\Delta X = \Delta t(v(t) + \Delta v)$ into the equation for Δv yields: $\Delta v = \Delta t(f(t) + \frac{\partial f}{\partial X}\Delta t(v(t) + \Delta v) + \frac{\partial f}{\partial v}\Delta v$. Letting I denote the identity matrix and regrouping the equation, finally we obtain:

$$(I - \Delta t\frac{\partial f}{\partial v} - \Delta t^2 \frac{\partial f}{\partial X})\Delta v = \Delta t(f(T) + \Delta t\frac{\partial f}{\partial X} v(t)),$$

Here, Δv can be solved thus ΔX, and then X.

Implicit methods are often unconditionally stable and allow large time steps to be used.

Choosing a suitable integration method:

Simulation accuracy, time-step, calculation stability, and computational cost are the principle factors to be considered in choosing a numerical integration method. For a given problem, an adequate integration method should be defined considering [86] :

1) The required accuracy of the simulation, that may limit the time-step;

2) The required accuracy for a given time-step;

3) The numerical stability, that may limit time-step;

4) The amount of time required for the computation of a single time-step;

5) Other factors limiting the time-step, such as contact between objects.

1.2.3.4 Collision detection

In the real world, deformable surfaces are rarely left to move unhindered. Garments do not exist in isolation, nor float in the air. They interact with other objects in their environment, in most instances either with the body that wears them or other garment pieces. Modeling and simulating these interactions are essential to realistic simulation. A garment takes the shape of the body that wears it and follows its movements not only through its elastic behavior, but also by its contact with the body. The aim of collision detection procedures is to compute the geometrical interactions between objects and to perform this task efficiently whatever the number and complexity of the objects may be. Breen, Volino [6] [86] [87] have presented a method to solve collision detection and response problems.

1.2.4 Sensory visualization

1.2.4.1 Sensory perceptions

In 1986, the concept of sensory-engineering (Kansei-engineering) was developed by the Mazda Company in Japan as a development of human factors [99]. Sensory means psychological feeling or image of a product. Sensory engineering refers to the quantitative translation of a consumers' psychological feeling about a product into perceptual design elements[74, 78]. This technique involves determining which sensory attributes elicit particular objective responses from people, and then designing a product using the attributes that elicit the desired responses. Sensory engineering has been applied with great success in the automotive industry (the Mazda Miata being a notable example) and is being extended to other product domains including new fiber manufacture [99].

Clothing products depend on the right combination of aesthetic and engineering quality for their success in the market place [56]. The modern consumer demands clothing products with superior multi-functional and comfort performance to satisfy their physiological and psychological needs. Garment mechanical comfort such as pressure comfort has been identified as one of the important attributes. Denton [17] pointed out that the discomfort level of clothing pressure was found to be between 20 and 40 g/cm^2, depending on the individual and the part of the body concerned, which is similar to the blood pressure in the capillary blood vessels near the skin surface. If the constricting pressure around the human body is greater than modest, the blood flowing uphill through the veins will be stopped or at least impeded. Ultimately fluid will be forced out of the veins into the tissues of the lower part of the legs to cause swelling. On the other hand if garment pressure is less than desirable at a body part, it may not dissatisfy its restraint function [90]. Therefore, the engineering design of clothing mechanical performance demands a different kind of logical structure to textile products. An important difference is that the human factors (physiologic and psychology) have to be concerned in engineering designing clothing mechanical performance, because the human is the master in presenting clothing’s aesthetic and functional effects.

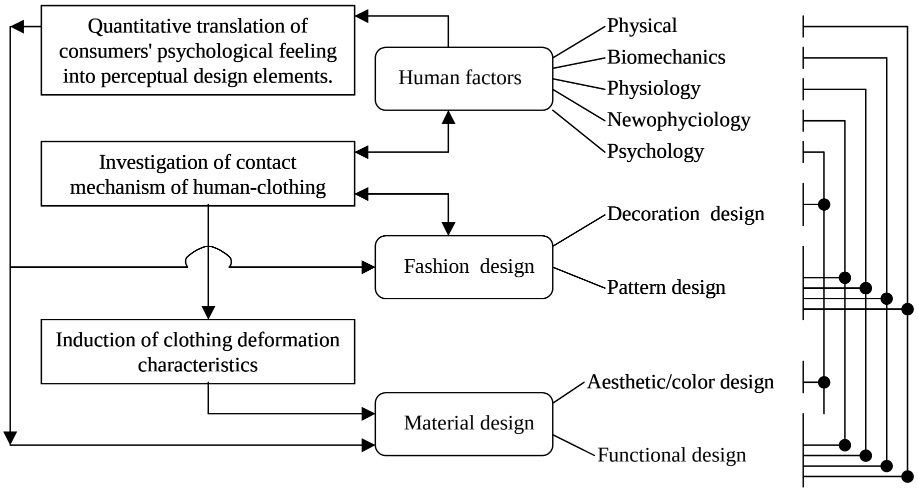


Figure 1.13 The concept of sensory engineering design for clothing mechanical performance

Figure 1.13 [99] shows the concept of the mechanical sensory engineering design of clothing performance taking into account human factors. These are concerned in two design processes: fashion design and clothing materials design, to achieve clothing aesthetic and functional effects. The human factors are mainly concern five aspects: (1) physical (such as the body size and the shape); (2) biomechanics of the human body (such as the deformation of the muscles, the skin and the soft tissue at different body parts); (3) physiology (formulating sensory signals from the interactions of the body with the clothing and surrounding environments); (4) neurophysiology and (5) psychology (subjective perception of sensory sensations from the neurophysiological sensory signals and then formulating subjective overall perception and preferences). As shown in Figure 1.13, the four factors of physical, biomechanics, physiology and neurophysiology must be considered in pattern design and material design, and the psychology factor in designing aesthetic effects of clothing.

Sensory engineering design of clothing mechanical performance should be based on quantitatively investigations of the relationship between clothing mechanical performance and human factors (physiologic and psychology) [54]. Figure 1.13 illustrates three fundamental investigations to achieve the concept. The first is the quantitative translation of consumers' psychological feeling about a product into perceptual design elements that will be important attributes in the evaluation of fashion design and material design. The second is the investigation of the dynamic mechanism involved in the contact interface between human body and clothing, which bridges the relation between human biomechanics and fashion design. The third is induction of clothing mechanical characteristics from the dynamic analysis, such as their deformation magnitude, stretch-recovery properties and rheological behavior during wearing. These physical and mechanical characteristics of clothing materials are the basic information for the engineering design of clothing materials.

1.2.4.2 Sensory visualization techniques

Sensory engineering of clothing mechanical performance should be based on quantitative investigations of the relationship between clothing mechanical performance and human sensory (physiological and psychological) factors.

During wear, clothing contacts with the skin at most parts of the body. Li [55] pointed out that the contact has three features: (1) large contacting areas with varying sensitivity; (2) changing physiological parameters of the body (such as skin temperature, sweating rate, and humidity at the skin surface); (3) a moving body that induces new mechanical stimuli from the contact between the body parts and clothing. The mechanical stimuli in turn induce responses from various sensory receptors and formulate various perceptions, such as touch, pressure, prickle, itch and inflammation, which affect the mechanical comfort of the wearer.

The study of clothing biomechanical engineering design can elucidate the relationship between clothing mechanical performance and the human body. The deformations of clothing and human muscles can be simulated dynamically. The sensory signals from the interactions of the body with the clothing and subjective perception of sensory sensation from the neurophysiological sensory signals can formulate subjective overall perception and preferences. So the study of the psychophysical process of perception of clothing mechanical behavior makes it possible to predict and evaluate mechanical sensory comfort of clothing from the mechanical properties and structural features of fibers, yarns and fabrics, as well as garments.

Mechanical comfort should be one of criteria to decide which design is optimal among several alternatives in the design process. The designer can judge whether the product meets comfort requirements by comparing the predictions with desirable values, such as desirable pressure distributions and subjective perceptions of comfort pressure.

Clothing comfort is very subjective. Evaluation of pressure comfort must combine the predicted pressure and the sensation index from a large volume of experiments involving wearing. It needs much work of subjective evaluation of garment pressure, from which a series of psychophysical models will be developed based on the investigation of the relationship between objective stimuli and subjective perceptions and the investigation of the relationship between the predictions and the objective measurements.

Currently, the 3D dynamic interaction between a human body and a garment has been visualized by using post-processing software based on numerical data from the solution of models, including the deformation and stress distributions in the garment, the deformation and stress distributions of the skin and soft tissues and the garment pressure distributions on the skin [55] [101] [104]. In future, visualization of mechanical sensory perceptions will be achieved by psycho-physical experiments using commercial visualization software.

To achieve the sensory evaluation of perception visualization in the CAD environment, a series of psycho-physical experiments has been implemented for mechanical comfort in different wear situations of jeans, by conducting mechanical sensory comfort perception trials [53] and objective measurement of dynamic pressure distributions [53]. Further, psychophysical models of mechanical comfort have been developed in different wearing situations, by using statistical methods and neuron network methods [55] [37].

1.3 STATEMENT OF PROBLEMS

From the literature review performed above, we have found that:

- The fundamental knowledge of clothing mechanical engineering design has been established.
- The methodology of investigating the perception of certain sensations has been introduced.
- The fundamental application of computer integration technology has been researched in different areas.
- The mathematical simulation of fabric biomechanical behavior has been well established.

However, computer integration technology has not been applied in textile and clothing biomechanical design. There are several mechanical simulation systems, but there is no uniform platform to combine them together to support the engineering design of clothing mechanical performance, especially for 3D numerical simulation of the mechanical interaction of the body-clothing and sensory evaluation in clothing mechanical applications. The hybrid model of clothing still needs to be researched to satisfy the clothing simulation. There are knowledge gaps in a number of aspects, including:

- The integration technology for clothing biomechanical engineering design has not been studied.

- The engineering database for clothing biomechanical engineering design, especially including textile structural and mechanical properties has not been developed.
- Hybrid technology for clothing simulation including developing an effective geometry model to determine the shape of clothing, and a user-friendly program packages for constructing 3D garment from 2D patterns is not available.
- Computer simulation of the mechanical sensory perception of clothing has not been systematically studied.

All the knowledge gaps listed above lead to the research and development of CAD technology for clothing biomechanical engineering design. A sound scientific study in these aspects needs to be carried out to fill the knowledge gaps.

The object of this research, therefore, is to fill the knowledge gaps to establish a sound scientific understanding for establishing a clothing biomechanical engineering design integration system. By identifying the major factors of textile materials and clothing structural characteristics that influence the mechanical behavior during the wear, the outcome of the research will be valuable to development of integration design procedures to guide users in designing clothing mechanical performance based on human factors. The research outcome of this project may contribute significantly to the physiological health and comfort of the wearer and pressure therapy in medical clinical practice.

The CAD technology for clothing biomechanical engineering design should possess the functions of design, analysis and evaluation and project management. The fundamental work needed to achieve the system includes: a comprehensive engineering design database to support design, analysis and evaluation for clothing biomechanical performance; an engineering design environment from the 2D apparel pattern into 3D for clothing design, including material properties, motion and dynamic mechanical properties; a linking platform with mechanical analysis and visualization software packages; and a software environment to visualize biomechanical sensory perceptions and preferences with considerations of psychophysics. The scope of clothing biomechanical engineering design system can be shown in Figure 1.14.

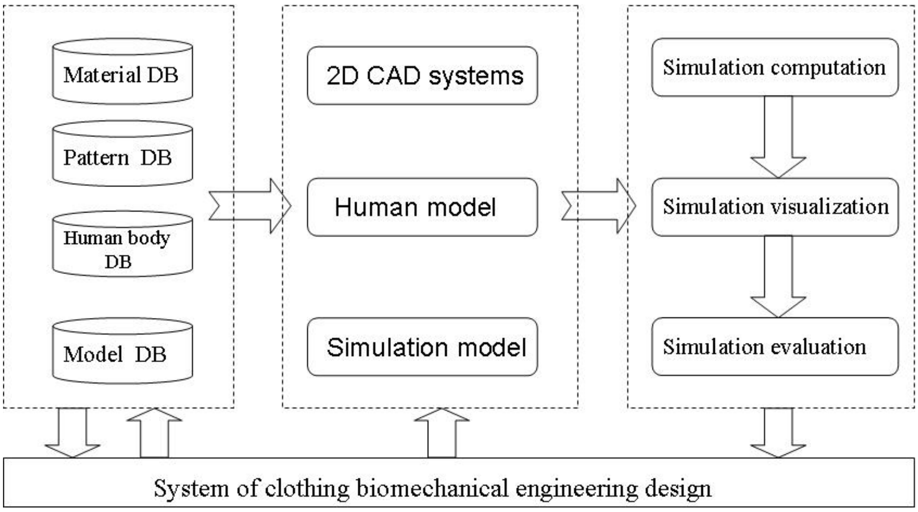


Figure 1.14 The clothing biomechanical engineering design system

1.4 RESEARCH OBJECTIVES

In order to develop an integrated CAD system for clothing biomechanical engineering design, the objectives will be achieved by developing a visualization platform for clothing biomechanical engineering design. A mathematical model and visualization environment will be developed to simulate the clothing biomechanical performance, including the pressure distributions in clothing and the human body and the psychological perceptions of the human being. The system will be applied to establish scientific principles for the development of new functional products with superior performance to meet the requirements of both consumers and doctors.

Specifically, the objectives of the project can be described as follows:

- To develop a comprehensive engineering design database to support design, analysis and evaluation for clothing biomechanical engineering design;
- To study and develop mathematical models and algorithms for constructing 3D garments from 2D apparel patterns, with specification of material properties, motion and dynamic mechanical properties;
- To establish a software platform for clothing biomechanical engineering design with mechanical analysis and visualization;
- To study and develop software to visualize biomechanical sensory

perceptions according to the quantitative relationships between clothing mechanical performance and human sensory perceptions.

1.5 METHODOLOGY

In order to achieve the above objectives, the following methodology has been adopted:

1. To develop a comprehensive engineering design database to support design, analysis and evaluation for clothing biomechanical engineering design

   To support the systematic design platform, an engineering database will be developed for the processes of design, analysis and evaluation with logical organization of various types of information. The engineering database will be developed with a number of important features to support the engineering design process:

   (1) A dynamic database to handle two kinds of information: the design environment (rules, methods, standard elements etc.) and data that are not known previously but defined during the design process for the iterative-decision making process in engineering design, which includes analysis and synthesis based on the knowledge of basic sciences, mathematics, and engineering sciences.

(2) A logical structure to meet the engineering design needs. Engineering design deals with a number of value types, so this database must support the design, analysis and evaluation phases in a systematic design process with various types of information. The database structure will be defined according to characteristics of the engineering design, to meet the needs of user-friendly program packages to input, store and display information about apparel products quickly and effectively in the time and space areas. The database will be developed using modern database technologies such as objective-oriented technology, component technology and knowledgebase and data mining.

2. To study and develop mathematical models and algorithms for constructing 3D garment from 2D apparel patterns, with specification of material properties, motion and dynamic mechanical properties

   In this stage, the mathematical models and computation algorithms to derive 3D garment data from a garment's 2D pattern will be developed. With this 3D garment data file, material properties, environment conditions and human body-garment contacting conditions can be defined for simulation.

3. To establish a software platform of clothing biomechanical engineering

design with mechanical analysis and visualization

Using computer technology, an integrated CAD software system platform for clothing biomechanical engineering design will be developed. This system will guide the user to analyze the logic of biomechanical engineering design processes, from selecting the garment, the human model, the garment 2D pattern, the 3D garment formation, and the garment-body contact conditions, assigning material properties to visualization of 3D garments.

4. To study and develop software to visualize biomechanical sensory perceptions according to the quantitative relationships between clothing mechanical performance and human sensory perceptions.

The software will be developed to visualize the biomechanical sensory perceptions according to the psychophysical relationships between psychological sensory perceptions and mechanical stimuli that are derived from the mechanical analysis. This will involve three stage of research: (1) transform the mechanical stimuli data such as garment pressure and stresses to biomechanical sensory perceptions such as tightness, stiffness and pressure sensations according to experimental psychophysical relationships; (2) transform the sensory data to colour; and (3) map the sensory perception colour to human body locations.

1.6 THESIS OUTLINE

The thesis consists of 8 chapters. Chapter 1 reviews literature in relevant disciplinary areas that cover related knowledge to identify the knowledge gaps, hence than to determine the objectives and methodology of the research project.

Chapter 2 presents the basic concepts of the engineering database. In this chapter, the functional requirements of the engineering database for clothing biomechanical engineering design are proposed. An engineering database to support the engineering design process is designed and implemented.

In Chapter 3, Representation and Conversion of Bezier surfaces in multivariate B-form are presented. Using this mathematical model and algorithm, 3D garment geometric data format can be constructed from 2D apparel patterns, and this geometric model can be used in simulation for pre-processing.

Chapter 4 describes the development of computational simulation. A particle model and a finite element method are used to simulate the clothing-human biomechanical performance according to different function requirements. The applications of these methods are presented for shirt design, sock design and so on.

Chapter 5 reports the research that how to transform the mechanical stimuli data such as garment pressure and stresses to biomechanical sensory perceptions such as tightness, stiffness and pressure sensation according to the experimental psychophysical relationships from experiments. The fuzzy logical model has been created to predict the pressure comfort in clothing biomechanical engineering design.

Chapter 6 expands the simulation visualization technology. The simulation results can be visualized in different ways. In particular, the clothing and human biomechanical sensory perceptions are visualized according to the simulation results.

In Chapter 7, an integrated engineering design environment is reported. It provides the data management, mathematical simulation, and data analysis/visualization for clothing biomechanical engineering design. The main features of this environment are presentation integration, data integration, process integration, and control integration.

Chapter 8 summarizes findings from previous chapters and discusses future work.

CHAPTER 2 ENGINEERING DATABASE

2.1 INTRODUCTION

“Database” is one of the most important terms in modern technical language. It has been widely used in various fields. The major advantages of database technology are that the organization of data does not necessitate specific programming for the application system, the application is easier to extend, and the application data can also be made accessible to other application systems [43] [94].

With the development of computer applications in engineering processes, engineering database assumes an important role. However, an engineering database is different from a business database [11]. The fundamental difference between the two is the stability of the administrative environment as compared to the dynamic engineering environment. The development of an engineering design database management system (EDDBMS for short) must carefully consider the character of the engineering design process.

2.2 FUNCTIONAL REQUIREMENTS

2.2.1 Characteristics of an engineering database

Engineering designing is a many-sided and wide-ranging activity [22]. It is based not only on mathematics, physics and their branches- mechanics, thermodynamics etc, but also on production technology, materials science, machine elements, industrial management and cost accounting. Such activity includes not only semantic information, as in the case of business databases, but also information details of engineering design, whereas a business database is a mere collection of related information used for consulting purposes.

Figure 2.1 shows the main concepts of the engineering design process.

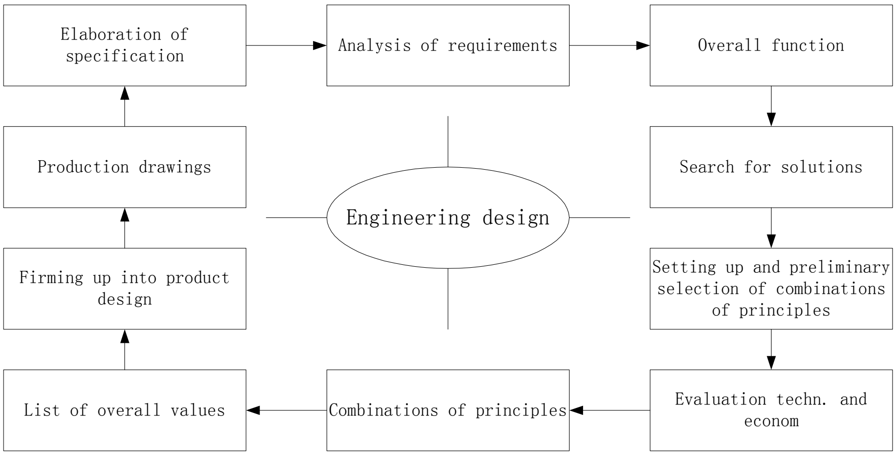


Figure 2.1 Main concept of engineering design

According to Figure 2.1, the engineering design process is a circular process. When the basic ideas of the engineering design approach are discussed, it is found that engineering design demands a constant flow of information. It needs to receive rich information to create elaborate of design specifications. The information can be received in different ways from market analyses, trend studies, patents, technical journals, questionnaires from customers, concrete assignments, design catalogues, analyses of natural and artificial systems, calculations, experiments, analogies, general and in-house standards and regulations, stock sheets, delivery instructions, computer data, test reports, accident reports, and also through asking questions [22].

According to the design specification, design requirements can be analyzed and defined. The succeeding design steps are function design, problem solution, and evaluation against the design requirements, and the final result is a product drawing. It must be noted, however, that the engineering process contains many loops in which activities of a routine character, such as analysis, are followed by activities with a creative character such as selection.

During the design process, design data plays an important role. These data can be processed by analysis and synthesis, calculation, experiment, the elaboration of layout drawings and also the evaluation of solutions. They can be transmitted by means of drawings, reports, production documents etc.

Data on engineering design is very dynamic in the sense that they are not known a priori but defined during the design process. Hence the database management system (DBMS for short) should not only deal with a constant part for the storage of standardized parts, design procedures and material properties, but also with structures, machines and installations composed from these elements. Furthermore the DBMS should be used for storage and retrieval of measured and calculated data in such a way that the origin of these data can be traced. The DBMS should support typical engineering activities such as the analysis and modification of complex structures. Various ways of presenting of the database contents must be possible, including graphical, representation of objects and measurement data [60].

Configuration management and control of the design processes within the engineering environment is a complex problem. Effective configuration management involves controlling not only the product data but the processes that create and affect the product design as well.

In all the discussions of engineering design and engineering database in this thesis, the main purpose for developing an engineering database is to support the clothing biomechanical engineering design.

2.2.2 The constitution of clothing engineering design

Clothing products depend on the right combination of aesthetic and engineering quality for their success in the market place. Modern consumers demand clothing products with superior multi-functional and comfort performance to satisfy their physiological and psychological needs. Garment mechanical comfort such as pressure comfort has been identified as one of the important attributes. Therefore, clothing biomechanical engineering design is becoming more and more important.

Clothing engineering design means creating new clothing by enhancing existing designs or by altering existing ones to perform new functions. It is a complex iterative-decision –making competitive process in which the basic sciences, mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective [99].

Clothing biomechanical engineering design is largely based on computer aided design, computer graphics, computer display technology, mathematical models, material sciences and experimental methodology developed for clothing biomechanical design. It involves mathematical models; different models describe different requirements for clothing engineering design, and the key technology for using these models is to prepare different data formats, different descriptive ways for data. How to management these mathematical models and data files is very important during clothing biomechanical engineering design.

The clothing engineering design process generates and uses a large volume of dynamic data, data structures and different categories of variables, such as specifications, engineering design orders, technical data, problem reports, design models and analysis files, etc. Each data category contains detailed of specific information, so the clothing engineering design is a product –oriented functional design process based largely on the experience and intuition of the designer. In order to support this complex design, it is important to develop an engineering database to support clothing biomechanical engineering, especially for 3D numerical simulation of the mechanical interaction of the body-clothing system and the sensory evaluation of clothing mechanical comfort.

Figure 2.2 shows the design procedures for a clothing biomechanical system in detail. The design starts with a project, which defines the specification of the clothing biomechanical design (e.g. jeans or bra), followed by selecting a fabric structure and the desired mechanical properties of fiber-yarn-fabric. The selection may be a revision obtained by searching or reworking some previous fabric structure, which reasonably approximates to the current design requirements. The next step is to define the garment style, to construct the geometry data or mesh data. From the input parameters of the human body and the garment, the deformation characteristics of clothing should be identified based on mechanism analysis of the dynamic contact between human body and garment. Next come a decision concerning the mechanical model of the body-garment, then to numerically simulate and analyze the mechanical performance of the garment and body. An iterative process has to be carried out before the garment is produced if the design is not satisfied through the simulation and evaluation steps.

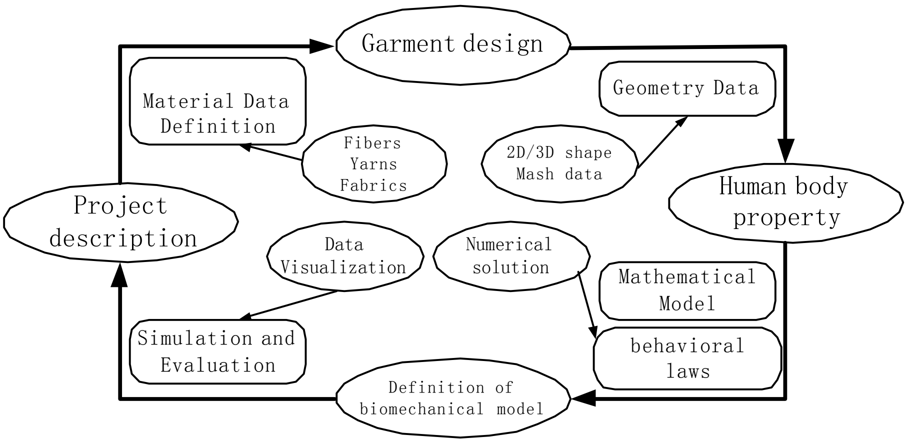


Figure 2.2 Clothing biomechanical design

According to Figure 2.2, clothing biomechanical engineering design involves different elements, namely: materials (fabrics, yarns, fibers,), human body, garment, and mathematical model.

Materials are important components in clothing engineering design. The properties of the material will affect the clothing biomechanical characteristics, such as the magnitude of its deformations magnitude, stretch-recovery properties and rheological behavior during wear. These physical and mechanical characteristics of clothing materials are the basic information for the engineering design of clothing biomechanical.

A garment is made from 2D patterns of cloth surfaces. These patterns are constructed using software, and are discretized into a triangular mesh. The planar patterns are then placed around a 3D virtual body using manipulators. Once the patterns have been placed around the body, a mechanical simulation is invoked to make the patterns approach along the seaming lines. As a result, the patterns are attached and seamed on the borders as specified, attaining the shape influenced by a shape of the body. Thus the garment is constructed around the body.

Human factors are concerned as a component in design. The human body is in direct contact with the clothing. Humans can reflect the feelings of wear comfort in different ways: physical physiological, biomechanical, neuro physiological and psychological. A human being's comfort is a complex process. The physical, physiological, biomechanical, and neurophysiological are deal needs with by pattern design and material design, while psychological factors are attended to in designing aesthetic effects of clothing and comfort evaluation. Physical, physiological, biomechanical, and neurophysiological data are used during the simulation, and psychological data in the evaluation process.

A mathematical model is the core of clothing engineering design simulation. It will represent the relationship between clothing mechanical performance and fabric mechanical properties in simple deformations (tension, shearing, bending and compression).   When the design phase has determined a feasible style and materials parameters, the simulation procedure will be called in to calculate mechanical performances of the dynamic system, such as distributions of stresses and strains in the garment.

During wear, clothing comes into contact with the skin at most parts of the body. This contact induces responses from various sensory receptors and formulates various perceptions like touch, pressure, prickle, itch and inflammation, which affect the mechanical comfort of the wearer. Therefore the evaluation model will analyze and evaluate the comfort of clothing.

An engineering design database management system for clothing biomechanical engineering design must provide powerful data management and support the design process efficiently. The development of this database must carefully consider the character of engineering design. The purpose of our work is to provide such a system.

As discussed above, the aims in developing a database for clothing engineering design are:

- To create a means of communication between researchers, technologists, designers, customers, manufacturers and other related sectors;
- To provide scientific and experience sourced data of clothing performance;

- To design a diversity of cloth products;
- To increase design automation in textile and clothing;

At the same time, the database can provide other management function related (a) product development; (b) design process control; (c) quality assurance and (d) performance evaluation.

Figure 2.3.shows a summary of clothing biomechanical engineering design using the database.

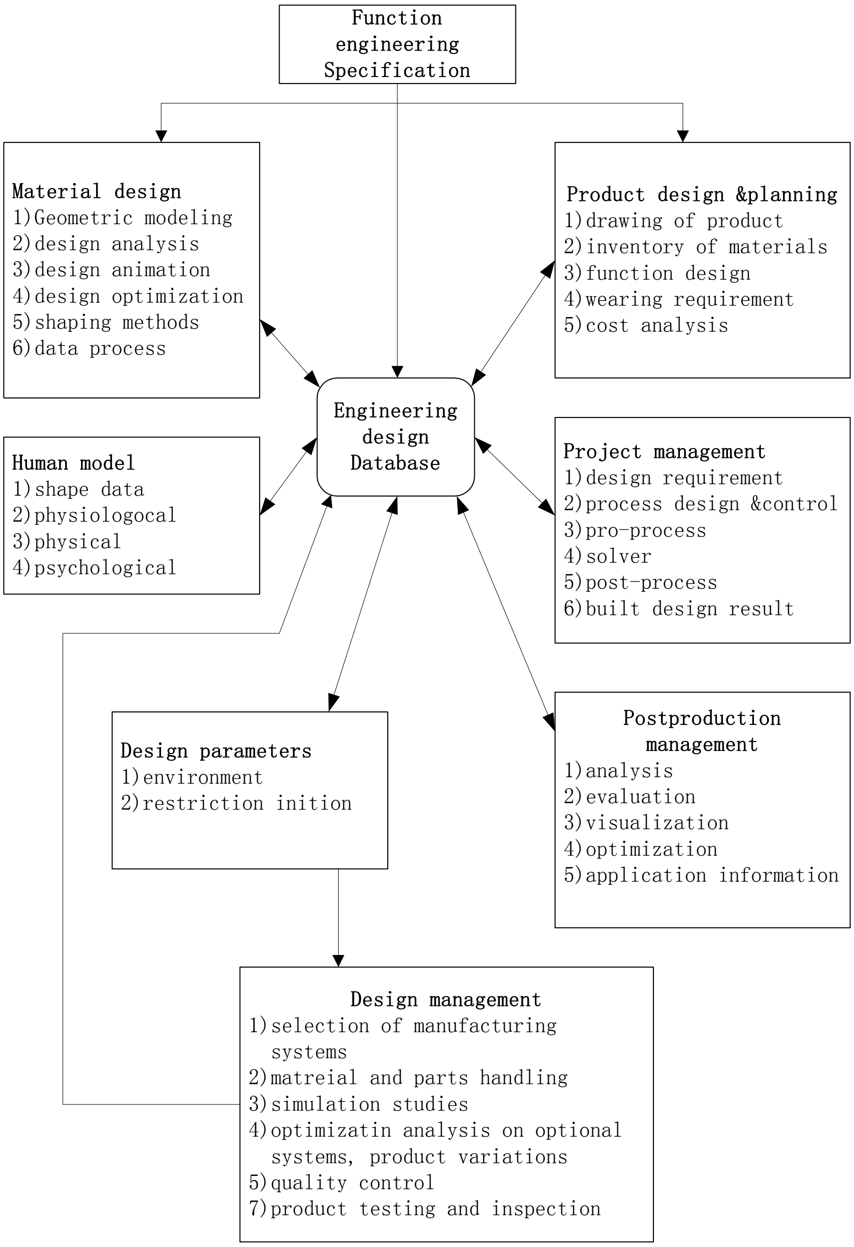


Figure 2.3 Main concept of clothing biomechanical engineering design and EDDBMS

The clothing engineering database can be separated into four main components:

1) Garment DB: storing the structure parameters, geometric parameters and images of products (fiber-yarn-fabric-clothing, 2 dimensional and 3 dimensional data file);

2) Human model DB: storing the information of the model used in biomechanical engineering design (human model factors (physical, bio-mechanical), manikin model (structure data), etc;

3) Material DB: storing the structure, mechanical and physical parameters (fiber, yarn, fabric) used in the design and analysis processing.

4) Project DB: storing the engineering design specification, methodology, design report and analysis file for different design processes.

2.2.3 Data description

Textile and clothing engineering function design is concerned with product performance, from a language of the mechanical, thermal, sensory and material properties. According the requirements and applications of engineering design, the appropriate data can be presented in different categories.

General data

General data is the summary description about the product. General data includes the following items:

1) Design file and product identification.

2) Customer information: name, address and so on.

3) Specification of the product’s special considerations, and instructions.

4) Commercial information.

Property data

This kind of data is about the property of product, it includes the following items:

1) Product structure description, including macroscopically and microcosmic: length, thickness, warp count and so on.
2) Product mechanical description: e.g., warp bend rigidity, shearing modulus.
3) Product's physical description: e.g., thermal conductivity, integral heat of sorption.

Geometric data

This kind of data is about the geometric characteristics of the product, it includes the following items:

1) Two dimensional geometric descriptions.
2) Three dimensional geometric descriptions.
3) Mesh data description.
4) Other data format for analyzing process.

Design data

This kind of data is about design requirements; it includes the design environment and specified constraints, as follows:

1) Design condition requirements: air density, atmospheric pressure and so on.
2) Constraints: specific skin blood flow rate, thermal conductivity of body tissue, etc.

3) Design method description.

4) Design processing description

Project data

This is about design data from previous projects. In cases where a current product has evolved from existing products, duplication of data files should be avoided; the designer can simply build current design data files on the basis of relevant existing ones. The items involved are as follows:

1) Project basic data, designers name, date;

2) Project processing status;

3) Project result;

4) All documents for this project.

Tables 2.1 to Table 2.3 describe the kind of information about the fabrics, fibers, and human body that needed to be available.

Table 2.1 Fabrics

General data	**Structural data**	**Mechanical data**	**Physical data**
Fabric ID	Finishing condition	Poisson’s ratio	Surface volume ratio
Fabric name	Length	Warp tensile modulus EA	Absorptivity of outer surface of clothing
Fabric type	Width	Weft tensile modulus EB	Thermal conductivity of fabric
Fabric picture	Thickness	Warp bend rigidity	Thermal capacity
Company	Area density	Weft bend rigidity	Water vapor diffusion
Price data	Volume density	Compression modulus	Liquid water diffusion
	Cover factor	Twisting rigidity	Diffusion coefficient
	Warp count	Shearing modulus	
	Weft count	Hystersis of shear	
	Warp crimp	Hystersis of bending	
	……	……	……

Table 2.2 Fibers

General data	**Structural data**	**Mechanical data**	**Physical data**
Fiber ID	Diameter	Tensile modulus	Differential heat of liquid sorption
Fiber name	Volume density	Flexural rigidity	Differential heat of moisture vapor sorption
Fiber type	Length	Shearing modulus	Integral heat of sorption
Fiber picture	Count	Friction factor	Differential radiation absorption constant of the fiber
Company	Effective contact angle between fiber surface and water	Compression modulus	Fiber sorption isotherm
Price data		Bending	Specific heat of fiber
		Torsional rigidity	Volumetric specific heat of fiber
			Diffusion coefficient
			Thermal conductivity of fiber

Table 2.3 Human body

General data	**Structural data**	**Physiological data**	**Material data**
Model ID	stature	Bone density	Specific heat at constant pressure of blood
Model file	shoulder	Bone compress mudulus	Specific heat at constant pressure of skin
Model picture	breast	Torsional rigidity	Diffusion coefficient/Mass diffusivity for moisture vapor diffuse through skin
Model type	waist	Bone poison ratio	Thermal conductance of body tissue
Size	hip	Soft tissue density	Thermal conductance of the skin
	arm	Soft tissue shear modulus	Absorptivity of skin surface to the solar radiation
	leg	Soft tissue poison ratio	Emissivity of skin surface
	neck	Skin density	Dubois body area
	weight	Skin tensile modulua	Total body mass
		Skin poison radio	

In the database, the fiber-yarn-fabric structure, mechanical and physical parameters are collated from a series of mechanical tests using the in Kawabata Instron testers. They include fabric simple deformations by the Kawabata testers, the relaxation deformations of fiber-yarn-fabric by Instron tester, and three dimensional deformations of fabric bagging lasted on the Instron. The major mechanical parameters taken from the tests are stored in the material database, as shown in Table 2.4. To set up a numerical database of textile properties without any assumption for the material properties, tension-recovery curves of fiber-yarn-fabric have been recorded in the material database by direct inputs from the experiments. The experimental curves have been recorded as the images in the database, which can be displaced during the design process by searching its identified number.

Table 2.4 Items of each database

Human model database	**Garment database**	**Material database**	**Project database**
Items	**Items**	**Items**	**Items**
Human body ID	Garment ID	Fabric ID	Project ID
Human image ID	Garment name	Fabric bending module	Design Info.
Stature	Garment image	Fabric shear module	…
Shoulder	Garment Commercial info.	Fabric poison ratio	…
Breast	…	Fabric frictional coefficient	Garment ID
Waist	…	Fabric roughness	Design state
Hip	Garment size	Fabric bagging resist	Pro-process file
Arm	Garment style	Fabric bagging fatigue	Method ID
Leg	Fabric ID	Yarn ID	…
Neck	Fabric ID	Yarn viscoelastic module	Post-process file
Weight	…	Yarn relaxation time	Result files
Skin thickness	…	Yarn bending module	…
Skin tensile modulus	2D pattern data file ID	Yarn compressor module	Evaluation rule
Skin densilty	3D garment data file ID	Yarn torsion module	Visualization file
Bone elastic modulus	…	Yarn poison ratio	
Bone density	…	Fiber ID	
Soft tissue thickness		Fiber viscoelastic module	……
Softtissue elastic modulus		Fiber relaxation time	
……	……	……	……

2.3 DESIGN AND REALIZATION

2.3.1 Data model

As mentioned above an engineering database has several important differences from an administrative database or a business database. Firstly, engineering design is an iterative-decision process with analysis and synthesis based on the knowledge and information of basic sciences, mathematics, and engineering sciences. Secondly, engineering design needs a dynamic database that involves two kinds of information: the design environment (rules, methods, standard elements etc.) and data that are not previously known but defined during the design process. Thirdly, engineering design deals with a number of value types (text, numbers, equations, diagrams, graphical, photographic images etc.).

Therefore, the main thrust in the construction of an engineering design database is to include efficient descriptions of the engineering design of all products and to provide production of detailed information necessary for manufacturing the final product. Such descriptions include not only semantic information, as in the case of business databases, but also information details of the engineering design.

There are three major data models that are used in the database system: the relational data model, the hierarchical data model and the network data model [84]. The relational data model in which all entities and dependencies between entities of the reality to be stored in a database are described structurally identical by their domains (names and kind of values). The hierarchical data model represents entities and hierarchical relationships among different entities. In this model, each entity is represented as a record and hierarchical relationships by a tree structure. The network data model allows the representation of arbitrary relationships between entities. Each entity is represented as a record, and it may be owned by more than one record, leading to a network structure.

Following on our analysis of the characteristics of the design process for clothing mechanical performance, a hierarchical data model is used in the present database system. The hierarchical relationships among fibers, yarns, fabrics and clothing are shown in Figure 2.4.

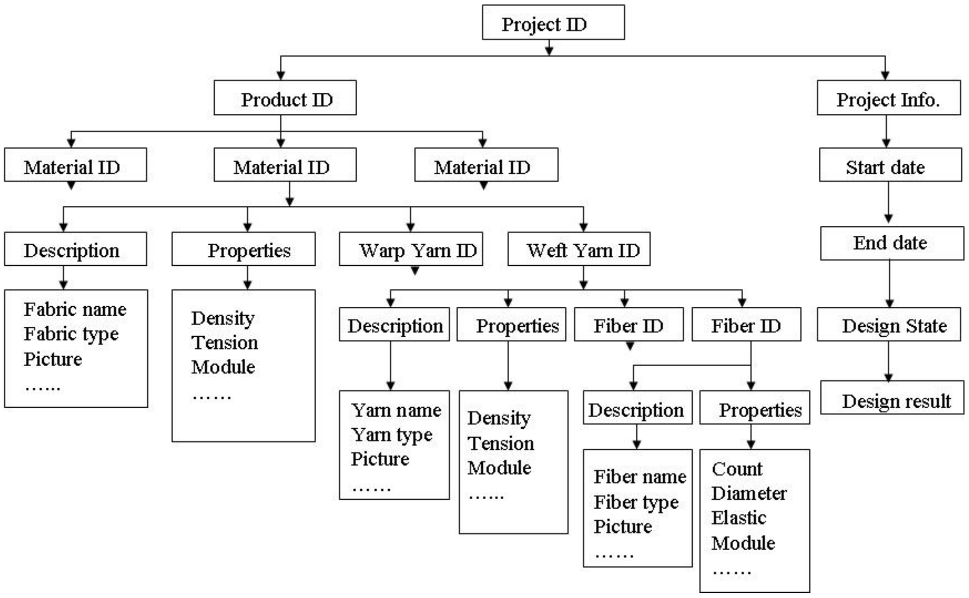


Figure 2.4 Hierarchical data model of the clothing engineering database

In the data model, a material object in different hierarchies (fiber-yarn-fabric-clothing) can be represented by abstractions: the ‘entity’. An entity has an identifiable number ID. An entity is a collection of values, each value describing a property of the entity. An identifiable number ID that involves its father’s ID or the tree’s node it belongs to indicates the hierarchical relationship. An identifiable number ID is specified as a unique name of an entity in the engineering database, by which all of its information in the database can be found. As examples of databases, Table 2.5 illustrates the records of nine denim jeans in the product database, and Table 2.6 their mechanical parameters recorded in the material database. For example, the garment ID of 001, is Levis’3D jeans and its fabric can be identified by the number of 001-01. The mechanical parameters of the fabric can be searched in the material database according to the identity number 001-01, and the tension-recovery curves of the fabric in the warp and weft directions according to the identified numbers Wp001-01 and We001-01 respectively, as shown in Table 2.6 [99].

Table 2.5 Records of nine denim jeans in the product database

Price	Garment Commercial name	Garment ID	Fabric ID	Fabric image ID	Fabric Structure	Fabric weight	Fabric thickness	Fabric density		Fibre composite	Yarn count Ntex		Fabric cover factor k		Yarn Crimp (%)	
						(g/m^2)	mm	ends/cm	picks/cm	%	warp	weft	warp	weft	warp	weft
$735	Levi's 3-D	**001**	001-01	E001-01	3x1 twill	431	0.88	26	19	25%Ly75%Cot	6.8	6.0	238.9	191.1	11.7	7.3
$535	Levi's	002	002-01	E002-01	3x1 twill	475	1.04	27	20	100%Cotton	6.2	6.2	265.6	192.3	18.0	6.9
$338	Andyrex	003	003-01	E003-01	3x1 twill	453	1.12	30	19	100%Cotton	7.0	7.4	274.2	172.1	21.5	8.0
$329.5	Apple	004	004-01	E004-01	3x1 twill	451	1.03	27	19	100%Cotton	6.9	6.2	248.2	187.7	18.7	7.1
$148	Mixed	005	005-01	E005-01	3x1 twill	438	1.06	28	21	100%Cotton	7.9	7.2	239	189.3	21.4	9.4
$250	Wagner's	006	006-01	E006-01	3x1 twill	428	1.04	25	20	100%Cotton	6.7	7.3	237.1	184.4	19.1	10.9
$550	CK	007	007-01	E007-01	3x1 twill	458	1.07	27	20	100%Cotton	7.0	6.2	245.9	191.5	20.2	7.7
$679	Edwin	008	008-01	E008-01	3x1 twill	459	1.09	28	20	100%Cotton	6.6	7.9	267.8	177.1	23.3	7.8
$190	Giordano	009	009-01	E009-01	3x1 twill	400	1.08	27	19	100%Cotton	9.6	5.5	213.1	199.2	21.3	8.9

Table 2.6 Records of nine denim jeans in the material database

Garment Commercial name	Garment ID	Fabric ID	Thickness	Density	EA	EB	Poison's BA	GAB	Curve-Wp	Curve-We
			mm	kg/m3	kgf/m2	kgf/m2		kgf/m2		
Levi's 3-D	**001**	001-01	0.88	492	50000.0	48000.0	0.38	13179.0	Wp001-01	We001-01
Levi's	002	002-01	1.04	455	40000.0	70000.0	0.48	16645.7	Wp001-02	We001-02
Andyrex	003	003-01	1.12	405	42000.0	80000.0	0.38	20026.4	Wp001-03	We001-03
Apple	004	004-01	1.03	439	36000.0	80000.0	0.45	20771.3	Wp001-04	We001-04
Mixed	005	005-01	1.06	413	40000.0	76000.0	0.38	21974.6	Wp001-05	We001-05
Wagner's	006	006-01	1.04	412	46000.0	52000.0	0.44	25899.6	Wp001-06	We001-06
CK	007	007-01	1.07	427	40000.0	96000.0	0.42	20714.0	Wp001-07	We001-07
Edwin	008	008-01	1.09	421	45000.0	112500.0	0.40	25298.0	Wp001-08	We001-08
Giordano	009	009-01	1.08	370	24000.0	60000.0	0.40	11431.4	Wp001-09	We001-09

2.3.2 Data structure

Each database contains details of specific information. According to the requirements and applications of engineering design, the material in the database can be presented in four categories: general information about the material description, structural, mechanical and physical properties of fibers, yarns and fabrics. These data are recorded and organized in the engineering database according the logical needs of the engineering design process. In the same way the human model database can be presented as general data, structure data, physiological data and human material data.

The describing and handling of the information elements must both reflect and support the design requirement efficiently, to represent incremental design changes as key elements in the engineering design system’s overall ability. This is particularly important when engineering design software is developed to support the design process. During clothing engineering functional design, a large amount of data will be processed and this data may involve a number of value types (text, numbers, equations, diagrams, graphical, photographic images etc.). So it is necessary to define the special data type to describe the data used in clothing engineering design. The new definitions are shown in Figure 2.5.

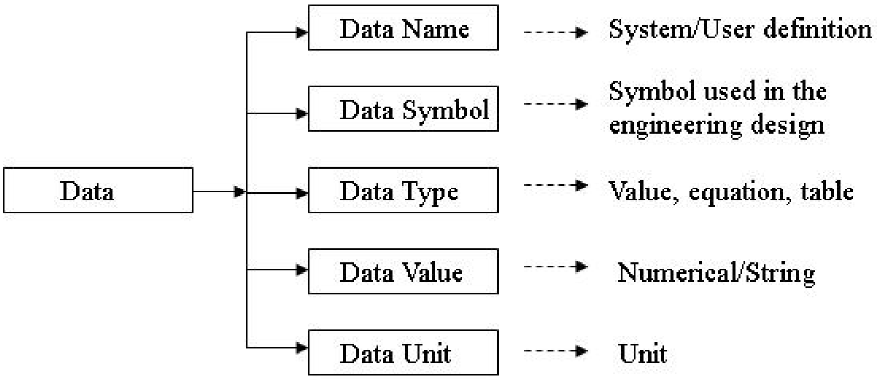


Figure 2.5 Data type

From Figure 2.5, each datum is described by five items: Data Name, Data Symbol, Data Type, Data Value, and Data Unit.

Data Name

Data Name is used to identify the special data of a material (fiber, yarn, fabric) or a human model. For example, fabric tension modulus, yarn compressor modulus etc. This item’s value is a string.

Data Symbol

A data Symbol is the mathematic symbol representing data stored in the database, and it will be used in the computing process. For an engineering design process, this data can be imported by an expression from a formalized model. This item’s value is a string. Table 2.7 shows an example of a data symbols their data name.

Table 2.7 data and symbol

_Symbol	Data Name
S_v'	surface volume ratio
ε_a	volume fraction of water vapor
ε	porosity of the fabric
ε_f	volume fraction of fiber
ε_l	volume fraction of liquid phase
δ	$\delta = (\varepsilon_l / \varepsilon)^m$
R_f	radius of fabric
C^*	saturated water vapor concentration

Data Type

Data Type is used to identify the data stored in the database in three types: Value, Equation, Table / Figure. This representation of data is useful in design because some data are generated according to engineering experience results, and others are dynamically generated during the engineering design process.

The type "Value" means that the data's value is a numerical or a string in the database and this data can be used directly in engineering design.

The type "Equation" means that an equation is stored in the database. When the design process uses this data, a special sub procedure can compute values using the equation and assign the values to the data variable.

The type “Table/Figure” means there is a table/figure stored in the database. During the engineering design process, there are mathematical methods to support the use of these values.

Data Value

Data Value is the data’s real expression, it may be a real value (numerical or string), an equation or a table/figure (file name of table /figure) decided by the item of Data Type.

Data Unit

Data Unit identifies the data’s unit; different unit sets are presented in different internal files, and the user can select them directly.

Table 2.8 shows an example the data “Surface volume ratio” stored in a database in different ways.

Table 2.8 Surface volume ratio data

name	**symbol**	**type**	**value**	**unit**
Surface volume ratio	$S_v^{'}$	value	1000	m^{-1}
Surface volume ratio	$S_v^{'}$	equation	$S_v^{'} = 2(\varepsilon_a / \varepsilon)(\varepsilon_f \delta / R_f) \cdot C^*(T)$	m^{-1}

Here, surface volume ratio is a typical of a woven fabric's physical data. When it is a real value, the value is about $1000\,m^{-1}$; however it can be described by an equation, and the importance of this is that when the design starts, the datum has an initial value, but when the design process is going on, its value changes according to the equation.

Another example concerns data of a fabric mechanical property (weft tensile modulus EA) stored in the database. It can be measured and the result presented value, as a figure, or in tabular style.

Figure 2.6 shows the woven fabric‘s mechanical extension data as a figure description (F: Force, ε : Elongation).

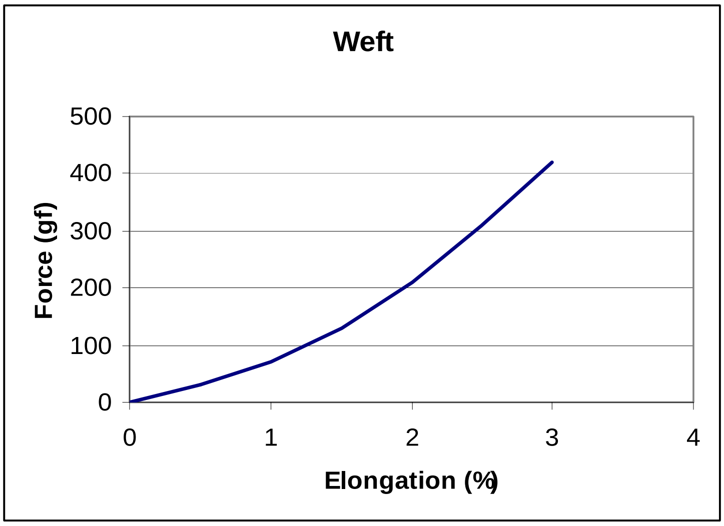


Figure 2.6 Weft tensile modulus EA ‘s data

Table 2.9 shows the woven fabric‘s Weft tensile modulus, EA, as a tabular description.

Table 2.9 Weft tensile modulus EA 's data

ε	0.	0.1	0.2	0.3	0.4	0.5	0.6	0.7
F(gf)	0.	5.	10.	18.	23.	32.	41.	49.
ε	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
F(gf)	60.	71.	80.	90.	102.	114.	130.	144.
ε	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3
F(gf)	160.	175.	188.	208.	226.	242.	258.	277.
ε	2.4	2.5	2.6	2.7	2.8	2.9	3.0	3.1
F(gf)	297.	319.	340.	363.	388.	413.	432.	459.

Therefore, the data "Weft tensile modulus EA" can be stored in database in different ways. Table 2.10 shows the data stored in EDDBMS.

Table 2.10 Weft tensile modulus EA data

Name	**Symbol**	**Type**	**Value**	**Unit**
Weft tensile modulus EA	E_2	value	50	gf/cm
Weft tensile modulus EA	E_2	table	t_p1_t_f.txt	gf/cm
Weft tensile modulus EA	E_2	figure	tensile.jpg	

2.3.3 System architecture

A database management system merges the user's need for sophisticated text, data and graphics manipulation techniques with the technological capabilities offered by the computer. Its function includes all issues associated with retrieving, sorting, updating and filing text, data and graphics. It answers fairly complex demands posed by engineering applications, running concurrently with the applications programs (processes) in the computer. Figure 2.7 shows the engineering database system for clothing biomechanical engineering design, which consists of several different layers.

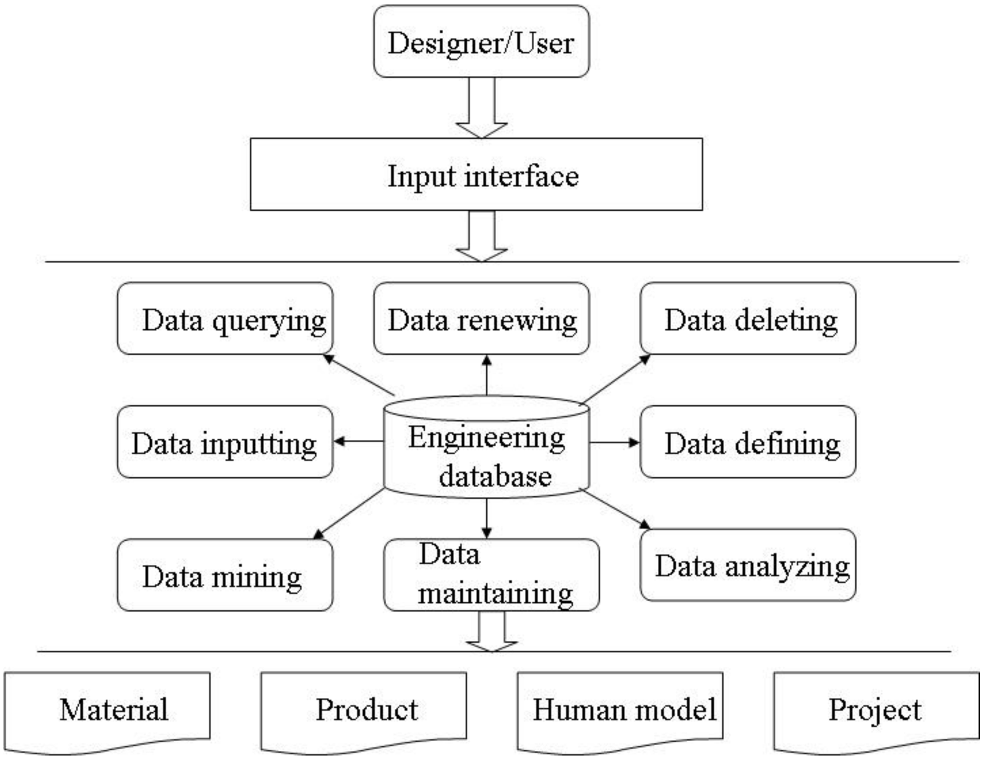
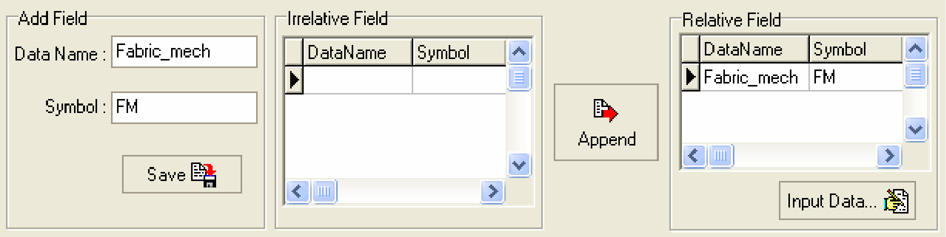


Figure 2.7 An engineering database system

The first layer is the user interface. The user can operate the database through the input interface. The middle layer is operation management. It provides various operations to the user. The third layer is the database physical store.

Engineering design is a dynamic process that involves engineering data from previous engineering experimentation or from the design process as it progresses. Thus, an engineering database should provide a redefinition function, so that the designer/user can define new data in the database and use them in future design.

For this purpose, there is an extra structure attached each database. When the designer/user wants to define their own data, they can define it through the interface. Figure 2.8 shows the redefinition interface.



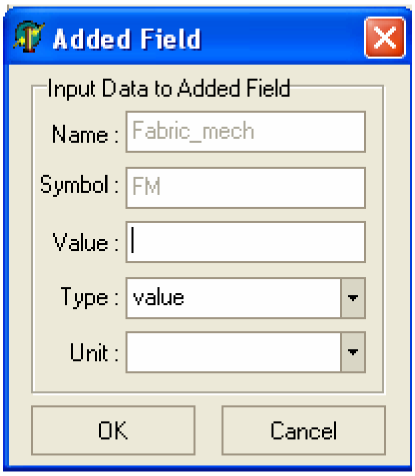
Data Name : Fabric_mech
Symbol : FM

DataName	Symbol

DataName	Symbol
Fabric_mech	FM

Figure 2.8 The redefinition interface

Once new data has been added into the database, the designer can input their value through the input interface (shown in Figure 2.9).



Name : Fabric_mech
Symbol : FM
Value :
Type : value
Unit :

Figure 2.9 Data input interface

When the item is stored in the database, all users can use it. This function ensures the engineering database system has a flexible character suitable for a dynamic process. It can provide wide application fields.

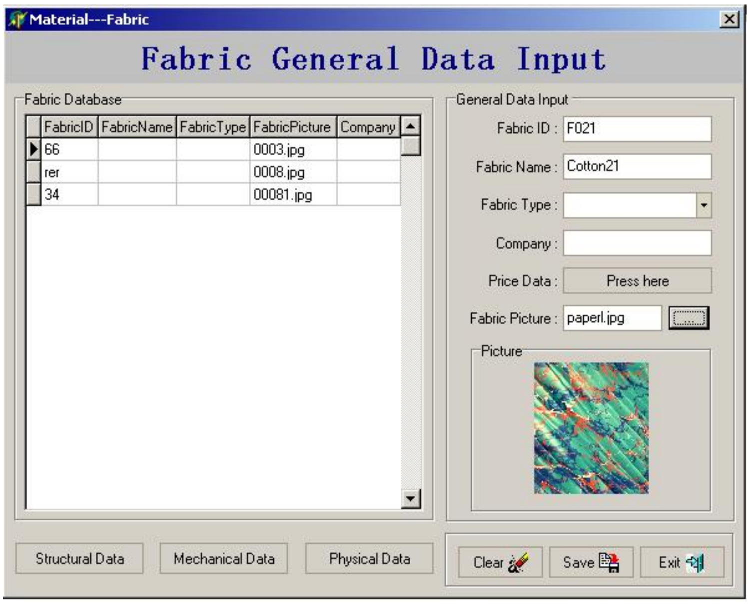
2.4 EXAMPLES

The aim is develop an engineering database with high performance, system availability and user-friendly interfaces. To provide a simple and intuitive friendly interface for analysis expertise, the user interface of the engineering database has been designed with as much image information and associated choices to clearly present the design environment and the progress of the design process at any time. A high-resolution graphics display is used to meet the geometric information and simulation function in the system.

Presentation of choices to the user utilizes pop-up menus with default suggestions to guide the user. The user interface is constructed in a PC operating system by using the Delphi + SQL Server. The following figures show the interfaces of the database used in the design process.

2.4.1 Input data

In the database, various data can be input into the flexible database. Here is an example for inputting fabric data. Figure 2.10 is the main interface for fabric data input. Four types of data can be inputted: general data, structure data, mechanical data and physical data.

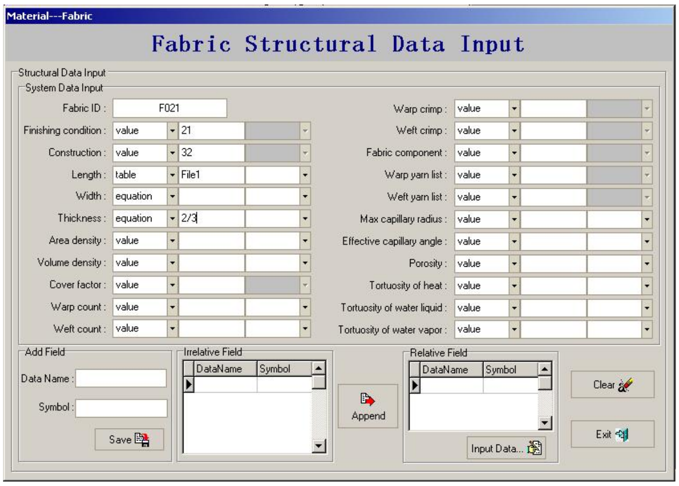


FabricID	FabricName	FabricType	FabricPicture	Company
66			0003.jpg	
rer			0008.jpg	
34			00081.jpg	

Fabric ID : F021
Fabric Name : Cotton21
Fabric Type :
Company :
Price Data : Press here
Fabric Picture : paperl.jpg

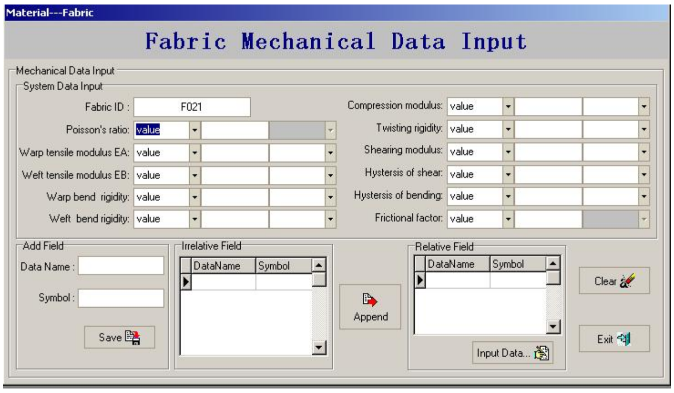
Figure 2.10 Fabric's general data input interface

At the bottom of this interface, there are buttons for inputting fabric's structure data, mechanical data, and physical data. Figures 2.11 -2.13 describe the input interfaces for these types of data.



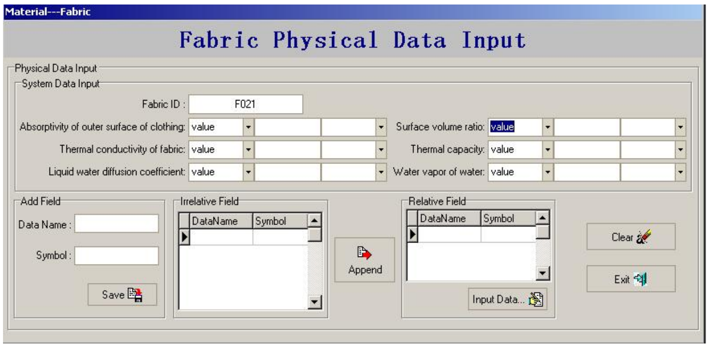
Fabric ID : F021
Finishing condition : value 21
Construction : value 32
Length : table File1
Width : equation
Thickness : equation 2/3
Area density : value
Volume density : value
Cover factor : value
Warp count : value
Weft count : value
Warp crimp : value
Weft crimp : value
Fabric component : value
Warp yarn list : value
Weft yarn list : value
Max capillary radius : value
Effective capillary angle : value
Porosity : value
Tortuosity of heat : value
Tortuosity of water liquid : value
Tortuosity of water vapor : value

Figure 2.11 Fabric’s structure data input interface



Fabric ID : F021
Poisson's ratio: value
Warp tensile modulus EA: value
Weft tensile modulus EB: value
Warp bend rigidity: value
Weft bend rigidity: value
Compression modulus: value
Twisting rigidity: value
Shearing modulus: value
Hystersis of shear: value
Hystersis of bending: value
Frictional factor: value

Figure 2.12 Fabric’s mechanical data input interface

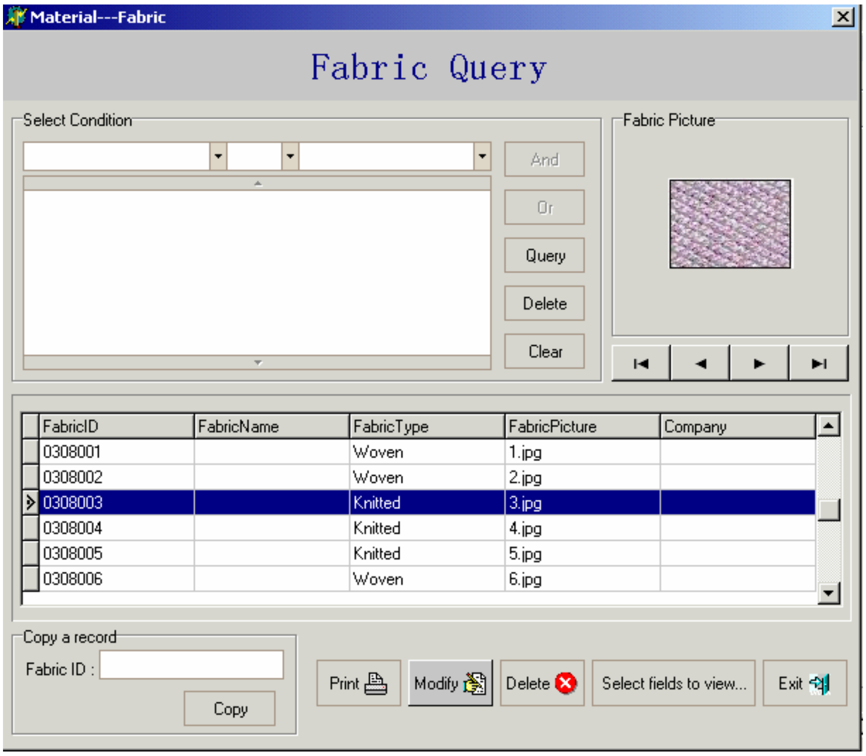


Fabric ID : F021
Absorptivity of outer surface of clothing: value
Thermal conductivity of fabric: value
Liquid water diffusion coefficient: value
Surface volume ratio: value
Thermal capacity: value
Water vapor of water: value

Figure 2.13 Fabric’s physical data input interface

2.4.2 Data query/ modify

The user can query and modify the data stored in the database through an interface (see Figure 2.14). The database provides several methods to support these operations.



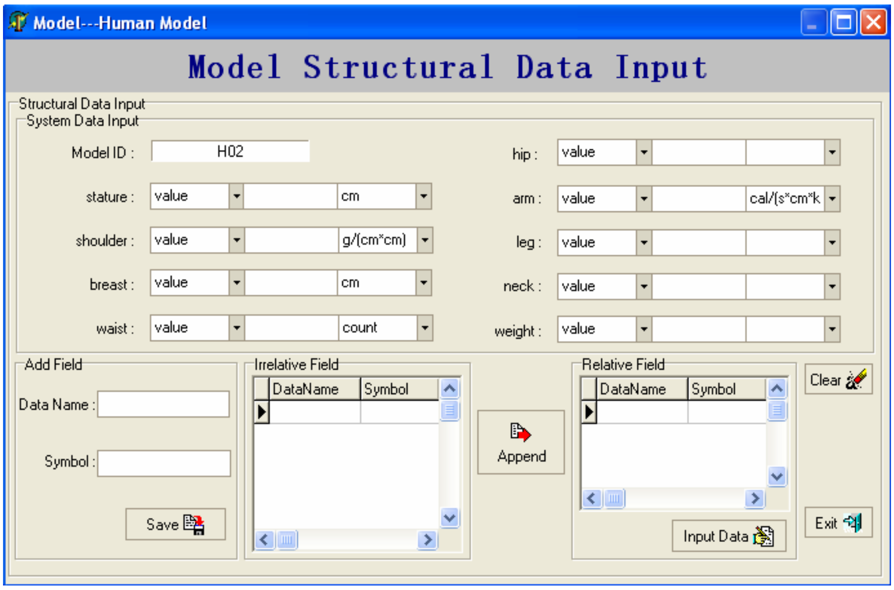
FabricID	FabricName	FabricType	FabricPicture	Company
0308001		Woven	1.jpg	
0308002		Woven	2.jpg	
0308003		Knitted	3.jpg	
0308004		Knitted	4.jpg	
0308005		Knitted	5.jpg	
0308006		Woven	6.jpg	

Figure 2.14 Fabric query interface

2.4.3 Design specification

In the design process, the first step is the specification of product design. The garment design information and the human body’s data need to be selected.

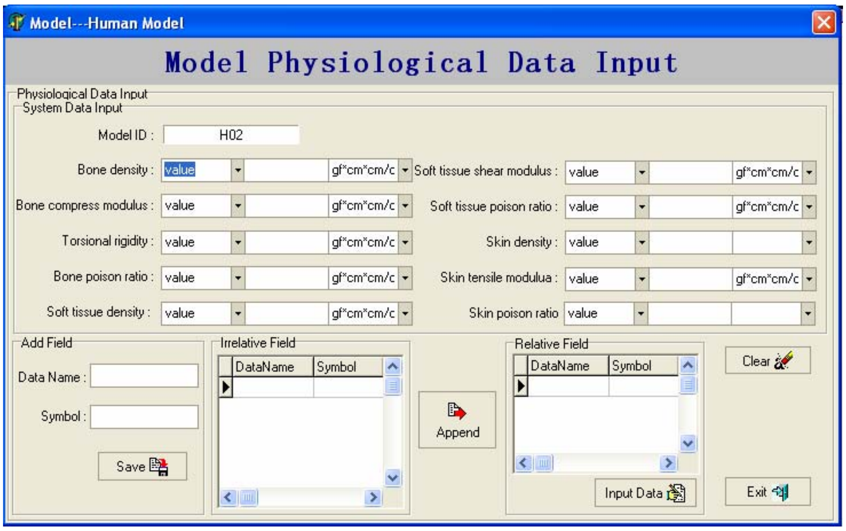
Figures 2.15, 2.16, and 2.17 show how the human body’s data are stored in the database.



Model Structural Data Input

Model ID : H02
stature : value cm
shoulder : value g/(cm*cm)
breast : value cm
waist : value count
hip : value
arm : value cal/(s*cm*k
leg : value
neck : value
weight : value

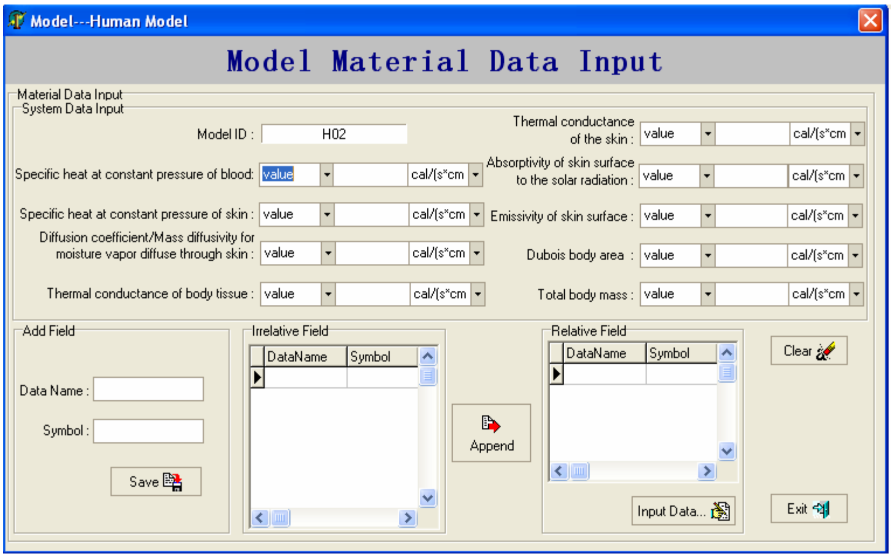
Figure 2.15 Structure data input interface



Model Physiological Data Input

Model ID : H02
Bone density : value gf*cm*cm/c
Bone compress modulus : value gf*cm*cm/c
Torsional rigidity : value gf*cm*cm/c
Bone poison ratio : value gf*cm*cm/c
Soft tissue density : value gf*cm*cm/c
Soft tissue shear modulus : value gf*cm*cm/c
Soft tissue poison ratio : value gf*cm*cm/c
Skin density : value
Skin tensile modulua : value gf*cm*cm/c
Skin poison ratio value

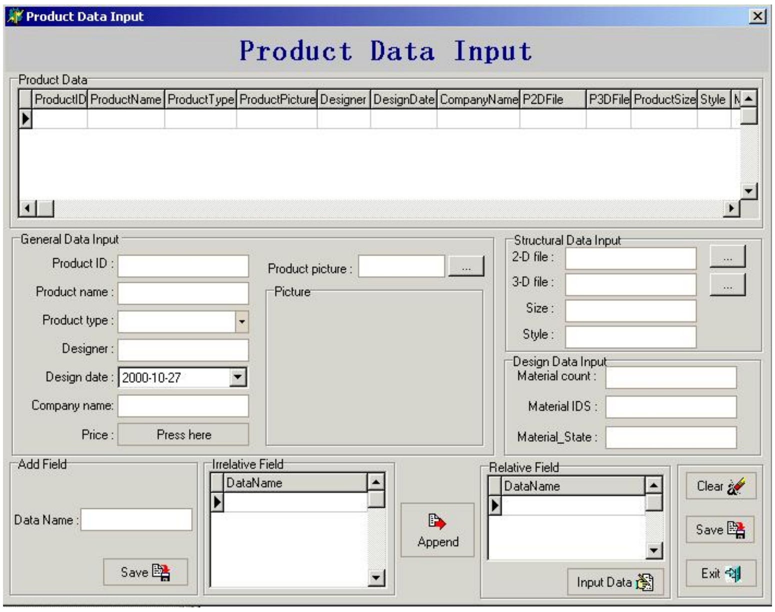
Figure 2.16 Physiological data input interface



Model ID : H02

Figure 2.17 Material data input interface

In the garment part, the garment style can be selected by searching a garment picture or a garment ID in the database. The 2D pattern data and the 3D geometric model can also be selected from the database. Figure 2.18 shows the garment's input interface.



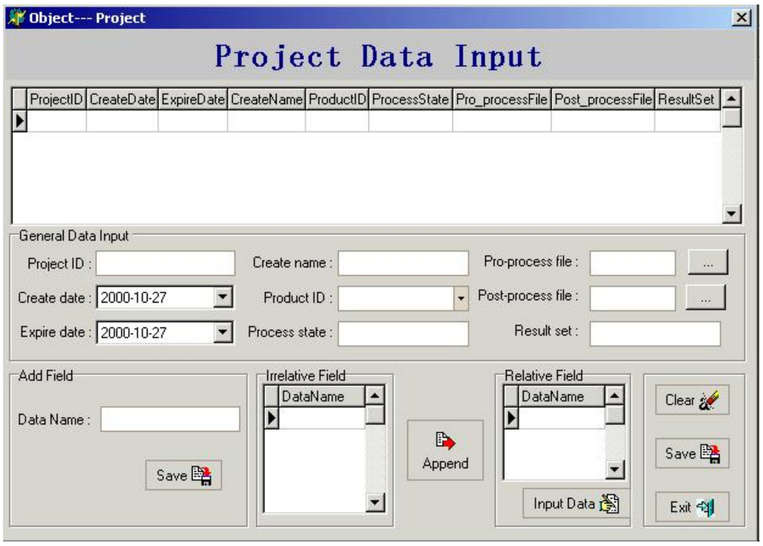
Design date : 2000-10-27

Price : Press here

Figure 2.18 Main interface of garment input interface

2.4.4 Project management

Project data management is the management of the engineering design process. It includes the design specification, definition, implementation, and control. Figure 2.19 shows the main input interface.



Create date : 2000-10-27

Expire date : 2000-10-27

Figure 2.19 The input interface of project data

2.5 CONCLUSION

In this chapter, an engineering database for textile and clothing engineering design has been developed. Textile and clothing function engineering design is a complex and dynamic process, involving varied data, and flexible data types. To support this dynamic and complex design process, it is important to develop an engineering database. An engineering database is different from a business database. The fundamental difference between the two is the stability of the administrative environment as compared to the dynamic engineering environment. According to the requirement of clothing engineering design, an engineering database management system has several characters: various complex structure data and various formal values of data. The main function of this database can meet the need of design requirements from design method, design description, design management and many others. It provides a communication environment for different users. It powerfully supports product development, design process control, quality assurance, and product performance evaluation. The system has been developed using advanced computer technology, multiplayer file structures, integrated descriptions of data, flexible data management and a friendly interface; it is easy to use for different users.

CHAPTER 3 CLOTHING MODEL IN CAD SYSTEM

3.1 INTRODUCTION

Clothing simulation requires a whole set of advances in a variety of fields: mechanical simulation, collision detection, geometric modeling, interactivity and others. There are many issues involved in the modeling and simulation of clothing. Shape is one of the most important aspects in the simulation. For clothing simulation and garment design, the best way to represent the shape of the clothing will affect the result of simulation.

A simple approach to cloth modeling is to geometrically characterize the shape of the clothing surface under given mechanical conditions and to reproduce this accurately in the computer models. However, this method has several deficiencies. It needs much professional knowledge.

A continuum mechanics model describes the mechanical state of clothing using continuous expressions defined on the geometry. Continuum models involve solving large systems of simultaneous ordinary differential equations. The computational cost is often very expensive.

Another approach is to discretize the fabric into a set of point masses, or particles, which interact through energy constraints or forces, and thus model approximately the behavior of the material. However, as well as problems of instability and high cost resulting from numerical calculation in solving ordinary differential equation systems, the resulting accuracy is also a problem.

Hybrid models combine a particle model and a geometrical model to mutual benefit. They usually employ a geometrical technique to determine a rough shape for the simulated cloth and then use a particle technique to refine the structure. The current hybrid models are limited to simulating specified or well-defined shapes and they seem to be difficult to apply in more general situations. In this chapter, the representation and conversion of rational recurrence surfaces in multivariate B-form is presented. These recurrence curves and surfaces can be used to construct a clothing model; the special advantage of this method is that can establish a universal storage data file format for different CAD systems so that the high-speed transmission and conversion of geometric graphics of two and three dimension are obtained.

3.2 RATIONAL RECURRENCE CURVES AND SURFACES

3.2.1 The definition of a rational W curve and its envelope property

Luo [58] [57], with respect to the needs of applications in some practical projects, has given the general definitions of the recurrence curves and surfaces. The L curve, W curve, L surface, and W surface are introduced.

Using homogeneous coordinates, W curves and surfaces are generalized to become rational W curves and surfaces. According to their envelope properties, the representation equivalents to rational Bézier curves and surfaces and convexity conditions of the plane rational W curves are given. Since W curves and surfaces are the generalization of B-spline curves and surfaces, Bézier curves and surfaces, rational W curves and surfaces are practically generalization of rational B-spline curves, surfaces and rational Bézier curves and surfaces.

Definition 3.1[57] Given n+1 points P_i (i=0, 1, …, n)of a plane or space, define

$$\begin{cases} D_{i,0}(t) = P_i, \\ D_{i,l}(t) = \lambda_{i,l}(t) D_{i,l-1}(t) + \mu_{i,l}(t) D_{i+1,l-1}(t), \end{cases} \tag{3.1}$$

where

$\lambda_{i,l}(t) + \mu_{i,l}(t) = 1, \ \ t \in [a,b]; \ \ i = 0, \ 1, \ ..., \ n-l; \ \ l = 1, \ 2, \ ..., \ n; \ \ D_{0,n}(t)$ is called the *n*-paces recurrence curve, abbreviated to $D_n(t)$.

If $\lambda_{i,l}(t) = a_{i,l}t + b_{i,l}$, $\mu_{i,l}(t) = 1 - \lambda_{i,l}t$; $i = 0,1,\ldots,n-l$; $l = 1,2,\ldots,n$; $D_n(t)$ is called an *n*-th recurrence curve.

Definition 3.2 [57] If n-th recurrence curve $W_n(t)$ satisfies the conditions

$$\begin{cases} a_{i,l}b_{i,l+1} = a_{i,l+1}b_{i,l,}, \\ a_{i,l+1}(1-b_{i+1,l}) = a_{i+1,l}(1-b_{i,l+1}), \\ a_{i,l}, a_{i,l+1}, a_{i+1,l} \neq 0, \end{cases} \tag{3.2}$$

where $i = 0,\ldots,n-l; l = 1,\ldots,n-1,$ and $0 \leq \lambda_{i,l}(t), \mu_{i,l}(t) \leq 1,\ \ t \in [a,b],\ \ i = 0,1,\ldots,n-l-1,\ \ l = 1,2,\ldots,n-1$, the $W_n(t)$ is called a W curve.

$W_n(t)$ can be written as

$$W_n(t) = \sum_{i=1}^{n} P_i G_{i,n}(t), \qquad t \in [a,b]$$

Here, the companion functions of $W_n(t)\{G_{i,n}(t), i = 0,\ldots,n\}$ are a group of base functions of the *n*+1 dimension polynomial space J_n; thus they are called W base functions.

Definition 3.3 Given *n*+1 characteristic vertices $P_i(i = 0,\ldots,n)$ and the corresponding weights $\omega_i > 0 (i = 0,\ldots,n)$, let

$$Q_n(t) = \frac{\sum_{i=0}^{n} P_i \omega_i G_{i,n}(t)}{\sum_{i=0}^{n} \omega_i G_{i,n}(t)}, \qquad t \in [a,b], \tag{3.3}$$

Formula (3.3) is called *n*-th rational W curve, where the $G_{i,n}(t)(i = 0,...,n)$ are W's base functions.

The formula (3.3) can be written as recurrent form.

$$Q_{i,l}(t) = \begin{cases} P_{i,} & l = 0 \\ \dfrac{\lambda_{i,l}(t)\omega_{i,l-1}(t)Q_{i,l-1}(t) + \mu_{i,l}(t)\omega_{i+1,l-1}(t)Q_{i+1,l-1}(t)}{\lambda_{i,l}(t)\omega_{i,l-1}(t) + \mu_{i,l}(t)\omega_{i+1,l-1}(t)}, & l = 1,2,...,n \end{cases} \tag{3.4}$$

Here, $i = 0,1,...,n-l$ and

$$\omega_{i,l}(t) = \begin{cases} \omega_i, & l = 0 \\ \lambda_{i,l}(t)\omega_{i,l-1}(t) + \mu_{i,l}(t)\omega_{i+1,l-1}(t), & l = 1,...,n \end{cases} \tag{3.5}$$

Hence, $Q_n(t) = Q_{0,n}(t)$.

Theorem 3.1 [57]

$$W_n^{'}(t) = na_{0,n}[W_{0,n-1}(t) - W_{1,n-1}(t)], \qquad t \in [a,b]. \tag{3.6}$$

Theorem 3.2 $Q_n(t)$ is the envelope of the curve family $\{\tilde{Q}_{n-l}(t,\tau); 0 \le \tau \le 1\}$, where

$$\tilde{Q}_{n-l}(t,\tau)=\frac{\sum_{i=0}^{n-l}\omega_{i,l}(\tau)Q_{i,l}(\tau)G_{i,n-l}(t)}{\sum_{i=0}^{n-l}\omega_{i,l}(\tau)G_{i,n-l}(t)}, \tag{3.7}$$

Here, $\omega_{i,l}(\tau)$ and $Q_{i,l}(\tau)$ respectively come from (3.5) and (3.4).

Proof Let

$$A_n(t)=\sum_{i=0}^{n}P_i\omega_iG_{i,n}(t),$$

$$B_n(t)=\sum_{i=0}^{n}\omega_iG_{i,n}(t),$$

$$A_n(t)=B_n(t)\times Q_n(t)$$

Finding the derivative with respect to *t*, the formula (3.8) can be obtained

$$\begin{aligned} Q_n^{'}(t)&=\frac{A_n^{'}(t)-B_n^{'}(t)Q_n(t)}{B_n(t)} \\ &=\frac{na_{0,n}\{[A_{0,n-1}(t)-A_{1,n-1}(t)]-[B_{0,n-1}(t)-B_{1,n-1}(t)]Q_n(t)\}}{B_n(t)}. \end{aligned} \tag{3.8}$$

Similarly let

$$\tilde{A}_{n-l}(t,\tau)=\sum_{i=0}^{n}\omega_{i,l}(\tau)Q_{i,l}(t)G_{i,n-l}(t),$$

and $$\tilde{B}_{n-l}(t,\tau)=\sum_{i=0}^{n}\omega_{i,l}(\tau)G_{i,n-l}(t)$$

Then there is

$$\tilde{Q}'_{n-l}(t,\tau)=\frac{\tilde{A}'_{n-l}(t,\tau)-\tilde{B}'_{n-l}(t,\tau)\tilde{Q}_{n-l}(t,\tau)}{\tilde{B}_{n-l}(t,\tau)}$$

From Theorem 3.1, the following formulas can be obtained.

$$\tilde{A}'_{n-l}(t,\tau)=(n-l)a_{0,n}[\tilde{A}_{0,n-l-1}(t,\tau)-\tilde{A}_{1,n-l-1}(t,\tau)],$$

$$\tilde{B}'_{n-l}(t,\tau)=(n-l)a_{0,n}[\tilde{B}_{0,n-l-1}(t,\tau)-\tilde{B}_{1,n-l-1}(t,\tau)]$$

It follows that

$$\tilde{Q}'_{n-l}(t,\tau)\Big|_{\tau=t}=\frac{n-l}{n}Q'_n(t)$$

The dual theorem of Theorem 3.2 holds also.

Theorem 3.3 $Q_n(t)$ is the envelope of the curve family $\{\tilde{Q}'_{n-l}(\tau,t);0\le\tau\le1\}$.

In (3.7), when $l=n-1$, $\tilde{Q}'_1(\tau,t)$ is a straight line family.

Theorem 3.4 $Q_n(t)$ is the envelope of the straight line family $\{\tilde{Q}_1(t,\tau);0\le\tau\le1\}$

$$\tilde{Q}_1(t,\tau)=\frac{\omega_{0,n-1}(\tau)Q_{0,n-1}(\tau)\lambda_{0,n}(t)+\omega_{1,n-1}(\tau)Q_{1,n-1}(\tau)\mu_{0,n}(t)}{\omega_{0,n-1}(\tau)\lambda_{0,n}(t)+\omega_{1,n-1}(\tau)\mu_{0,n}(t)}\qquad(3.9)$$

3.2.2 The convexity of rational W curves

Let $\Omega_{i,l}(t)=\omega_{i,l}(t)Q_{i,l}(t)$, and write

$$Q_n(t)=\frac{\sum_{i=0}^{n-l}\Omega_{i,l}(t)G_{i,n-l}(t)}{\sum_{i=0}^{n-l}\omega_{i,l}(t)G_{i,n-l}(t)}=\frac{[\Omega_l(t),G_{n-l}(t)]}{[\omega_l(t),G_{n-l}(t)]} \tag{3.10}$$

Then from Theorem 3.4, with respect to the equivalent representation of L curves into Bézier curves in the reference [57], we can obtain the following theorem.

Theorem 3.5 If let

$$\begin{cases} b_i &= \dfrac{[\Omega_{n-i}(t),G_i(1)]}{[\omega_{n-i}(0),G_i(1)]}, \\ \delta_i &= [\omega_{n-i}(0),G_i(1)], \qquad i=0,1,\ldots,n. \end{cases} \tag{3.11}$$

then, formula (3.12) can be obtained

$$Q_n(t)=\frac{\sum_{i=0}^{n}\delta_i b_i B_{i,n}(t)}{\sum_{i=0}^{n}\delta_i B_{i,n}(t)}, \qquad t\in[0,1] \tag{3.12}$$

Here, $B_{i,n}(t)(i=0,1,\ldots,n)$ is the Bernstein base function.

Lemma 3.1 When $\omega_i>0(i=0,1,\ldots,n)$, then $\delta_i>0(i=0,1,\ldots,n)$. Since

$$Q(t)=\frac{\lambda_{i,l}(t)\omega_i Q_i+\mu_{i,l}(t)\omega_{i+1}Q_{i+1}}{\lambda_{i,l}(t)\omega_i+\mu_{i,l}(t)\omega_{i+1}} \tag{3.13}$$

Here, $i=0,1,\ldots,n-l$, $l=1,2,\ldots,n$, wholly represent the straight line segment connecting two points Q_i and Q_{i+1}, thus we can get similar result by the proof method of the theorem 3.5 with respect to the convexity of W curves in reference [57].

Theorem 3.6 If the characteristic polygon of the *n*-th rational W curve $P_0, P_1, \cdots, P_n$ is convex, then the characteristic polygon of the corresponding *n*-th rational Bézier curve $b_0 b_1, \cdots, b_n$ is convex also.

Since plane rational Bézier curves preserve convexity, from Theorem 3.6 we have the following theorem.

Theorem 3.7 *n*-th plane rational W curves have preserving convexity.

3.2.3 Rational W surfaces in Multivariate B-Form in some regions

Luo [57], presents a general definition of the surface of a multivariate B-form and the method for constructing the surfaces of B-forms by raising the dimension of polyhedron. This method applied to some regular regions (parallelogram, regular hexagon and regular octagon) can be used to construct smart few families of surfaces and discuss their properties.

Let R^m denotes m dimension real vector space and Z_+^m denote the set of all m-multiple nonnegative integers. If $a = (a_1, \cdots, a_m) \in Z_+^m$, we take that

$$|a| = \sum_{j=1}^{m} a_j, a_1! \cdots a_m!, \begin{pmatrix} n \\ a \end{pmatrix} = \frac{n!}{a!}$$

When $n \in Z_+$.

Definition 3.4. If M is an m dimension $C^{'}$ class manifold, $P : M \rightarrow R^n$ and P is a $C^{'}$ class injection, then the concept of the combination of M and P is referred to as the surface of R^m (or insert sub manifold). When m=1,2,…,n-1, all are referred to as the surface.

Definition 3.5. If Ω is a n dimensional simplex, ω is a $C^{'}$ class manifold, and $\omega \subset \Omega$, then

$$P(u) = \sum_{|a|=k} P_a B_a(\tau), \qquad u \in \omega$$

is called the surface of the k-th B-form on ω.

Here, $\tau = (\xi_0, \xi_1, \cdots, \xi_n)$ is the barycentric coordinate of u in Ω, and the subscript $a = (a_0, a_1, \cdots, a_n) \in Z_+^{n=1}$.

$$B_a(\tau) = \begin{pmatrix} |a| \\ a \end{pmatrix} \tau^a = \begin{pmatrix} |a| \\ a \end{pmatrix} \cdot \xi_0^{a_0} \xi_0^{a_1} \cdots \xi_0^{a_n}$$

is a multivariate Bernstein polynomial.

Let the parallelogram region be

$$\sigma = \left[v^1, v^2, v^3, v^4\right] = \{v \middle| v = \sum_{j=1}^{4} \xi_j v^j, \sum_{j=1}^{4} \xi_j = 1, \xi_j \geq 0\}$$

Here, $\sigma \subset R^2$. Turn σ into

$$\Omega = [u^1, u^2, u^3, u^4] = \{u \middle| u = \sum_{j=1}^{4} \xi_j u^j, \sum_{j=1}^{4} \xi_j = 1, \xi_j \geq 0\}$$

by raising the dimension of σ, from Definition 3.5. We choose

$$\omega = \{u \middle| u = \sum_{j=1}^{4} \xi_j u^j, \sum_{j=1}^{4} \xi_j = 1, \xi_1 + \xi_2 + \xi_3 + \xi_4 = \frac{1}{2}\}$$

We can get the surface of the *n*-th B-form on ω

$$P(u) = \sum_{|a|=n} P_a B_a(\tau), \qquad u \in \omega$$

Given regular mesh nodes $P_{ij}\,(i, j = 0, \cdots, n)$,left $P_{i_1 i_2 i_3 i_4}\Big|_A = P_{ij}$,where A represents following restricted conditions.

Definition 3.6 Given $(n+1)(m+1)$ characteristic vertices $P_{i,j}\,(i = 0,1,\ldots,n;\quad j = 0,1,\ldots,m)$ and the corresponding weights $\omega_{i,j} > 0$. If $\{G_{i,n}(u) H_{j,m}(v),\ \ i = 0,1,\ldots,n;\quad j = 0,1,\ldots,m\}$ are the base function of W surfaces [57, 58], then

$$R(u,v)=\frac{\sum_{i=0}^{n}\sum_{j=0}^{m}\omega_{i,j}P_{i,j}G_{i,n}(u)H_{j,m}(v)}{\sum_{i=0}^{n}\sum_{j=0}^{m}\omega_{i,j}G_{i,n}(u)H_{j,m}(v)} \tag{3.14}$$

$$(u,v)\in[a,b]\times[c,d]$$

Formula (3.14) is called the $n\times m$-th rational W surface.

The definitions mentioned above can also be written as recurrent form. Set

$$[W^{k,l}(u,v)]_{i,j}=\begin{bmatrix} W_{i,j}^{k,l}(u,v) & W_{i,j+1}^{k,l}(u,v) \\ W_{i+1,j}^{k,l}(u,v) & W_{i+1,j+1}^{k,l}(u,v)\end{bmatrix}$$

$$\omega_{i,j}^{k,l}(u,v)=\begin{cases} \omega_{i,j}\ , & k=l=0 \\ [\lambda_{i,k}(u),\mu_{i,k}(u)][\omega^{k-1,l-1}(u,v)]_{i,j}[\psi_{j,l}(v),\varphi_{j,l}(v)]^{T}\ , & \\ & k=1,2,\ldots,n;\quad l=1,2,\ldots,m \end{cases} \tag{3.15}$$

Then

$$R_{i,j}^{k,l}(u,v)=\begin{cases} P_{i,j}\ , & k=l=0 \\ \dfrac{[\lambda_{i,k}(u),\mu_{i,k}(u)][\omega^{k-1,l-1}(u,v)R^{k-1,l-1}(u,v)]_{i,j}[\psi_{j,l}(v),\varphi_{j,l}(v)]^{T}}{\omega_{i,j}^{k,l}(u,v)} & \\ & k=1,2,\ldots,n;\quad l=1,2,\ldots,m \end{cases} \tag{3.16}$$

Here, $i=0,1,\ldots,n-k;\quad j=0,1,\ldots,m-l$; $\lambda_{i,k}(u),\ \ \mu_{i,k}(u)(i=0,1,\ldots,n-k;\ \ k=1,2,\ldots,n)$ and $\psi_{j,l}(v),\varphi_{j,l}(v)(j=0,1,\ldots,m-l;\ \ l=1,2,\ldots,m)$ are the 1-th polynomial function satisfying the conditions of W curves. When *k=n* , *l=m* then $R_{0,0}^{n,m}(u,v)=R(u,v)$.

Using similar method to that, of theorem 3.2 we have the following envelope theorem.

Theorem 3.8 $R(u\ ,v)$ are the envelope of the following surface family.

$$\tilde{R}(\varepsilon,\eta,u,v)=\frac{\sum_{i=0}^{n-k}\sum_{j=0}^{m-l}\omega_{i,j}^{k,l}(\varepsilon,\eta)R_{i,j}^{k,l}(\varepsilon,\eta)G_{i,n-k}(u)H_{j,m}(v)}{\sum_{i=0}^{n-k}\sum_{j=0}^{m-l}\omega_{i,j}^{k,l}(\varepsilon,\eta)G_{i,n-k}(u)H_{j,m}(v)} \tag{3.17}$$

Here, $1\le k\le n-1;1\le l\le m-1$ .When $k=n-1,\ l=m-1$, the rational W surface $R(u,v)$ is the envelope of a ruled surface family. The dual theorem of the theorem 3.8 holds, namely, $R(u,v)$ is also the envelope of the surface family $\tilde{R}(u,v,\varepsilon,\eta)$. For rational W surfaces there are equivalent Bézier surfaces also.

Theorem 3.9 If we set

$$\begin{cases} q_{i,j}=\dfrac{[G_i(1),\omega^{n-i,m-j}(0,0)R^{n-i,m-j}(0,0),H_j(1)]}{[G_i(1),\omega^{n-i,m-j}(0,0),H_j(1)]}, \\ \delta_{i,j}=[G_i(1),\omega^{n-i,m-j}(0,0),H_j(1)], \end{cases} \tag{3.18}$$

$i=0,...,n;\quad j=0,1,...,m.$

then we have

$$R(u,v)=\frac{\sum_{i=0}^{n}\sum_{j=0}^{m}\delta_{i,j}q_{i,j}B_{i,n}(u)B_{j,m}(v)}{\sum_{i=0}^{n}\sum_{j=0}^{m}\delta_{i,j}B_{i,n}(u)B_{j,m}(v)} \tag{3.19}$$

where $B_{i,n}(u)(i=0,1,...,n)$ and $B_{j,m}(v)(j=0,1,...,m)$ are respectively the *n*-th and *m*-th Bernstein base functions.

3.3 REPRESENTATION AND CONVERSION OF BEZIER SURFACES

3.3.1 Representation of Surfaces of B-form on simplex region

For practical applications, Bezier surfaces on simplex region have an important role. Barnhil and Luo [71] [96], given a general definition of the Bezier surface in B-form. These surfaces can be used to establish different data formats for CAD systems.

Lemma 3.2 [58]**.** For any nonnegative integers *k* and *l*, we have

$$\sum_{\substack{i_1+i_2=k,i_1+i_3=l\\ i_1+i_2+i_3+i_4=n}}\frac{n!}{i_1!i_2!i_3!i_4!}=\binom{n}{k}\binom{n}{l} \tag{3.20}$$

Theorem 3.10 [58]. Given a group of characteristic vectors R_{kl} $(k,l=0,1,\dots,n)$, let

$$P_{i_1,i_2,i_3,i_4} = R_{kl}\,(i_1 + i_2 = k, i_1 + i_3 = l, i_1 + i_2 + i_3 + i_4 = n)$$

Then the double n-th degree Bezier surface with characteristic vertices R_{kl} (k ,l=0,1,…,n) is the surface of an n-th degree B-form on a three-dimension simplex region. In the fact, this result can also be generalized to the case of the mn-th degree of Bezier surface by the formula for raising the degree of Bernstein polynomial.

Lemma 3.3 [58]. Let $A^{n,k_1,\ldots,k_\mu}_{i_1,\ldots,i_m}$ (or A) denote the restriction conditions:

$$\begin{cases} i_1 + i_2 + \cdots + i_{\frac{m}{2}} = k_1 \\ i_1 + \cdots + i_{\frac{m}{4}} + i_{\frac{m}{2}+1} + \cdots + i_{\frac{3m}{4}} = k_2 \\ \cdots\cdots \\ i_1 + i_3 + \cdots + i_{m-3} + i_{m-1} = k_\mu \\ i_1 + i_2 + \cdots + i_{m-1} + i_m = n \end{cases} \tag{3.21}$$

$$m = 2^\mu, n > 1$$

then we have

$$\sum_A \frac{n!}{i_1!i_2!\cdots i_m!} = \prod_{1\le j\le\mu} \binom{n}{k_j}.$$

Theorem 3.11 [58] [57] Given a group of characteristic vectors $R_{k_1,k_2,\ldots,k_\mu}(k_1,k_2,\ldots,k_\mu = 0,1,\ldots,n)$, if we take $P_{i_1,i_2,\ldots,i_n}\big|_A = R_{k_1,k_2,\ldots,k_\mu}$, then the μ-multiple tensor product Bezier surface of degree n with characteristic vertices $R_{k_1,k_2,\ldots,k_\mu}$ is surface of n degree B-form on a $2^\mu - 1$ dimensional simplex region. The more general formula can be expressed as follows:

$$P_{i_1,i_2,\dots,i_n}\Big|_A = R_{k_1,k_2,\dots,k_\mu} = \left(\sum_A P_{i_1,i_2,\dots,i_n}\frac{n!}{i_1!i_2!\dots,i_n!}\right) / \prod_{1\le j\le\mu}\binom{n}{k_j} \tag{3.22}$$

According to theorem 3.10 and 3.11, we can obtain the relationship between the surface of a multivariate B-form and the Bezier surface.

Proposition 3.1 [58] The multivariate B-form of degree *n* defined on the *m*-th degree Bezier surface of a two dimension simplex region can be represented in the *mn*-th degree surface.

Proposition 3.2 [58]The *n*-th degree multivariate B-form defined on a doubled *m*-th degree surface can be represented in a double *mn*-th degree Bezier surface.

3.3.2 Connection conditions of Bezier surfaces on a simplex region

The problem of connection between Bezier surfaces has been considered more and more frequently. We present a simple GC^{μ} continuity sufficiency condition of Bezier surfaces connected in triangular and rectangular regions.

Two Bezier surfaces are expressed as follows:

$$\begin{cases} P^*(u) = \sum_{|a|=n} b^*(a) B_a(\tau), & a \in Z_+^3, \quad b^*(a), b(a) \in IR^m \\ P(u) = \sum_{|a|=n} b(a) B_a(\tau), & n = \xi_1 u^1 + \xi_2 u^2 + \xi_3 u^3, \quad a = (a_1, a_2, a_3) \end{cases} \tag{3.23}$$

Then the GC^1 continuative condition of surfaces $P^*(u)$ and $P(u)$ connected on connection line u^1u^2 can be expressed:

$\begin{cases} b^*(a) = b(a), & a_3 = 0, a_1 + a_2 = n \\ b^*(a+e^3) = \alpha_1 b(a+e^1) + \alpha_2 b(a+e^2) + \alpha_3 b(a+e^3), & \\ \alpha_1 + \alpha_2 + \alpha_3 = 1, & a_3 = 0, a_1 + a_2 = n-1 \end{cases}$	(3.24)

Converting (3.24), we get

$$b^*(a+e^3) - b^*(a+e^1) = \alpha_2 (b(a+e^2) - b(a+e^1)) + \alpha_3 (b(a+e^3) - b(a+e^1)), \tag{3.25}$$
$$a = (a_1, a_2, 0), a_1 + a_2 = n-1.$$

Which is a necessary and sufficient condition of GC^1 continuative that Bezier surface $P^*(u)$ and $P(u)$ on simplex be connected on connection position. We can present the GC^μ continuity condition that $P^*(u)$ and $P(u)$ be connected on the connection line u^1u^2:

$$b^*(a+re^3) = \sum_{|c|=r} \alpha_r(c) b(a+c), \tag{3.26}$$
$$\sum_{|c|=r} \alpha_r(c) = 1, r = 0,1,\ldots,\mu; a = (a_1, a_2, 0), |a| = n - r, c \in Z_+^3$$

Proposition 3.3 [58] The Bezier surfaces on triangle and rectangle region can be defined:

$$P(u) = \sum_{|a|=n} b_{i,j,k} B_a(\sigma), \qquad a \in Z_+^3, a = (i, j, k)$$

$$P(\varepsilon,\eta) = \sum_{i,j=0}^{n} r_{i,j} B_i^n(\varepsilon) B_j^n(\eta), \qquad \varepsilon,\eta \in [0,1]$$

Then the GC^1 continuative condition that surfaces $P^*(u)$ and $P(u)$ be connected on connection line u^1u^2 can be expressed as

$$\begin{cases} r_{i0} = b_{n-i,i,0}, & i = 0,1,...,n-1 \\ r_{i1} = \alpha_1 b_{n-i,i,0} + \alpha_2 b_{n-i-1,i+1,0} + \alpha_3 b_{n-i-1,i,1}, & \\ r_{n-i1} = \beta_1 b_{i,n-i,0} + \beta_2 b_{i+1,n-i-1,0} + \beta_3 b_{i,n-i-1,1}, & \\ \alpha_1 + \alpha_2 + \alpha_3 = 1, \beta_1 + \beta_2 + \beta_3 = 1, i = 0,1,...,n-1 & \end{cases} \tag{3.27}$$

According to (3.27), the GC^1 continuative condition of connection can be presented as

$$r_{i1} - r_{i0} = \frac{i}{n}\mu_1 e_{i-1} + (1-\frac{i}{n})\mu_0 e_i + \frac{i}{n}\lambda_1 f_{i-1} + (1-\frac{i}{n})\lambda_0 f_i \tag{3.28}$$

Here, $i = 0,1,...,n; \mu_1 = -\beta_2, \mu_0 = \alpha_2, \lambda_1 = \beta_3, \lambda_0 = \alpha_3; e_i = b_{n-i-1,i+1,0} - b_{n-i,i,0}$ and $f_i = b_{n-i-1,i+1,1} - b_{n-i,i,0}$.

In fact, (3.27) represents two conditions of Bezier surface GC^1 continuative connection in $\Delta u^1u^2u^3$, $\Delta u^1u^2u^4$ and $\Delta u^1u^2u^3$, $\Delta u^1u^2u^5$.(see Figure 3.1)

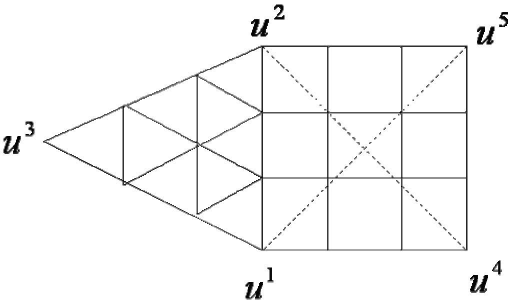


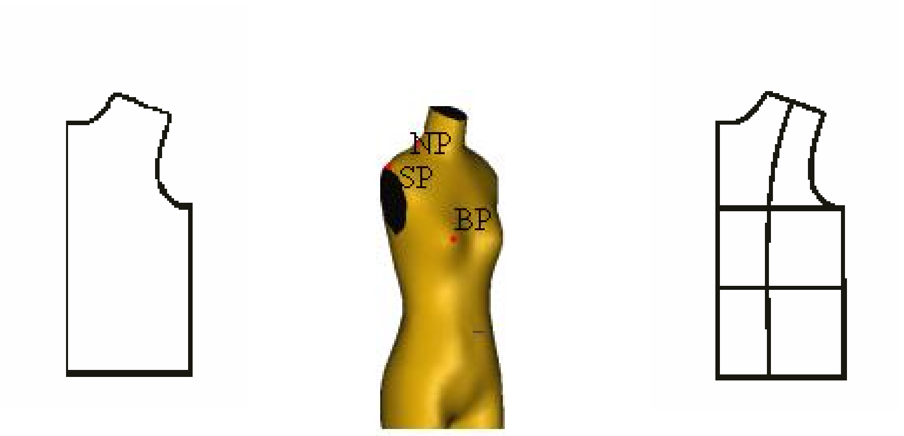
Figure 3.1 The connection of two surfaces

Luo [96] [57], constructed the same degree hypersurface forms of multivariate B-form on a regular quadrilateral region, a regular hexagon and a regular octagon region, and obtained a group of GC^{μ} continuity conditions between adjacent rectangular and triangular Bezier surface patches. These methods can be applied in CAD systems; the results show that they could solve some practical problems.

3.4 APPLICATIONS IN CLOTHING ENGINEERING DESIGN

With the development of computer technology, CAD applications in textile and clothing industry become more and more important, particularly in apparel functional design. There are many important issues in apparel engineering functional design to be addressed, one of which is how to generate three dimensional apparel models. The hybrid method is one of the important. The first step in this method is constructing a 3D geometric model.

In order to construct a 3D garment geometrical model, the researcher can select a 2D pattern. According to the geometry, the topological information of the pattern, and the key points on the human body, an initial 2D pattern mesh model can be constructed. The result is shown in Figure 3.2.



(a) 2D pattern (b) Key points on the body (c) Initial 2D mesh pattern

Figure 3.2 Construction of initial 2D pattern

Using information from the initial 2D mesh pattern, a 3D initial mesh geometrical model can be constructed on the human body directly. The process for constructing 3D model should satisfy the restriction conditions (key points matching and the same topology relationship) (Figure 3.3).

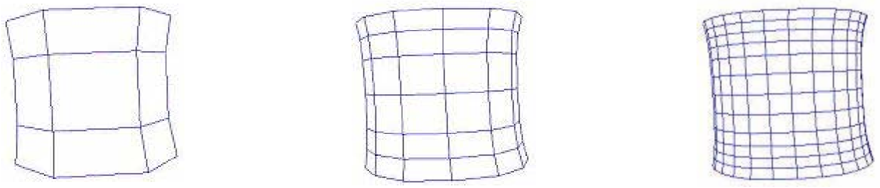
Figure 3.3 Initial 3D model

Using the geometrical modeling method of Bezier surfaces in multivariate B-form mentioned above, an initial 3D garment rough surface data model can be obtained. The subdivision scheme [15] [26] can be used to mesh the surface in detail.

Subdivision surfaces are powerful and useful techniques in modeling free-form surfaces. Gao [23] used a four-point subdivision scheme to construct 3D surfaces. The points set of the four-point subdivision scheme can be described as follows:

$$\begin{cases} P_{2i,2j}^{k+1} & -1 \le i \le 2^k n+1, -1 \le j \le 2^k m+1 \\ P_{2i+1,2j}^{k+1} = (\frac{1}{2}+\omega)(P_{i,j}^{k}+P_{i+1,j}^{k})-\omega(P_{i-1,j}^{k}+P_{i-2,j}^{k}) & -1 \le i \le 2^k n, -1 \le j \le 2^k m+1 \\ P_{2i,2j+1}^{k+1}(\frac{1}{2}+\omega)(P_{i,2j}^{k+1}+P_{i,2j+2}^{k+1})-\omega(P_{i,2j-2}^{k+1}+P_{i,2j+4}^{k+1}) & -1 \le i \le 2^k n+1, -1 \le j \le 2^k m \end{cases}$$

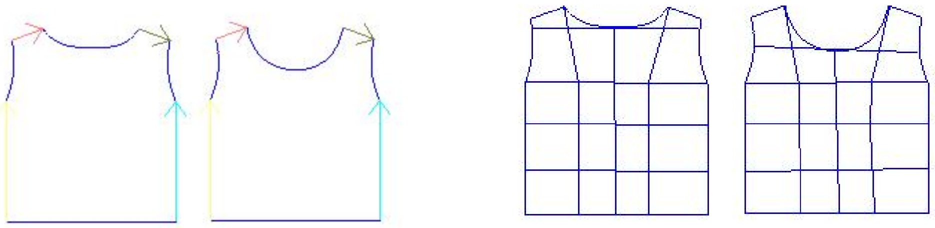
When $\omega = \frac{1}{16}$, the process of subdivision is as shown in Figure 3.4.



Initial mesh One-step subdivision Two-step subdivision

Figure 3.4 Four-point subdivision scheme

Figures 3.5 -3.7 show the construction of a 3D clothing rigidity surface. The first step is the selection of vest style, seam line definition, and 2 dimensional pattern initial meshes.



(a) 2D pattern (b) 2D initial mesh pattern

Figure 3.5 2D pattern modeling

Using key points on the human body and the topological relationships between the 2D geometrical graph, a 3D initial control mesh can be constructed. Figure 3.6 shows the result.

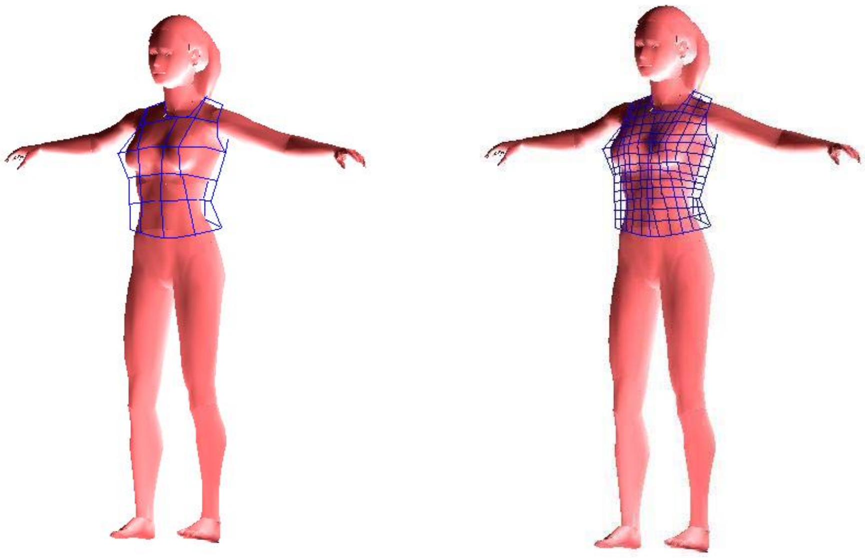

3D initial control mesh 3D garment rough surface

Figure 3.6 3D garment geometrical model

3.5 CONCLUSION

In some cases, it is required to construct a surface which not only satisfies interpolating conditions or preserves shape, but also has C^1 or C^2 continuity or exact conformity regardless of whether the geometric distribution of characteristic vertices is uniform or not. In a CAD system, the interpolation on a space mesh is usually defined on a rectangular partition of a rectangular region. But for more complex projects, if the mesh nodes distribution is not uniform, the bicubic spline interpolating method and Coons surface method are hardly sufficient to find a suitable parameter domain and its partition. In this chapter, the rational recurrence Curves and recurrence surfaces in multivariate

B-Form on some regions is presented. The advantages of this method that make

Bézier curves and surfaces, rational W curves and surfaces practical are the generalization of rational B-spline curves, surfaces and rational Bézier curves and surfaces. These surfaces can be used to establish different data format for CAD systems.

Applying this method, a 3D rough clothing shape can be constructed. The main process loop is 2D pattern selection, 2D initial pattern mesh (according to the key points defined on the human body), 3D initial geometrical model construction, four-point subdivision scheme applied on the 3D initial model, then to obtain the 3D rough clothing geometrical model. This 3D geometrical model can be used in a clothing dynamic simulation system.

CHAPTER 4 COMPUTATIONAL SIMULATION SYSTEMS

4.1 INTRODUCTION

Computer aided design for the biomechanical engineering of clothing design is a simulation process to analyze and evaluate the functional performance of clothing. The aim of biomechanical simulation is the virtual reproduction of the mechanical behavior of an item of clothing subjected to various geometrical and mechanical conditions, or of the interaction between a piece of clothing and a human body. This system utilizes a range of technical advances in a variety of fields: geometric modeling, mechanical simulation, collision detection and response, interaction with the environment, numerical solvers and others.

There are several issues in building up a cloth simulation system [86]: material analysis, mechanical modeling, geometrical modeling, a simulation scheme, and numerical integration. When addressing these issues, it must be kept in mind that the quality of a good mechanical system is defined by the tradeoff between accuracy and simulation efficiency, as well as the robustness necessary for dealing with a wide range of situations [44].

A human-clothing biomechanical numerical simulation can simulate the quantitative description of mechanical behaviors such as the garment deformation process, the garment pressure distribution, the human body deformation and the inner stress on the skin.

There are three phases in the implementation of a simulation system, namely: pre-processing, solving and post-processing. Figure 4.1 shows the main components of a simulation system. The pre-processing phase prepares the various parameters of the simulation system. 2D apparel patterns are the basis of constructing a garment. There are methods available for the construction of a 3D garment from 2D patterns. The mechanical properties of the material will affect the mechanical performance of the clothing during the simulation, such as imposed deformations, constraints or force patterns.

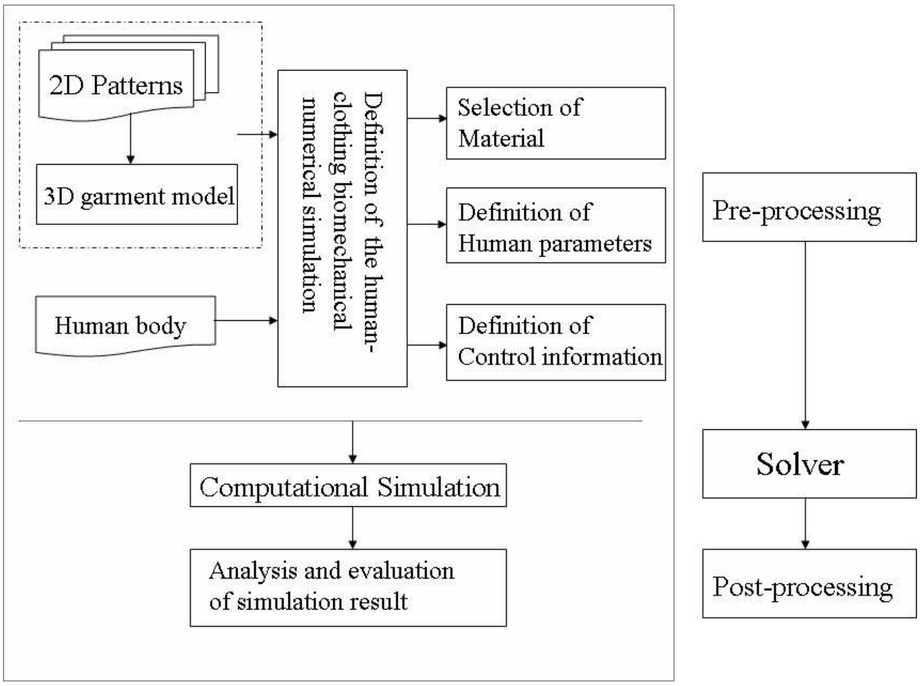


Figure 4.1 Simulation loop

The method used to generate a human model can be divided into two parts, namely, the geometry model and the entity model. The geometry model uses point, line, circle, and spline curve to describe the three-dimensional object. This method is characterized by limited data, and is easy to edit and modify. However, this gives limited information for describing the human body and it is difficulty to mesh with the processing. The entity method describes the body using more geometry and topology information. It can therefore support all operations, but it takes much longer and may waste time.

Combining the equations of material behavior with mechanical laws yields complex systems of mathematical equations, usually partial differential equations or other types of differential systems. The particle system and continuum mechanics are most commonly used for performing mechanical simulations.

Some commercial Finite Element (FE) software packages are convenient tools for carrying out mechanical analysis. However, these generalized tools for mechanical analysis can be insufficient for solving the complicated problems involved with textile products, especially as there is no way to integrate the whole design process. There are also many specific systems and models which have been developed for the biomechanical engineering of clothing design. This chapter reports on the development and usage of these types of simulation schemes.

4.2 PARTICLE MODELS

4.2.1 System framework

4.2.1.1 System flow chart

Breen and House [4] developed a non-continuum particle model for fabric drape in 1992 that explicitly represents the micro-mechanical structure of a fabric via a particle system. Their model is based on the observation that a fabric is best described as a mechanism of interacting mechanical parts rather than a continuous substance, and derives its macro-scale dynamic properties from the micro-mechanical interaction between threads. Breen [5] also extended this model to include dynamics using a force-based formulation approach. Dai et al [98] developed a particle model by deriving the general force/displacement relationships between various deformations according to fundamental elasticity mechanical laws.

Using this basic principle in Dai's model, a biomechanical simulation system for clothing has been developed [105]. In order to support the design efficiently, this system is integrated with an engineering database. The system flow chart is shown in Figure 4.2.

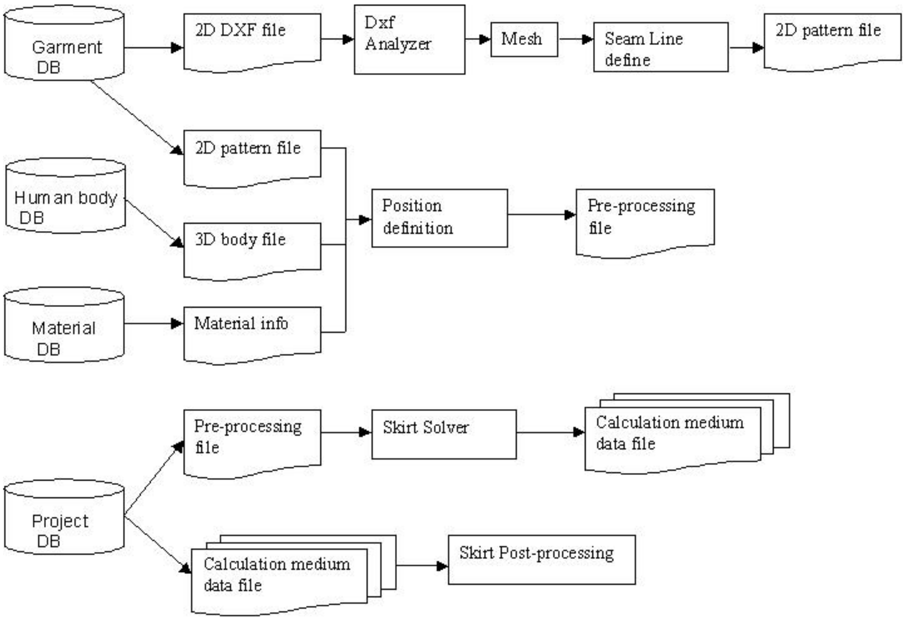


Figure 4.2 System flow chart

The geometrical model of the garment, the material model, and the human body model are considered in the design system. The geometrical models are built to enable further mechanical simulation. In this design process, a 2-D cloth pattern describes boundaries as 2D curves. The regions enclosed by the curves are then discredited into polygonal meshes. In order to proceed to a mechanical simulation of an object, its mechanical behavior must be described by relevant mechanical parameters and expressed as a set of relations among the geometrical and mechanical values of the object that can be easily manipulated. For clothing of different types, the major elasticity parameters include the Young modulus, the Poisson ratio, the bending modulus and the shearing modulus. For simplicity, the Young’s modulus and the Poisson’s ratio are the usual parameters used. For a dynamic simulation, the mass density of an object is also necessary. A large amount of material data must be stored, as all the required data must be obtainable from the database.

4.2.1.2 Data structures

The format of the data in the database is vital if the data is to be described efficiently. By analyzing the data used in the design system, some of the data structure can be defined. 2D pattern numbers, a set of pattern points, and seam line information needs to be recorded. The detailed description is shown in the Table 4.1.

Table 4.1 2D pattern file

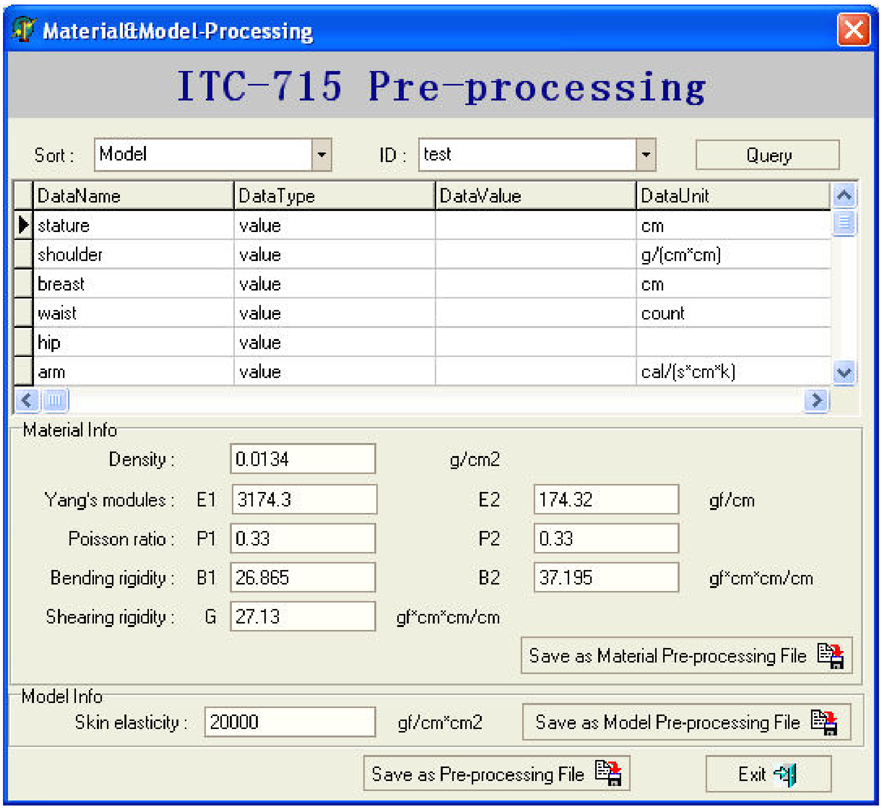
Pattern info.	Pattern Number			
	Matrix Row for storing the pattern points		Matrix Col for storing the pattern points	
	Point Matrixes 1 data (flag, x, y, z)			
	Point Matrixes 2 data (flag, x, y, z)			
Seam Line info.	Seam Line Number			
	Seam line number		Points in each seam line	
	Pattern Index of line 1	Line Index of Line 1	Pattern index of Line 2	Line Index of Line2
	Points number in Seam Line 1		Points number in Seam Line 2	
	Point indexes of Seam Line 1			
	Point indexes of Seam Line 2			

The pre-processing file can be constructed or selected from the database according to the requirements of the design. This file includes three parts: the pattern information, human body information, and material information. The detailed description is shown in Table 4.2.

Table 4.2 Pre-processing file

Pattern info.	Pattern Number			
	Matrix Row for storing the pattern points		Matrix Col for storing the pattern points	
	Point Matrixes 1 data (flag, x, y, z)			
	Point Matrixes 2 data (flag, x, y, z)			
Seam Line info.	Seam Line Number			
	Seam line number		Points in each seam line	
	Pattern Index of line 1	Line Index of Line 1	Pattern index of Line 2	Line Index of Line2
	Points number in Seam Line 1		Points number in Seam Line 2	
	Point indexes of Seam Line 1			
	Point indexes of Seam Line 2			
Human Body data	Matrix Row for storing the body data		Matrix Col for storing the body data	
	Points position (x ,y, z)			
	Skin_elasticity			
Material info.	Density			
	Yangs of weft and warp			
	Poisson ration P1 P2			
	Bending of weft and warp			
	Shearing			

Therefore, the interface that has been created between the design system and the database can be used for the design of products. Figure 4.3 shows the interface of the pre-processing file using the database.



Material&Model-Processing

ITC-715 Pre-processing

Sort : Model

ID : test

DataName	DataType	DataValue	DataUnit
stature	value		cm
shoulder	value		g/(cm*cm)
breast	value		cm
waist	value		count
hip	value		
arm	value		cal/(s*cm*k)

Material Info

Density : 0.0134 g/cm2

Yang's modules : E1 3174.3 E2 174.32 gf/cm

Poisson ratio : P1 0.33 P2 0.33

Bending rigidity : B1 26.865 B2 37.195 gf*cm*cm/cm

Shearing rigidity : G 27.13 gf*cm*cm/cm

Model Info

Skin elasticity : 20000 gf/cm*cm2

Figure 4.3 Interface in the constructing of the pre-processing file

4.2.2 Functions description

The software can simulate the various deformations in the garments. Table 4.3 shows different simulation results using this software.

Table 4.3 Display of simulation results

Types	**Simulation results**
wire-frame	Display the 3D model’s wire frame
flat shading	Display the 3D model in flat shading style
smooth shading	Display the 3D model in smooth shading style
act spring force	Display the spring force on different parts of the model
act bend force	Display the bend force on different parts of the model
act trellis force	Display the trellis force on different parts of the model
act twist force	Display the twist force on different parts of the model
act repulse force	Display the repulse force on different parts of the model

4.2.3 Simulation example

In order to illustrate the use of the mechanical engineering design system, a skirt simulation is used as an example.

The user first needs to prepare the geometric models. 2D patterns for a skirt described by boundary curves are inputted as shown in Figure 4.4.

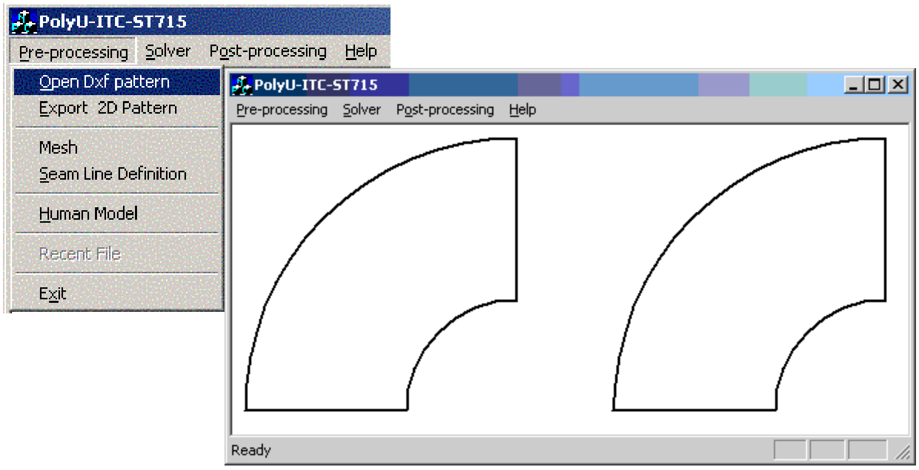
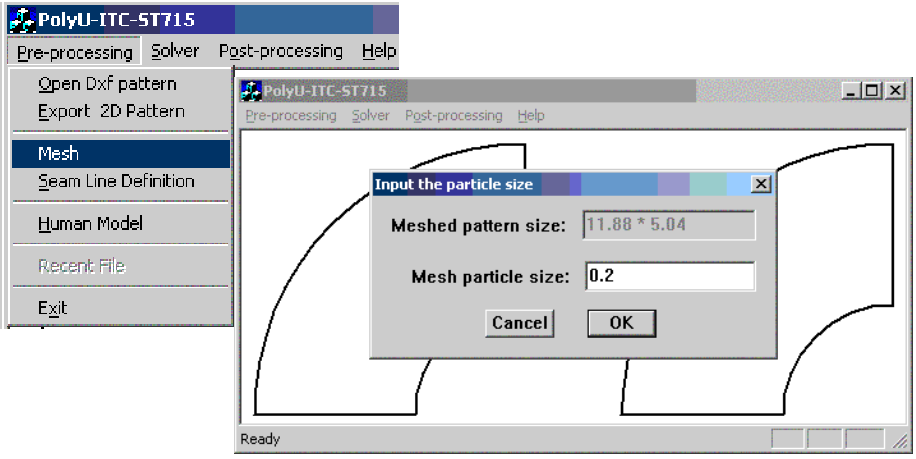


Figure 4.4 2D patterns

The patterns are then discretized by user defined mesh size. Figure 4.5 shows the quadrangular mesh size as defined by the user.



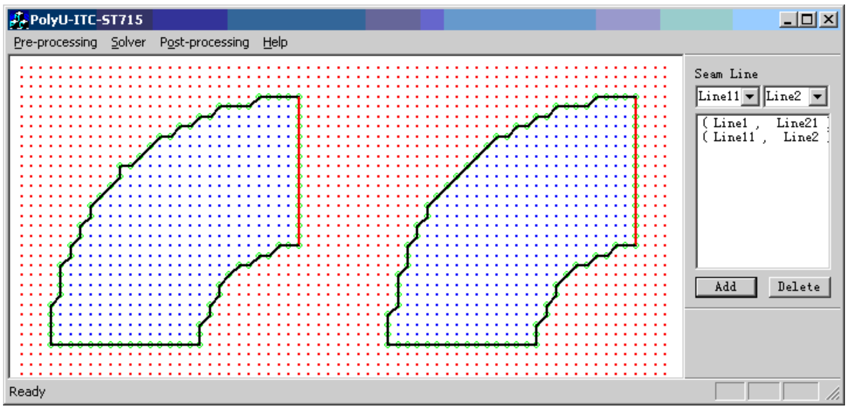
Meshed pattern size: 11.88 * 5.04

Mesh particle size: 0.2

Figure 4.5 Input mesh parameters

The user may input the mesh particle size here. According to the pattern size shown on the right side of “Mesh pattern size”(11.88*5.04), the mesh particle size might not be smaller than 1% of the Pattern’s width or height. The smaller the mesh particle size, the more calculations the system needs to carry out, and therefore the more time it takes.

After meshing, the points located within the boundary edges are recorded representing the cloth patterns for further simulation. Figure 4.6 shows the pairs of lines to be sewn together, defined as seam lines.

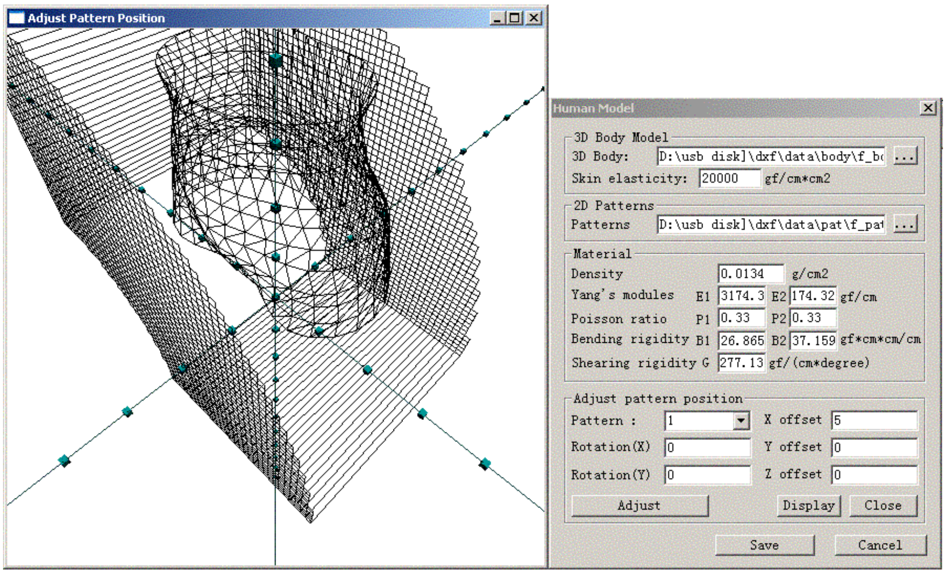


Seam Line
Line11 Line2

(Line1 , Line21
(Line11 , Line2

Figure 4.6 Mesh and seam line definition

Figure 4.7 shows the interactive interface to require for the preparation of the skirt simulation. The 2D meshed cloth patterns and the 3D body model need to be inputted first. In order to decrease the computational cost, only the waist, an abdomen and hip part of the human body in contact with the skirt is modeled. The body part is modeled as an elastic shell. The material parameters for both cloth and human body can be inputted from a database supporting the system. They can also be inputted and edited through the interface directly. Usually, the relative positions of the body and the patterns need to be adjusted properly. This positioning process can also be performed within this interface.



3D Body Model
3D Body: D:\usb disk]\dxf\data\body\f_b
Skin elasticity: 20000 gf/cm*cm2

2D Patterns
Patterns D:\usb disk]\dxf\data\pat\f_pa

Material
Density 0.0134 g/cm2
Yang's modules E1 3174.3 E2 174.32 gf/cm
Poisson ratio P1 0.33 P2 0.33
Bending rigidity B1 26.865 B2 37.159 gf*cm*cm/cm
Shearing rigidity G 277.13 gf/(cm*degree)

Adjust pattern position
Pattern : 1
X offset 5
Rotation(X) 0
Y offset 0
Rotation(Y) 0
Z offset 0

Figure 4.7 Interactive interface of pre-processing

Finally, the whole skirt construction system is ready for numerical calculation, as shown in Figure 4.8.

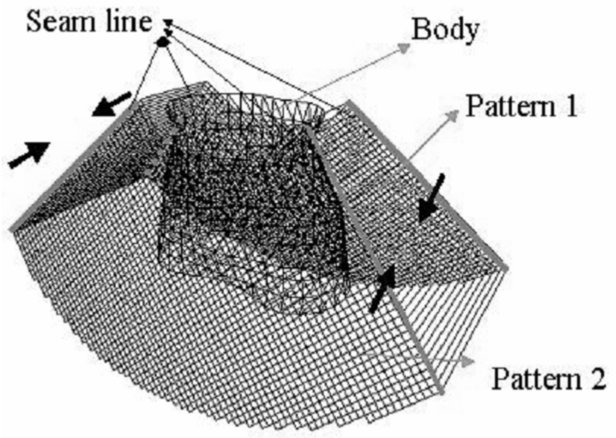
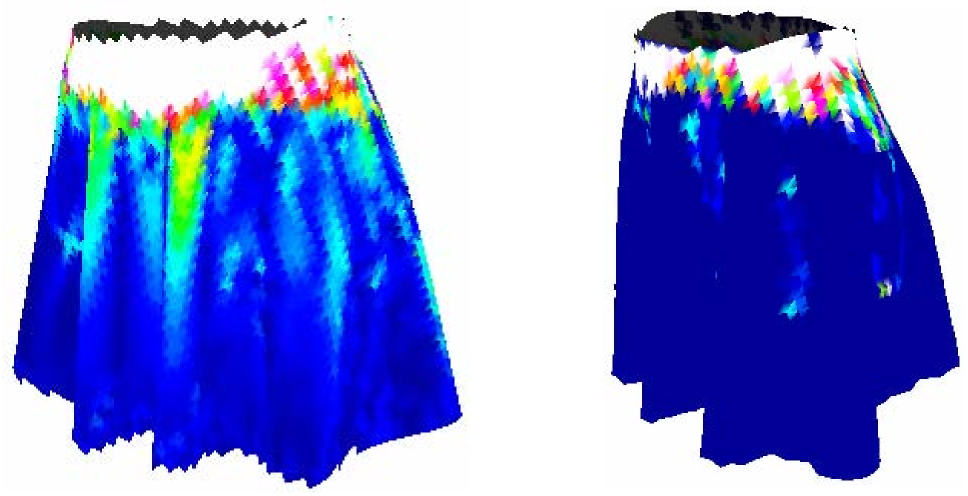


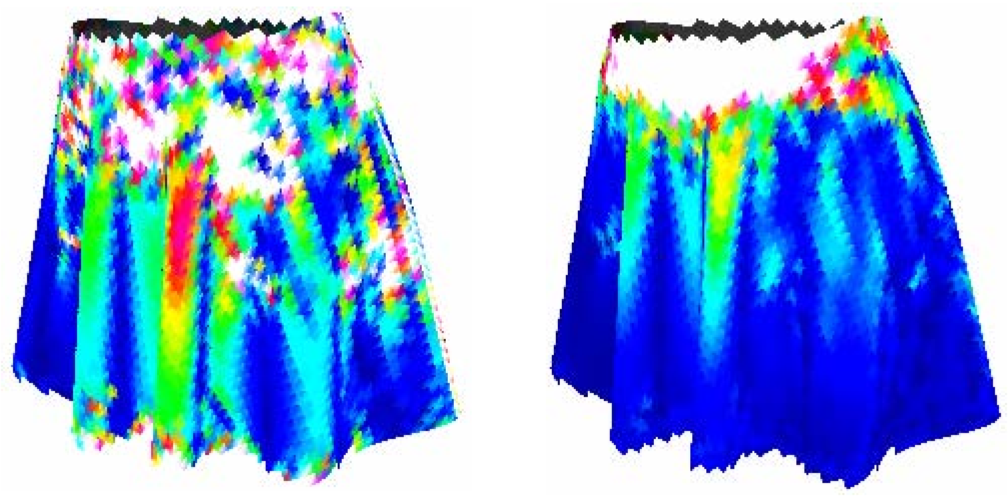
Figure 4.8 The position of the resulting of clothing and human body

With the numerical results of the mode, the mechanical performance analysis can be executed through the 3D virtual reality of the human body and clothing. Figure 4.9 shows the different mechanical performance results of the clothing.



(a) Tensile

(b) Pressure



(c)Bend

(d) Shearing

Figure 4.9 Mechanical performance of the clothing

From the Figure 4.9, it is clear that the tension/compression and shearing stress are distributed all over the specimen and that large shearing stress is concentrated where large bending stresses occur.

4.3 HYBRID MODELS

4.3.1 Methodology

Clothing simulation and garment animation raise diverse scientific questions: textile material properties, human body physiology characters, garment modeling, and simulation modeling. As mentioned above, the main textile physical properties (Young modulus, Poisson ratio, bending modulus and shearing modulus) and the human body physiology properties (Young's modulus and Poisson's ratio) are taken into account during the clothing biomechanical engineering design. The garment modeling is important during simulation. The traditional particle method describes the garment using distribution points, which interact with energy constraints or forces. The particle model is widely used to simulate the mechanical behavior of clothing during wear. The biggest advantage of this method is its simplicity However, instability and high cost remains a problem. The hybrid model combines the particle model and geometrical model together to their mutual benefit. The geometrical technique is used to determine the rough shape of the clothing, and then the particle technique is used to simulate the mechanical behavior of the clothing. In the following section, the software system developed using the hybrid model (M-Smart for short) is presented. The main process of this system is shown in Figure 4.10.

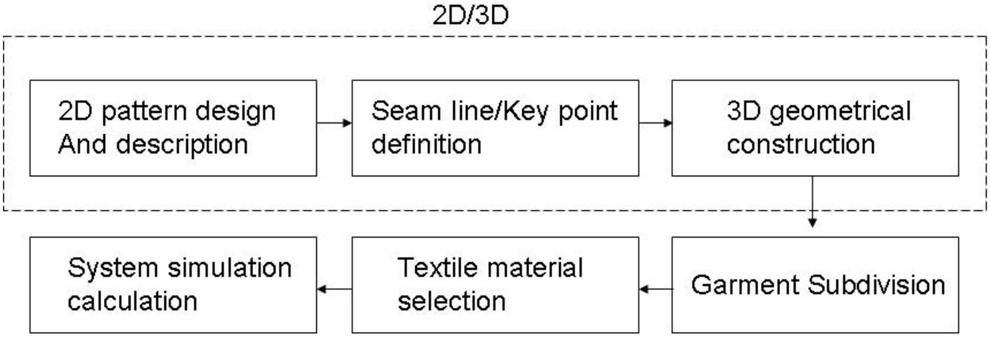


Figure 4.10 The Process using the hybrid model

In the Figure 4.10, the first component is the 2D pattern design. The 2D patterns can be described in different file formats. The description of the geometrical models must be accurate enough to capture all the characteristics of the geometry, while minimizing the total amount of geometrical data to be handled. Normally, the graphic formats, such as “iges”, “dxf”, “sat”, “3ds”, and so on, can be used to describe the 2D patterns. On the other hand, special formats defined by the designer can be used too, permitting the performance of these formats to be transformed into different forms. In M-Smart, the 2D patterns are described through points, lines, and curves. Figure 4.11 shows the 2D pattern description.

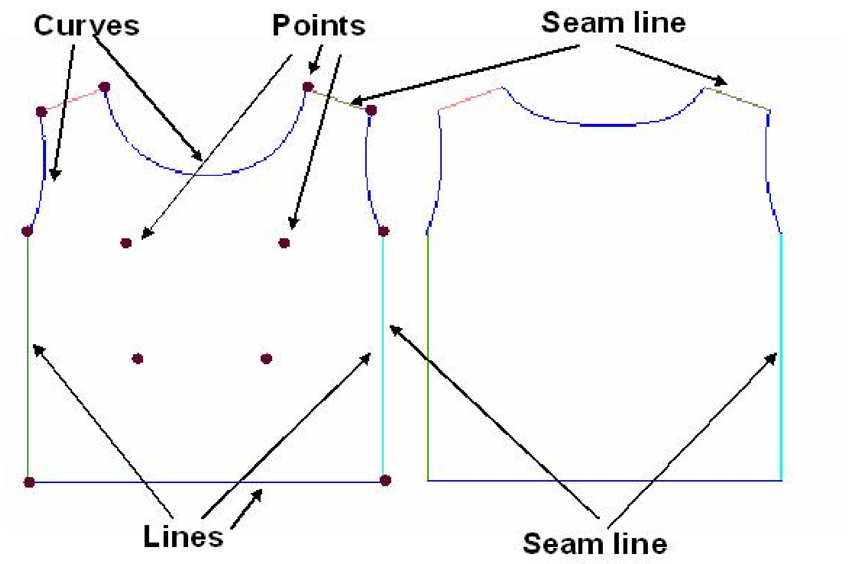


Figure 4.11 2D pattern description

The detail definitions of point, line, and curve are shown in Table 4.4.

Table 4.4 Description of point, line, and curve

Point	Point position (x,y)
	Flag (To describe the character of a point)
	Point Index
Line	Start Point(sx,sy), End Point (ex,ey)
	Flag (To describe the character of a line)
Curve	Set of Point P0 (x0,y0),P1(x1,y1),…,Pn(xn,yn)
	Flag (To describe the character of a curve)

The curve is constructed using a spline curve. For set of point, let $\Delta t : t_0 < t_1 < \dots t_{n-1} < t_n$, $t_{i-\frac{1}{2}} = \frac{t_{i-1} + t_i}{2}(i = 1,\dots,n), t_{-\frac{1}{2}} = t_0, t_{n-\frac{1}{2}} = t_n$, then the curve can be described as follows:

$$\begin{cases} P(t) = P_i + m_i(t - t_i) + \frac{1}{2} M_i (t - t_i)^2, \\ t \in \left[t_{i-\frac{1}{2}}, t_{i+\frac{1}{2}} \right], i = 0,1,\ldots,n \end{cases} \tag{4.1}$$

Here, the curve obtains (4.2) and (4.3).

$$P^{(k)}(t_{i-\frac{1}{2}} - 0) = P^{(k)}(t_{i-\frac{1}{2}} + 0), k = 0,1 \tag{4.2}$$

$$P(t_i) = P_i, i = 0,1,\ldots,n \tag{4.3}$$

The m_i, M_i can be obtained from the following formulas:

$$\mu_i m_{i-1} + 3m_i + \lambda_i m_{i+1} = C_i, i = 1,2,\ldots,n-1,$$

$$\begin{cases} C_i = 4\left(\mu_i \frac{P_i - P_{i-1}}{l_i} + \lambda \frac{P_{i+1} - P_i}{l_{i+1}} \right), \\ \mu_i = \frac{l_{i+1}}{l_i + l_{i+1}}, \lambda_i = \frac{l_i}{l_i + l_{i+1}}, \end{cases} \quad i = 1,2,\ldots,n-1$$

$$\begin{cases} M_{i-1} = \frac{4(P_i - P_{i-1})}{l_i^2} - \frac{3m_{i-1} + m_i}{l_i}. \\ M_i = -\frac{4(P_i - P_{i-1})}{l_i^2} + \frac{3m_i + m_{i-1}}{l_i}. \end{cases} \quad i = 1,2,\ldots,n$$

The seam line/key point can be defined interactively. Then, the 3D garment can be roughly constructed using the method discussed in section 4.3.1. Using the subdivision technique [59], the rough shape can then be meshed in detail. The simulation processing is based on the particle model.

4.3.2 System introduction

4.3.2.1 3D garment building from 2D patterns

Building a garment involves several steps: a) the definition of 2D patterns, b) the definition of key points, and c) the geometrical modeling of the 3D garment. The 2D patterns are represented by a geometrical format. The information in the 2D patterns includes close borderline and characteristic points on the patterns. The software, M-smart, can generate the 2D patterns from commercial software as the 2D patterns can be saved in commonly used graphic formats, such as "iges", "dxf", and so on. Figure 4.12 shows a 3D rough garment shape constructed using the geometrical method.

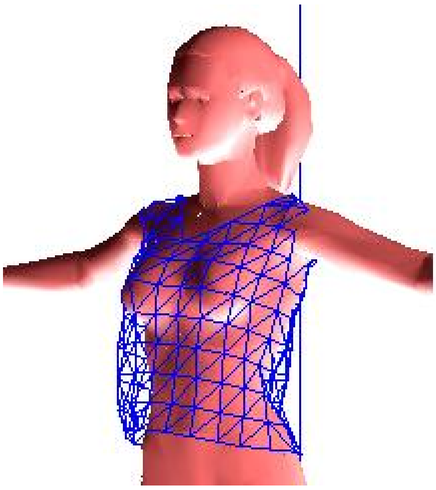
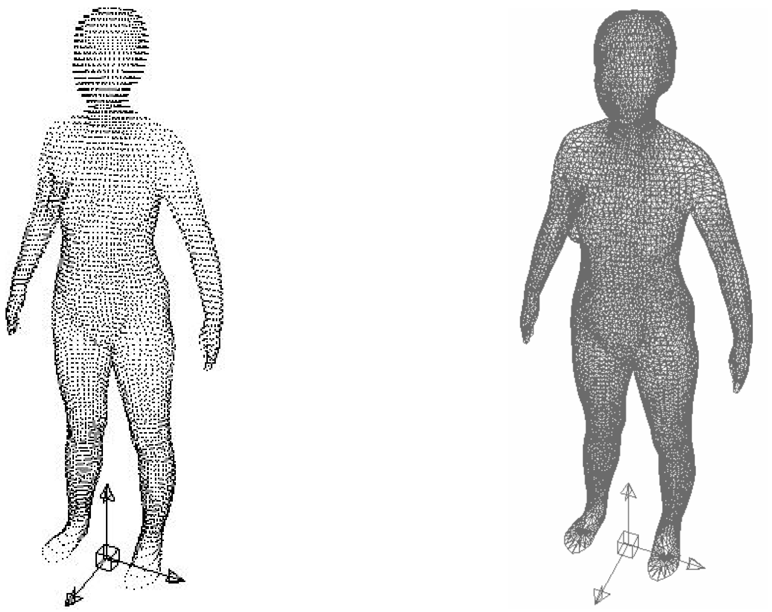


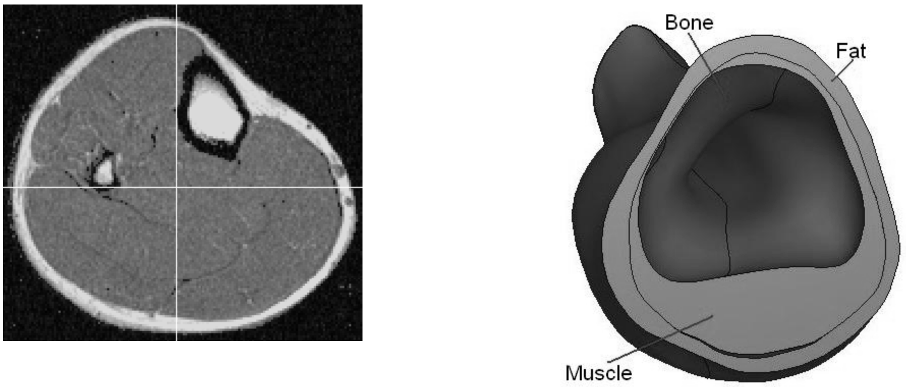
Figure 4.12 3D garment shape

4.3.2.2 Human body modeling

There are two main ways of obtaining the geometry of a human body: using 3-D body scanners to obtain a surface shape (Figure 4.13(a)) or using a CT or MRI scanner to obtain a solid result (Figure 4.13 (b)). The first approach gives information on the position of discrete points on the body surface, and these can often be reconstructed using a mathematical surface description, or remain as a discrete description of points, or a triangle or a rectangular patch. Computerized Tomography (CT) (Figure 4.13 (c)) or Magnetic Resonance Imaging (MRI) (Figure 4.13 (d)) images contain more information about inner body details. These images usually allow for the construction of more complicated 3-D body models consisting of several layers, such as bone, muscle, fat and skin. The models can be constructed by using 3-D image processing software such as “MIMICS” (Materilise, Leuven, Belgium). These models, which describe the surfaces of the objects, are shells rather than solids. In biomechanical engineering design, a solid human body is often preferred. The shell models can be converted to solid models by using software such as “Solidworks” (SolidWorks Corporation, Massachusetts).



(a) 3-D scanner data (b) Body surface



(c) MRI image (d) Leg model (top view)

Figure 4.13 Human body modeling adopted from Y. Li,X-Q. Dai, Biomechanical engineering of textiles and clothing, Woodhead publishing limited, Cambridge CB1 6AH, England, 2006

In order to develop 3D clothing software, the human body model required can be generated from commercial software. Here, a human model from Poser software is used. The original model has a large number of data. In order to simulate processing efficiently, this model needs to be simplified. Figure 4.14 shows a human model from Poser.

Figure 4.14 Human body

The human model used in the M-smart includes 4999 pieces of triangular data and 3316 points. The data format of the human model is described as follows:

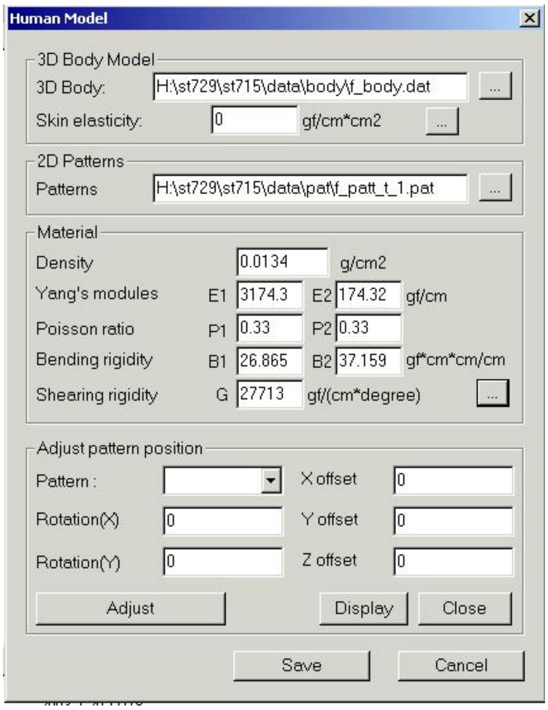
```
begin
v 0 0.422534 -0.021712
v 0.00146684 0.39776 -0.0296696
v -0.00284398 0.404315 -0.0273545
v -4.53292e-005 0.387419 -0.0304181
…….
v -0.00092067 0.690648 -0.0536258
f 172 183 173
f 82 69 83
f 49 68 39
……
f 3293 3308 3306
```

```
end
```

Here, *v* is the tag of the point, *f* is the tag of the triangular. For examples, “*v* 0 0.422534 -0.021712” means the point coordinates are x=0, y = 0.422534, and z = -0.021712, “*f* 172 183 173” means the points coordinates of the triangular is 172,183,173.

4.3.2.3 Material properties

In order to proceed to a mechanical simulation of an object, its mechanical behavior must be described by relevant mechanical parameters and expressed as a set of relations between the geometrical and mechanical values of the object which can be easily manipulated. For clothes at different levels, the major elasticity parameters include the Young modulus, the Poisson ratio, the bending modulus and the shearing modulus. For the human body, we can simplify the parameters to Young’s modulus and Poisson’s ratio. For a dynamic simulation, the mass density of the object is also necessary. To address the non-linearity of the mechanical properties, various stress-strain curves can be approximated by a piece-wise linear expression, polynomials or tables of test data. All these data can be obtained from the database, where a large amount of material data should be stored. Figure 4.15 shows the material properties used in this software.



3D Body: H:\st729\st715\data\body\f_body.dat

Skin elasticity: 0 gf/cm*cm2

Patterns H:\st729\st715\data\pat\f_patt_t_1.pat

Density 0.0134 g/cm2

Yang's modules E1 3174.3 E2 174.32 gf/cm

Poisson ratio P1 0.33 P2 0.33

Bending rigidity B1 26.865 B2 37.159 gf*cm*cm/cm

Shearing rigidity G 27713 gf/(cm*degree)

Pattern :

X offset 0

Rotation(X) 0

Y offset 0

Rotation(Y) 0

Z offset 0

Figure 4.15 Material properties

4.3.3 Simulation scheme

In the real world, deformable surfaces are rarely left to move unhindered. A garment does not exist in isolation, nor float in the air. It interacts with objects in the environment, in most instances either with the body wearing it or other garment pieces. Modeling and simulating these interactions is essential for realistic simulation. A garment takes the shape of the body that wears it and follows its movements not only through its elastic behavior, but also by its contact with the body. The aim of collision detection procedures is to compute the geometrical interactions between objects and to perform this task efficiently whatever the number and complexity of the objects may be. Various writers, [2], [88] [86], have presented a method to solve the collision detection and responses.

To implement the mechanical simulation, the behavioral laws of the material must be combined with mechanical laws. This yields complex systems of equations, usually ordinary or partial differential equations. The equation system needs to be solved under the boundary conditions denoting various constraints.

The numerical solution needs to discrete the objects in the space domain, and maybe the time domain for dynamic cases. Space division can either be accomplished through numerical solution techniques, or on the mechanical model itself. Depending on the method of the discretization, there are two major schemes for performing a mechanical simulation: continuum mechanical models and discrete models.

Using continuum mechanical models, an object is considered as a continuum, and mechanical laws are represented as a set of partial differential equations defined throughout the volume of the material. Numerical resolution for the equations then requires discretization of the equations in the volume space. Finite difference, and finite elements are common methods used for the numerical solutions. The finite element method is the most powerful and widely used today.

The mechanical behavior of the material is expressed as the local deformation energy related to material properties at any point (r) on the object. Various mechanical deformation energies are integrated at this point as its internal energy

$\varepsilon(r)$. The equation system is then solved numerically using discretization over the whole object. Usually a regular grid is defined over the object.

Using discrete models, the object is discretized as a set of points with a mass (particles), which interacts with a set of “forces”, or energy constraints, to model the mechanical behavior of the material. Breen reported that fabric represent the micro-mechanical structure of a fabric via a particle system. This model is based on the observation that a fabric is best described as a mechanism of interacting mechanical parts rather than a continuous substance, and derives its macro-scale dynamic properties from the micro-mechanical interaction between threads.

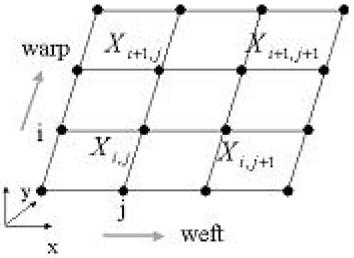


Figure 4.16 Particle representation

The particle model represents a fabric sheet by using particle meshes, as illustrated in Figure 4.16, where $X_{i,j}$ with three components ($x_{i,j}, y_{i,j}, z_{i,j}$) denotes the 3-dimentional position of a particle. The mass of each particle is the mass of the particle’s local regular area and its strain energy represents the aggregate of the strain energies in the local area. Nevertheless, the particle grid still preserves the underlying woven structure of the fabric, and the various inter-crossing strain energies are computed based on simple geometric relationships among local particle neighbors. The energy functions account for the four basic mechanical interactions of yarn compression, stretching, out-of-plane bending and trellising. The total energy for particle *i* is given by:

$$U_i = U_{repel_i} + U_{stretch_i} + U_{bend_i} + U_{trellis_i} + U_{gravity_i}$$

The energy function U_{repel_i}, prevents particles connected to particle *i* from approaching it, and the function $U_{stretch_i}$, capturing the energy of tensile strain between each particle and its four-connected neighbors, is given by generated approximation functions; the energy functions U_{bend_i} and $U_{trellis_i}$ are derived from Kawabata bending and shearing tests [45]. This particle-based approach was first applied to the problem of computing static drape. The simulation was in two stages. In the first stage, particles were allowed to fall freely. Any collision with the object or the ground was determined during this step. The particle positions can be obtained using the equation

$$ma + cv = mg$$

where *a* is the acceleration, *v* is the velocity, m is the mass, *c* is the air resistance, and *g* is the gravitational acceleration constant. The result is a rough shape of the draped fabric. In the second stage, an energy minimization process was applied to the inter-particle energy functions to generate fine detail in the shape of the fabric. The final equilibrium shape of the fabric occurs when there is minimum energy over the whole fabric.

A common way to numerically simulate a discrete model system is to directly integrate Newton's second law for a mass particle over all particles. The forces exerted on each particle include internal elasticity and viscosity forces, gravity, and various external constraints. These forces then determine the current mechanical state of the system, which is represented by the position and the speed of all the particles.

Figure 4.17 shows the deformation on the garment. Figure 4.18 shows the forces, which acted on the human body.

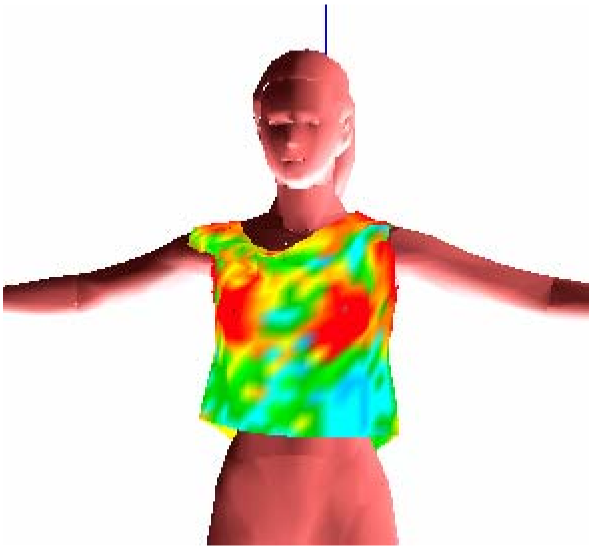


Figure 4.17 Clothing deformation

Figure 4.18 Forces on the human body

4.4 FINITE ELEMENTS

4.4.1 Functions description

The finite element method is a numerical procedure for obtaining solutions to many of the problems encountered in engineering analysis. It has two primary subdivisions [76]. The first utilizes discrete elements to obtain the joint displacements and member forces of a structural framework. The second uses the continuum elements to obtain approximate solutions to the problems of heat transfer, fluid mechanics, and solid mechanics.

The finite element method combines several mathematical concepts to produce a system of linear or nonlinear equations. The number of equations is usually very large. The method has little practical value if a computer is not available. The finite element method is the computational basis of many computer assisted design programs. Some commercial software packages have been developed using the finite element method. These commercial Finite Element (FE) software packages are convenient tools to carry out mechanical analysis [21]. Integrating FE software such as LS-DYNA (Livermore Software Technology Corporation) [29], ANSYS (Ansys Inc., USA) [18], ABAQUS (Hibbitt, Karlsson & Sorensen Inc., USA) [1], into the clothing biomechanical engineering system is an effective way to construct the mechanical simulation system.

The biomechanical engineering of clothing design involves clothing deformation and human body deformation. In particular, the researcher wants to simulate the biomechanical performances of the clothing to predict the human body physiology and psychology comfort performance. The M-smart software can simulate the biomechanical performance of the clothing and then the biomechanical performances of the human body can be simulated by a commercial software package. Here, the software ‘Ansys’ has been used for this purpose. The key problem to be researched was how to combine these two software packages. The core technology required the programming and the data transfer between the software packages. The analysis flow using Ansys to simulate the human body biomechanical performance is shown in Figure 4.19.

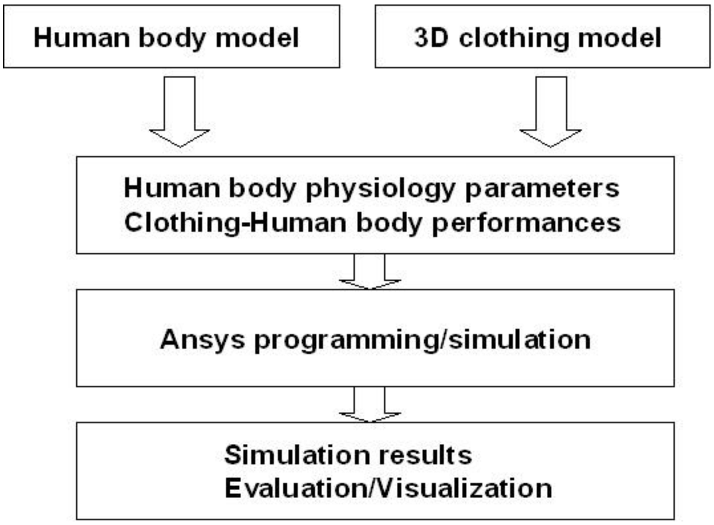


Figure 4.19 Analysis flow in the Ansys software package

Using the software M-smart, information regarding the clothing deformation can be obtained, as well as information regarding the forces acting on the human body.

As the aim of clothing is to cover the human body, then the body model is necessary in clothing simulation. The human body is supported by bone and is separated from the external environment by the skin. The movement of the human body is accomplished by the contraction of skeletal muscles acting within a system of levers and pulleys formed by bones, tendons, and ligament [69]. When the body is subject to a small external force when wearing, a garment, then the bone can be considered as a stiff material without deformation, and the skin with elastic deformation. The soft tissue that consists of the adipose tissue and the skeletal muscles when passive can be regarded in the same way as compressed rubber. Therefore, in the simulation of biomechanical human body models, the human body is assumed to have skin, soft tissue and bone. Based on the analysis of the biomechanical characteristics of the human body, a series of biomechanical human models has been developed. In order to increase the simulation speed, in this chapter, the human model is a simplex object.

4.4.2 Simulation flow chart

In order to simulate the human body biomechanical performance using Ansys software, the first step is to create the finite element algorithm flow. Figure 4.20 shows the main steps in the algorithm.

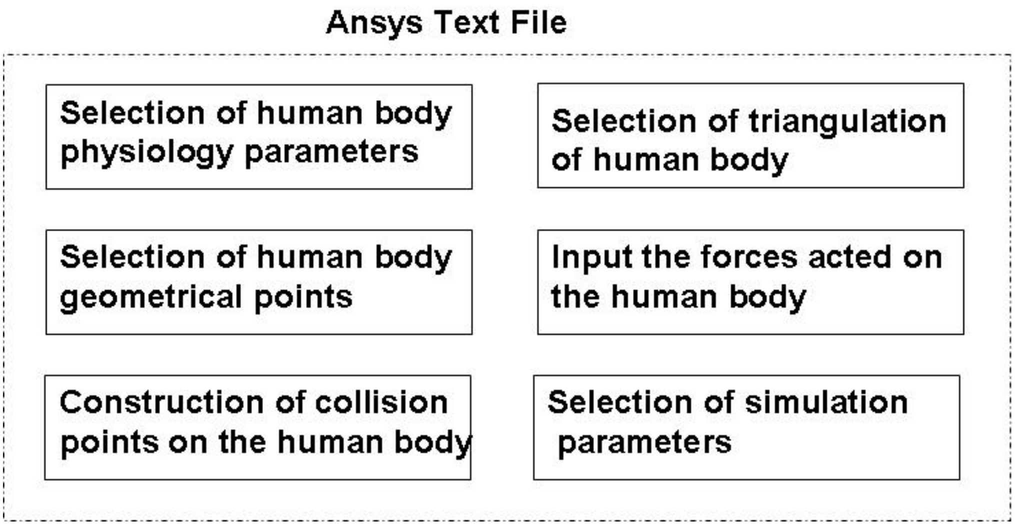


Figure 4.20 Algorithm of finite element

Here is the sample of the Ansys Text File.

```
/PREP7
!Definition of parameters
```

```
et,1,shell63
mp,ex,1,2.05e-2!modulue N/cmˆ2
r,1,6,6,6,6,40
!Key points on the human body
k,1,75.390,100.251,15.540
k,2,75.734,94.429,13.670
k,3,74.721,95.969,14.214
……
k,3386,59.325,136.310,20.564
k,3387,61.043,137.209,19.982

!Definition of triangular
a,172,183,173
a,82,69,83
a,49,68,39
……
a,3293,3308,3306

!Forces acted on the human body
fk,3317,fx,2.378
fk,3317,fy,0.632
fk,3317,fz,-0.159
……
!Mesh definition
esize,,1
mshape,1,2d
MSHKEY,0
```

Figure 4.21 shows the human body and the forces on it, in the Ansys environment.

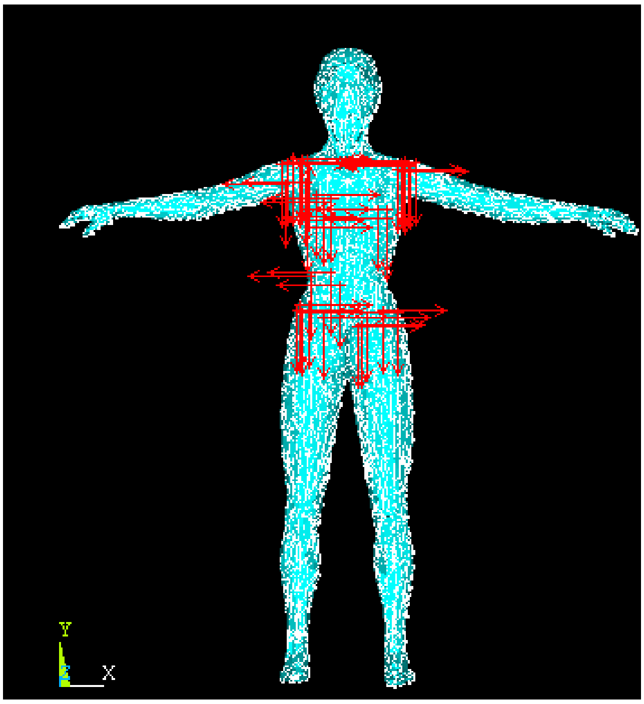
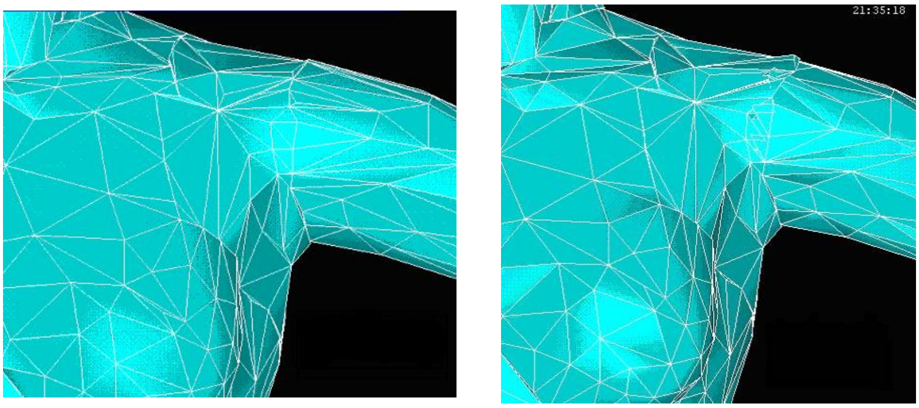


Figure 4.21 Human body showing the forces

4.4.3 Results

Using the Ansys program, the human body deformation can be obtained. Figure 4.22 shows the human body deformation. Figure 4.22 (a) is the original body. Figure 4.22 (b) shows the deformation body.



(a) Original body (b) Deformation body

Figure 4.22 The human body

Analysis of the simulation results shows that the maximum deformation position in *x* and *z* direction is node 1151. In *y* direction, the node is 452.

```
 ***** POST1 NODAL DEGREE OF FREEDOM LISTING *****
  THE FOLLOWING DEGREE OF FREEDOM RESULTS ARE IN GLOBAL COORDINATES
   NODE       UX            UY            UZ            USUM
   1151   0.14822E-02 0.17681E-03 0.88863E-03 0.17372E-02
   1152   0.97184E-03 0.23932E-03 0.45338E-03 0.10988E-02
   1694 -0.10168E-02 0.32514E-03-0.13787E-03 0.10764E-02
   ......
   3354    0.0000        0.0000        0.0000        0.0000
   MAXIMUM ABSOLUTE VALUES
   NODE        1151          452          1151          1151
   VALUE    0.14822E-02-0.98007E-03 0.88863E-03 0.17372E-02
```

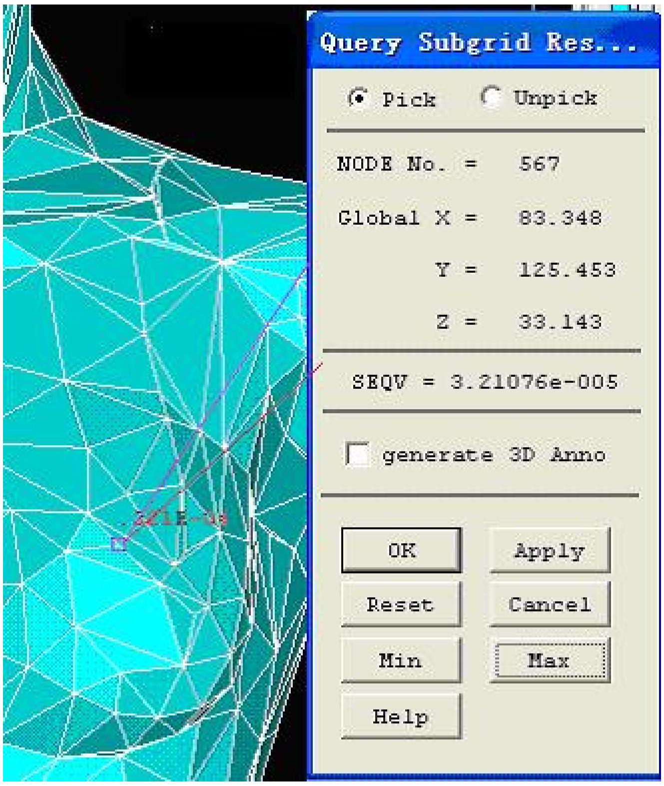
The stress of node is shown as follows:

```
    PRINT S    NODAL SOLUTION PER NODE
    ***** POST1 NODAL STRESS LISTING *****
    SHELL NODAL RESULTS ARE AT TOP

    NODE     S1            S2            S3            SINT          SEQV
    1151          0.31641E-13-0.65500E-06-0.14692E-05      0.14692E-05
0.12749E-05
    1152        0.64755E-05     0.64719E-07-0.21309E-05     0.86063E-05
0.77456E-05
    1694          0.19002E-11-0.32529E-05-0.45117E-05      0.45117E-05
```

```
0.40325E-05
     452      -0.15152E-11-0.23058E-04-0.32057E-04      0.32057E-04
0.28638E-04
     ......
    3354    0.0000        0.0000        0.0000        0.0000        0.0000
 MINIMUM VALUES
 NODE        1146          452           549           685           685
 VALUE   -0.25991E-06-0.23058E-04-0.33844E-04  0.0000        0.0000
 MAXIMUM VALUES
 NODE         567          389          1630           567           567
 VALUE          0.28321E-04   0.95594E-05   0.59702E-06   0.34880E-04
0.32108E-04
```

Figure 4.23 shows the maximum stress position on the human body.



● Pick ○ Unpick

NODE No. = 567

Global X = 83.348

Y = 125.453

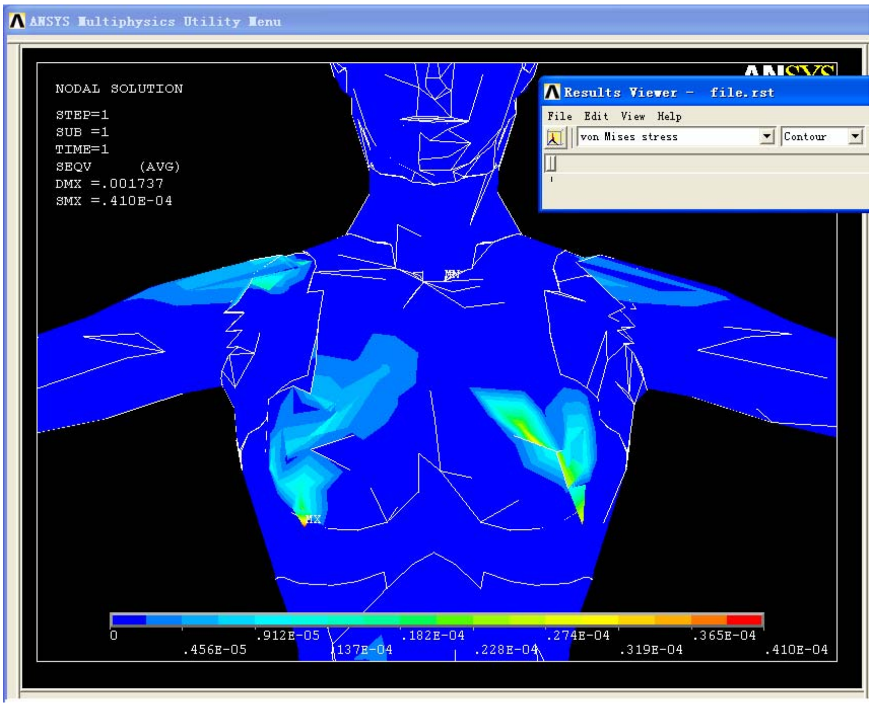
Z = 33.143

SEQV = 3.21076e-005

☐ generate 3D Anno

Figure 4.23 The maximum stress position on the human body

Figure 4.24 shows the mean stress picture from the front of the human body.



```
NODAL SOLUTION

STEP=1
SUB =1
TIME=1
SEQV      (AVG)
DMX =.001737
SMX =.410E-04
```

von Mises stress

Contour

Figure 4.24 The mean stress picture from the front of the human body

4.5 CONCLUSION

In this chapter, the clothing biomechanical engineering design software method is presented. The software systems for biomechanical engineering of clothing design are based on a series of fundamental works. The main methods include an improved particle method for the textile mechanical design, the hybrid method for 3D clothing modeling and mechanical simulation, and the finite element mixed with a hybrid method for human body physiology performance simulation. The software methods cover four major aspects: (1) the consideration of human factors in the engineering design of clothing products; (2) the simulation and visualization of the wearing performance of clothing and human body deformation; (3) combination with a commercial software package to simulate the human body biomechanical performance; (4) a core with an engineering design database to input, store and display the information during the design process. The software has been developed using computer language; it can be used to predict the biomechanical performance of the clothing and the human body.

CHAPTER 5 PRESSURE SENSORY MODELING

5.1 INTRODUCTION

Biomechanical engineering design for textile and clothing products is a typical kind of human-clothing engineering, in which human body interacts dynamically with a garment on large areas of contact surface. In biomechanical simulation, the main results are garment pressure distributions, deformations, stresses and stains in human body. Designers and/or engineers need to know whether the garments they designed are comfortable to wear or not, which can be achieved by investigating and evaluating the quantitative relationships between the skin pressures induced by garments and pressure comfort sensations. As discussed in previous chapters, pressure sensations can predict the perception of pressure comfort during wear. The numerical simulation models in Chapter 4 can generate garment deformation, tensile, shearing and bending forces distributed in the garment and skin pressure distributions on the body. This simulation result shows that different fabric can generate different garment deformation and different skin pressure distribution on human body.

There are three factors influencing the pressure exerted by garments: 1) shape of the body parts, the greater the degree of curvature, the greater pressure exerted; 2) type of fabrics used; and 3) design and fit of the garment. A badly designed garment may lead to the body suffer by being subjected to unnecessary pressure.

In general, the investigations of pressure distribution on the human body can be classified into two categories: experimental and numerical. In the experimental category, it can be divided into psychological and physical aspects. Morooka et al [65] found that the perception of clothing pressure reported by females in their forties was twenty percent less than the pressure felt by females in their teens and twenties. Furthermore, the influence of leg circumference of the clothing pressure tended to become lower with increasing age. Zhang et al [103] carried out a series of investigations in relation to pressure by using a force-deformation of fabric bagging method, which can be described as a planar fabric forced to conform to a spherical surface. Mitsuno et al [64] used a hydrostatic pressure-balanced method to measure clothing pressure qualitatively. They found that subjects perceived pressure discomfort mainly on the front waist line and the thigh base. They also noticed that when clothing pressure reached more than 30 to 40 mmHg, subjects began to complain about the pressure discomfort.

Theoretical investigations have been carried out to develop an understanding of the mechanisms of pressure distribution by establishing mechanical-mathematical models on the basis of physical laws. The models can be worked out by numerical computation, which are then used for numerical simulation of wear process. In the numerical simulation, the 3D human body model is usually generated through a commercially available virtual human model or a scanned human body, and pressure distributions of a garment can be predicted on the basis of fabric properties. Zhang et al [104] investigate the dynamic interactions between the human body and garments in various wear situations, such as a bra and a pair of tight-fitting trousers, by considering the biomechanical structures of the human body, the contact mechanics between body, garment and 3D garment constructions.

Theoretical investigation of the influence of fabric mechanical properties on clothing dynamic pressure distribution and clothing pressure comfort has been studied extensively. It was found that the clothing pressure distribution varies from different garments with different fabric properties. Result also indicated that the clothing pressures at different body locations are significantly different, and can be predicted theoretically from fabric mechanical properties [92].

This chapter presents the development of model to predict pressure comfort from the skin pressures obtained through experiments and/or computer simulations. This model can transform the mechanical stimuli such as skin pressure to predict the pressure comfort perceptions.

5.2 DEVELOPMENT OF PRESSURE COMFORT MODEL

5.2.1 Perception of mechanical stimuli

Human skin is the interface between human body and external environment. It has a very complex sensory system to receive various skin stimuli, such as skin pressure. In human skin, there are many nerve endings as receptors, including corpuscular and non-corpuscular endings, to produce sensations of touch, warmth and/or pain [55]. For perception of mechanical stimuli, there are two groups of mechanoreceptors, including encapsulated receptors and receptors having an organized and distinctive morphology such as hair follicle receptors. Each mechanoreceptor has a distinctive range of properties that enable it receive and respond to particular parameter of mechanical stimuli. The neural signals from the nerve endings are passed to the somatosensory cortex of the brain to formulate sensations through neural pathways. There is a regular relationship between where a stimulus is applied to the skin and where neural activity occurs in the somosensory cortex, as shown in Figure 5.1 [55].

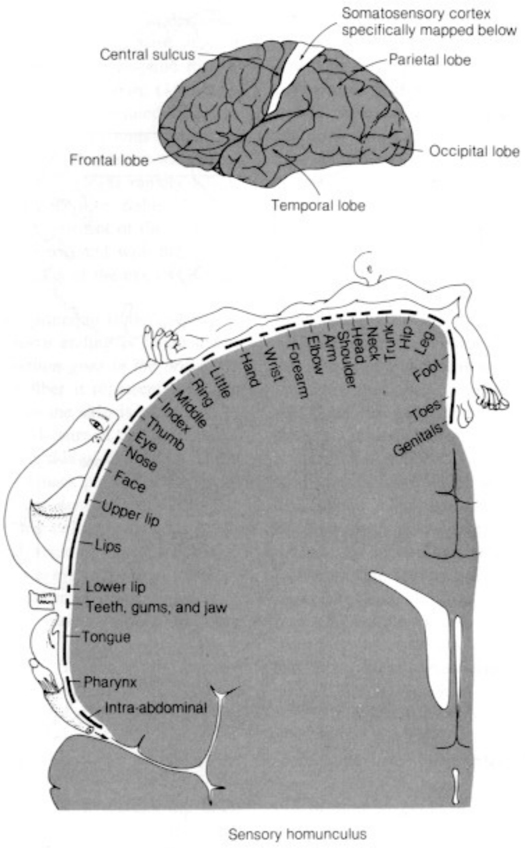


Figure 5.1 Renfield and Rasmussen's topographic map adopted from S.Coren, L.M. Ward. Sensation and perception, Harcourt Brace Jovanovich, New York, NY,USA, 1989.

As a point on the cortex was stimulated, the patients pointed out where they felt the sensation. This finding shows that pressure sensation is perceived at different body location individually, depending on the intensity of the mechanical stimuli and the sensitivity of the nerve endings at a specific location. This was confirmed by experimental study.

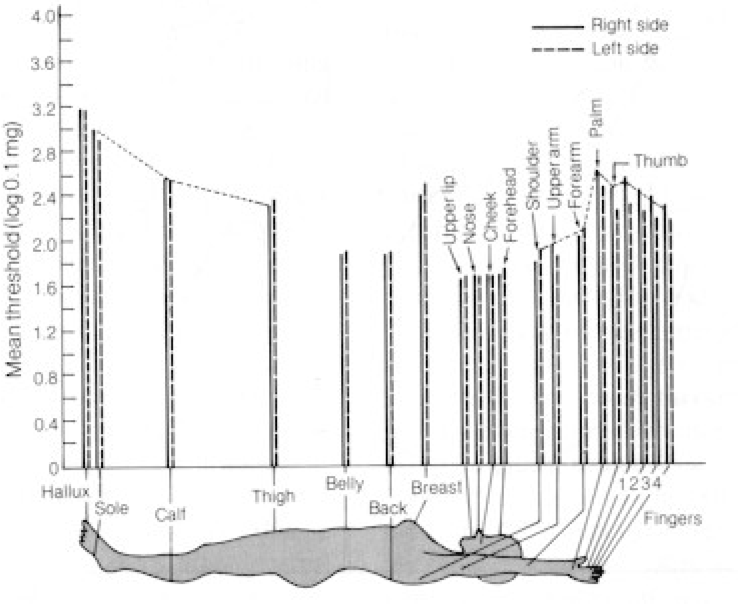


Figure 5.2 Average absolute thresholds for different regions of the female skin adopted from S.Coren, L.M. Ward. Sensation and perception, Harcourt Brace Jovanovich, New York, NY,USA, 1989.

As shown in Figure 5.2 the absolute threshold of pressure sensations on a female skin surface varies significantly at different body locations. The threshold of touch sensation depends on both frequency and force of the mechanical stimulus. Each pressure sensation located at a particular place on the skin is directly related to the amount of neural presentation in the touch cortex [74]. In the process of fabric-skin contact and mechanical interaction during wear, clothing exerts pressure and dynamic mechanical stimuli to the skin, which will in turn trigger various mechanoreceptors and generate a variety of touch sensations.

The overall perception of the pressure comfort is dependent on the individual pressure sensations perceived. The brain receives neural signals and interprets them into individual pressure sensations, evaluates and weighs them to formulate a subjective perception of overall pressure comfort. The biomechanical simulation model reported in Chapter 4 produces quantitative skin pressure values from the mechanical interaction between human body and clothing during wear. The mechanical interaction induces two pressure components: the pressure to the skin by the garment deformation and the pressure to internal tissues/organs due to the skin deformation, which determine the perception of pressure sensations. Due to the difficulty in measuring the neural signals of the mechanoreceptors and how the brain cortex formulates pressure sensations from the neural signals, psychophysical relationships are normally used to estimate how pressure sensations are derived from skin pressure stimuli.

5.2.2 Psychophysical relationships between skin pressure and pressure sensations

During wear, clothing establishes extensive contact with the skin of various parts of the body. Li [55] pointed out that the contact has three features: (1) large areas of contact with varying sensitivity; (2) changing physiological parameters of the body (such as skin temperature, sweating rate, and humidity at the skin surface); (3) a moving body that induces new mechanical stimuli from the contact between the body parts and clothing. The mechanical stimuli in turn induce responses from various sensory receptors and formulate various perceptions, such as touch, pressure, prickle, itch and inflammation, which affect the pressure comfort of the wearer.

The data derived from a wear trial experiment reported by Wong [92] [93] are used to compare the predictions on skin pressure and to establish quantitative relationship between skin pressure and psychological pressure sensations. The experiment was conducted to investigate the effect of garments made of different fabrics on psychological pressure sensations and pressure distributions when wearing in tight-fitting garments [34]. Skin pressures and pressure sensations were measured at nine different locations on the body, including chest, side lats, waist (front, side and back) side pelvis and thigh (front, side and back), as shown in Figure 5.3. A skin sensitivity index at different body locations was defined as the ratio of psychological sensation and skin pressure distributions for each body location.

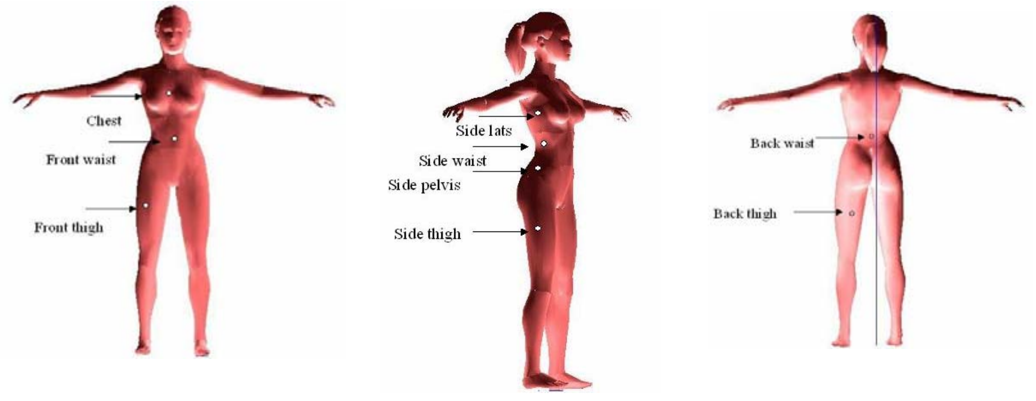


Figure 5.3 Locations of skin pressure on human body

Eight garments made in different fabric are used in the experiment. Table 5.1 shows the basic structural properties of the eight fabrics. Tables 5.2 show the mechanical properties of the eight fabrics.

Table 5.1 Basic structural properties of the eight fabrics

Fabric code	Average weight (g/m^2)	Average thickness (mm)	Fabric content
N88P	280.0	0.84	88% polyester & 12% spandex
C98L2	179.0	0.73	98% cotton & 2% spandex
N85L15	215.0	0.57	85% nylon & 15% spandex
R95C	260.0	1.10	95% cotton & 5% spandex
P98L2	220.0	1.27	98% polyester & 2% spandex
E95C	240.0	1.01	95% cotton & 5% spandex
A92Np	360.0	1.12	92% nylon & 8% spandex
N95C	410.0	1.50	94% cotton & 6% spandex

Table 5.2 Mechanical properties of the eight fabrics

	Fabric							
Symbol	**N88P**	**C98L2**	**N85L15**	**R95C**	**P98L2**	**E95C**	**A92Np**	**N95C**
LC	0.43±	0.29±	0.51±	0.032±	0.58±	0.32±	0.45±	0.36±
	(0.03)	(0.02)	(0.06)	(0.01)	(0.05)	(0.01)	(0.01)	(0.02)
WC	0.22±	0.26±	0.12±	0.29±	0.37±	0.42±	0.24±	0.41±
	(0.00)	(0.01)	(0.01)	(0.19)	(0.02)	(0.01)	(0.02)	(0.02)
RC	59.60±	49.28±	75.14±	44.47±	46.04±	40.79±	44.85±	37.26±
	(2.82)	(1.44)	(6.40)	(1.27)	(1.31)	(0.92)	(0.95)	(1.42)
B	0.03±	0.03±	0.02±	0.05±	0.04±	0.03±	0.08±	0.20±
	(0.01)	(0.00)	(0.00)	(0.02)	(0.04)	(0.00)	(0.01)	(0.15)
2HB	0.06±	0.03±	0.04±	0.07±	0.06±	0.05±	0.17±	0.23±
	(0.01)	(0.01)	(0.01)	(0.03)	(0.04)	(0.00)	(0.02)	(0.15)
G	0.76±	0.77±	0.66±	0.77±	0.46±	0.52±	1.26±	1.08±
	(0.03)	(0.02)	(0.13)	(0.03)	(0.10)	(0.02)	(0.05)	(0.06)
2HG	2.09±	2.21±	1.57±	1.77±	1.47±	1.42±	4.79±	3.18±
	(0.20)	(0.14)	(0.50)	(0.14)	(0.18)	(0.12)	(0.13)	(0.16)
2HG5	2.28±	2.47±	1.70±	1.89±	1.57±	1.49±	4.96±	3.50±
	(0.26)	(0.22)	(0.50)	(0.13)	(0.19)	(0.10)	(0.13)	(0.17)
LT	1.09±	0.83±	1.00±	0.96±	0.78±	1.05±	1.14±	1.01±
	(0.04)	(0.15)	(0.11)	(0.10)	(0.11)	(0.02)	(0.03)	(0.04)
WT	11.01±	3.76±	10.02±	9.13±	6.28±	13.36±	8.79±	8.18±
	(1.06)	(1.62)	(8.26)	(4.27)	(1.58)	(0.59)	(0.89)	(5.37)
RT	72.47±	57.26±	72.89±	56.01±	54.02±	65.32±	60.10±	51.31±
	(2.75)	(12.17)	(17.77)	(2.93)	(15.10)	(2.02)	(6.02)	(1.46)

Figure 5.4 shows the mean skin pressure measured on the nine body locations. Wong [92] reported that pressure sensation was not uniformly distributed at different locations of the body. Greatest pressure was perceived at side waist for all postures except curling-up, in which greatest pressure was perceived at front waist. The result showed that skin pressure sensitivity varies from one body location to another.

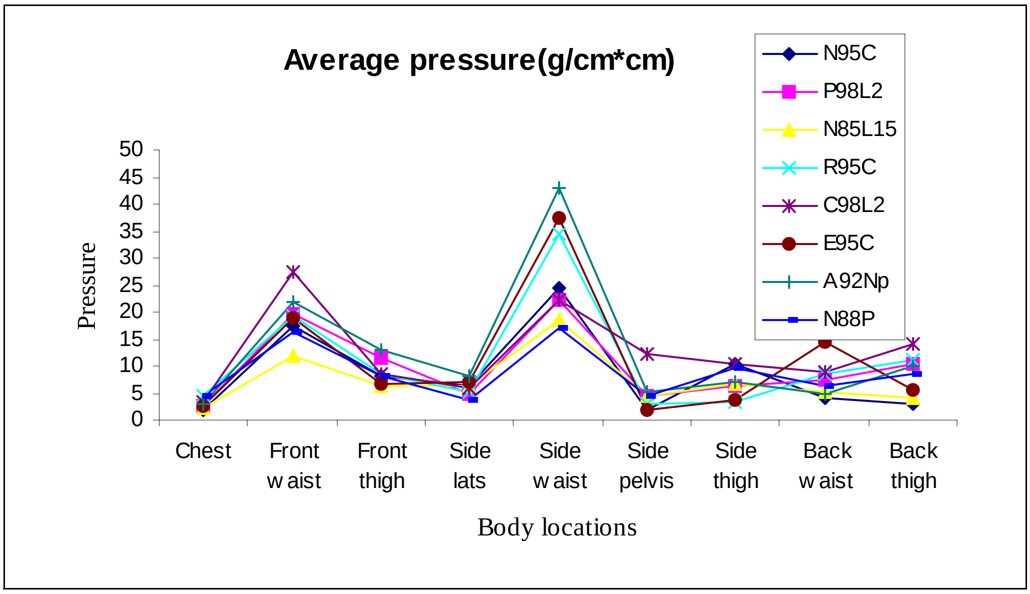
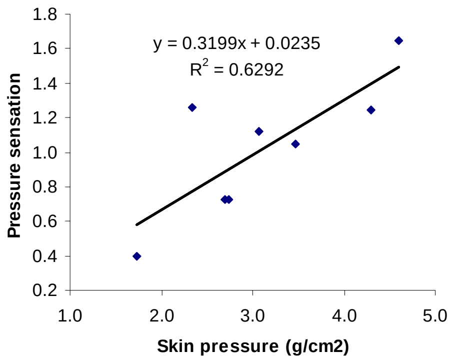
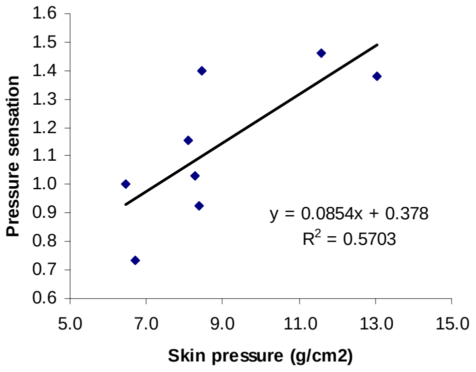
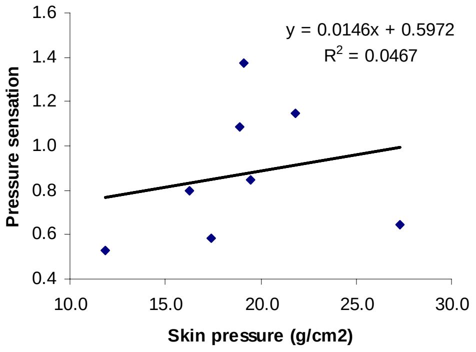


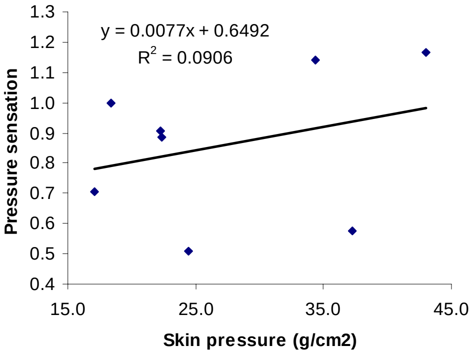
Figure 5.4 Average skin pressure measured at different locations when wearing different garments

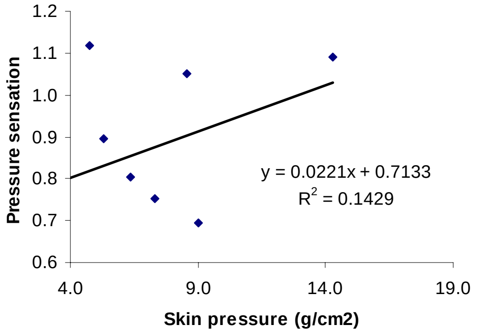
In order to derive the psychophysical relationships, the measurements on skin pressure and pressure sensations are analyzed according to different body locations as described above. The psychological pressure sensation was measured by asking subjects to rate perception of pressure sensation from 0-neutral (no pressure), 1-comfortable (light pressure), 2-uncomfortable (medium pressure), 3-very uncomfortable (high pressure) to 4-extremely uncomfortable (very high pressure) at the same body location. Figure 5.5 shows the relationships between skin pressure and pressure sensations for different body locations.

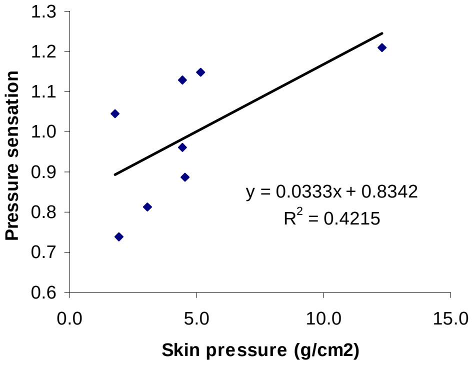

(a) Chest


(b) Front Thigh


(c) Front waist


(d) Side waist


(e) Back waist


(f) Side Pelvis

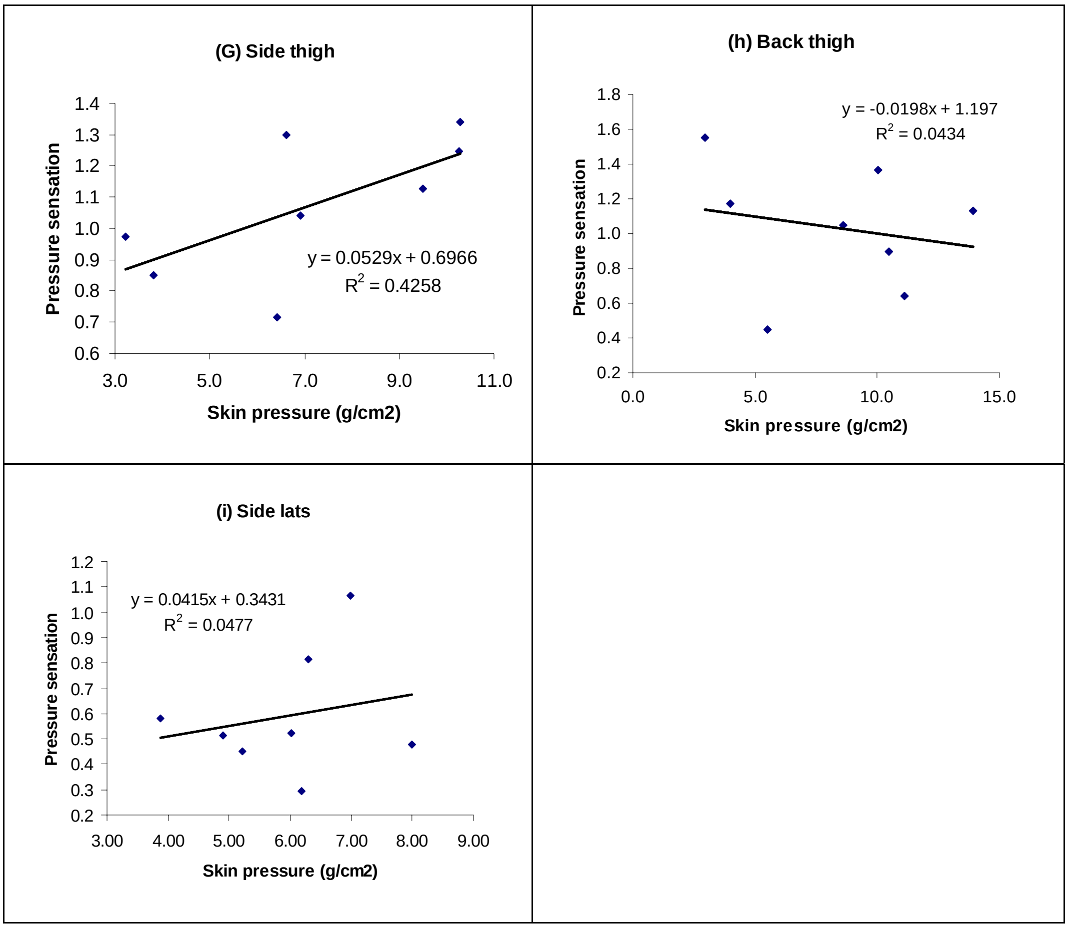


Figure 5.5 Psychophysical relationships between skin pressure and pressure sensations at different body locations

As shown in Figure 5.5, pressure sensitivity at different body locations varies significantly. At the chest location (Figure 5.5a), pressure sensation starts from skin pressure of l.7 g/cm^2 and then increase linearly with skin pressure. Similar trends are found for the body location at side pelvis, side thigh and front thigh with skin pressure starting from 1.7, 3.2 and 6.7 g/cm^2 respectively. Meanwhile, at the body locations of front waist, side waist, back waist, back thigh and side lats, pressure sensation is not sensitive, even at much higher skin pressure of 11.9, 17.1, 4.0, 2.9 and 3.9 g/cm^2. The psychophysical relationships between skin pressure and pressure sensation are not statistically significant. These findings may be due to the fact that both the skin pressure and pressure sensation data were obtained from wear trials when human subjects worn the test garments, which are still in the comfort zone of skin pressure. On the other hand, these observations show the nature of sensitivity of pressure sensation at different body locations. Therefore, the empirical equations shown in Figure 5.5 are used as the psychological relationships between skin pressure and pressure sensation.

5.2.3 Pressure comfort model

As discussed in previous sections, the somatosensory cortex of the brain receives the neural signals from the nerve endings at different body locations to formulate individual sensations and evaluates and weighs them to formulate a subjective perception of overall pressure comfort. With identified psychophysical relationships for skin pressure sensations, the processes of how brain cortex formulates pressure sensation from the neural signals that were induced by skin pressure were simulated statistically. The process of how brain to formulate overall pressure comfort perception from individual pressure sensations at different body locations needs to be modeled.

Statistical method, artificial neural network method [62, 63] and fuzzy method can be used to predict the pressure sensation. However, a common weakness in both statistical models and artificial neural networks is that neither method can simulate the perception and judgment of human brain on the basis of incomplete or fuzzy information and rules. Therefore, a model of simulating the fuzzy judgment process of human brain is developed using fuzzy logic.

A fuzzy system is defined as "a system whose variables (or at least, some of them) range over states that are fuzzy sets" [48]. In order to utilize a fuzzy system to identify the dynamic clothing pressure comfort, the related variables (linguistic variable quintuples) and the identification principles (inference rules) need to be defined. Fuzzy Logic Toolbox in *Matlab 6.0* from *Mathworks Inc.* was used as the fuzzy inference system constructor. The structure of the fuzzy inference system to formulate perception of clothing pressure comfort is illustrated in Figure 5.6.

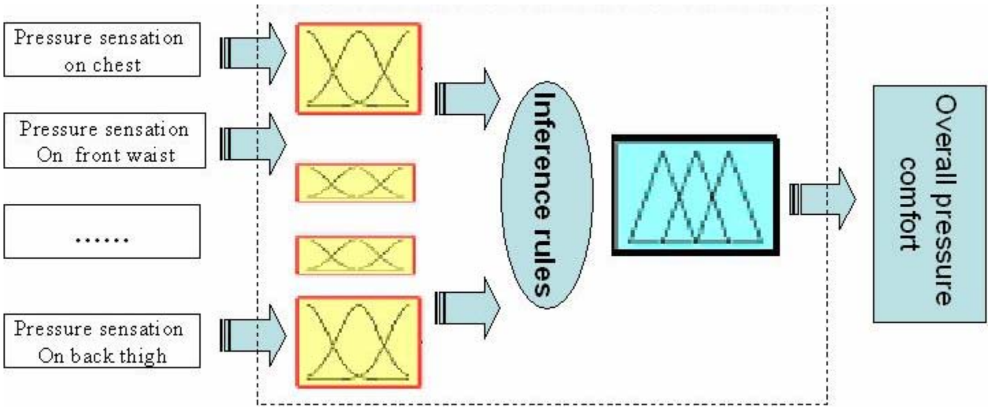


Figure 5.6 Schematic diagram of the fuzzy inference system

In this fuzzy inference system, the input variables are the calculated pressure sensations (P1 to P9) at different body locations, including Chest, Front waist, Front thigh, Side lats, Side waist, Side pelvis, Side thigh, Back waist, Back thigh, and the overall pressure comfort (RP) is the output variable. The membership functions at different body locations needs to be defined and inference rules need to defined to simulate the process in which the brain formulate the perception of overall pressure comfort. Table 5.3 lists the definition of the linguistic variables of pressure sensation and overall pressure comfort.

Table 5.3 Linguistic expressions

v- ***Name***	***T-*** ***Linguistic terms***	***X-*** ***Universal range***	***g-*** ***Syntactic rule***	***m-*** ***Semantic rule***
P_1	(Neutral, comfortable, uncomfortable, very comfortable, extremely uncomfortable)	[0,4]	defined	defined
…	…	…	…	…
P_9	(Neutral, comfortable, uncomfortable, very comfortable, extremely uncomfortable)	[0,4]	defined	defined
R_p	(Acceptable, Comfortable, Uncomfortable,)	[0,4]	defined	defined

The inference rules for dynamic pressure comfort identification need to be created. It is assumed that the overall pressure comfort is determined by the combined effects of pressure sensations from different body locations. Corresponding to linguistic terms in Table 5.3, Table 5.4 lists *conditional-and-unqualified* propositions [48] that are developed as inference rules based on the following scheme:

- Two conditional and unqualified proposition forms are used:
  - if (A is a), then (Z is z)
  - if (A is a) AND (B is b), then (Z is z)

- Extreme sensations like extremely uncomfortable, very uncomfortable, uncomfortable for every P_i are defined as *Uncomfortable* for R_p, using the first proposition form.
- Other sensations, (Neutral, comfortable) for every P_i are interacted based on one-to-one relationships, using the second proposition form, with the logical operand 'AND' to deduce the possible status for R_p, ranging over the three options (Acceptable, Comfortable, Uncomfortable).

The rules are summarized in Table 5.4.

Table 5.4 Inference rules

If there is a P_i is Uncomfortable or Very uncomfortable or extremely uncomfortable then R_p is Uncomfortable
If all P_i are Comfortable then R_p is comfortable
If every P_i is Neutral or comfortable then R_p is Acceptation

Prediction model

To implement the model shown in Figure 5.6, a prediction procedure is developed as follows:

1) *Experimental process*: Eight types of garments numbered 1~8 were tested [92]. The pressure comfortable sensations of different body locations, as well as the overall pressure comfort sensation are measured. The experiment provides the source for the following two processes.

2) *Preparation process*:

- Based on the experimental results, the membership functions for P_1 to P_9 are defined.
- The inference rules for the fuzzy system are developed.
- By performing a calculation with the same experimental data for garments 1~4, the related psychophysical relationship for the pressure sensations are then developed for different body locations.

3) *Prediction process*: the pressure comfort for garments 5~8 to be calculated:

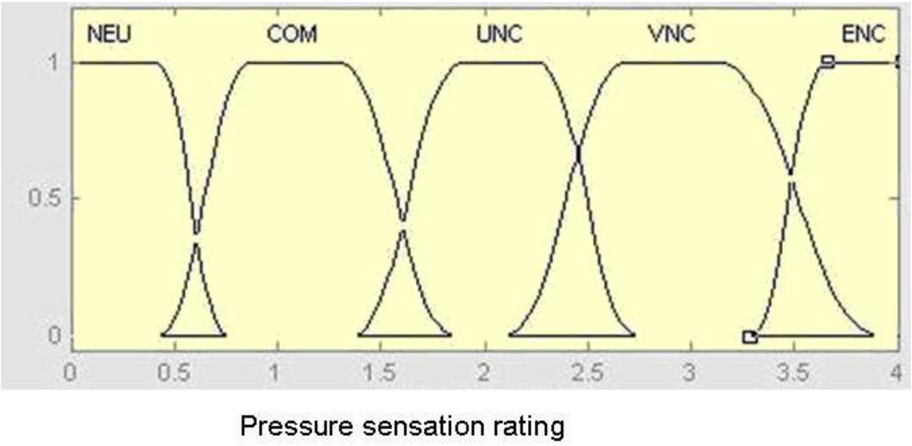
- The simulation for garments 5~8 with the same conditions as the experiments is performed.
- Using the psychophysical relationship discussed above in the preparation process the pressure sensations during the simulation ($P_1 \ldots P_9$) are calculated next.
- Based on the fuzzy logic system developed in the preparation process, use ($P_1 \ldots P_9$) as input variables to deduce the overall pressure comfort R_p.

- Finally the calculated R_p is validated by comparing it with the experimental results for garments 5~8.

By examining the experimental data using histograms, it is found that the subjective ratings of the sensations follow normal distributions, which are characterized by bell-shape and single peak. Therefore bell-shape membership functions in the form of Equation 5.2 are used for each linguistic term.

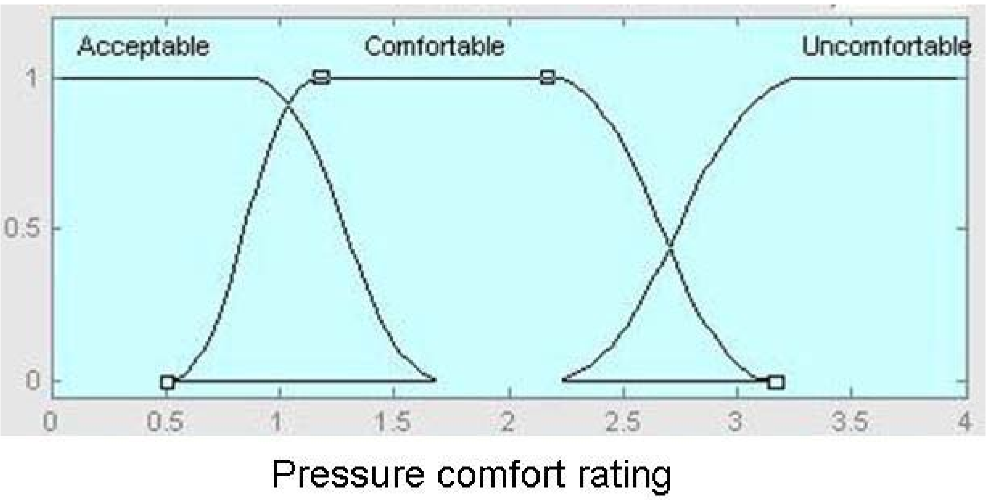
$$m(x \in X; a, b, c) = \left(1 + \left|\frac{x - c}{a}\right|\right)^{-2b} \qquad (5.1)$$

According to the experimental results shown in Figure 5.5, using the try-and-error method identifies the related coefficients for the membership function of individual sensations. Figure 5.7 shows the sample figures of chest and output for the bell-shape membership functions for the fuzzy system.



a. Membership function for chest sensation

(Note : NEU=Neutral, COM=Comfortable, UNC=Uncomfortable, VNC=Very uncomfortable, ENC=Extremely uncomfortable)



b. Membership function for pressure comfort

Figure 5.7 Membership functions

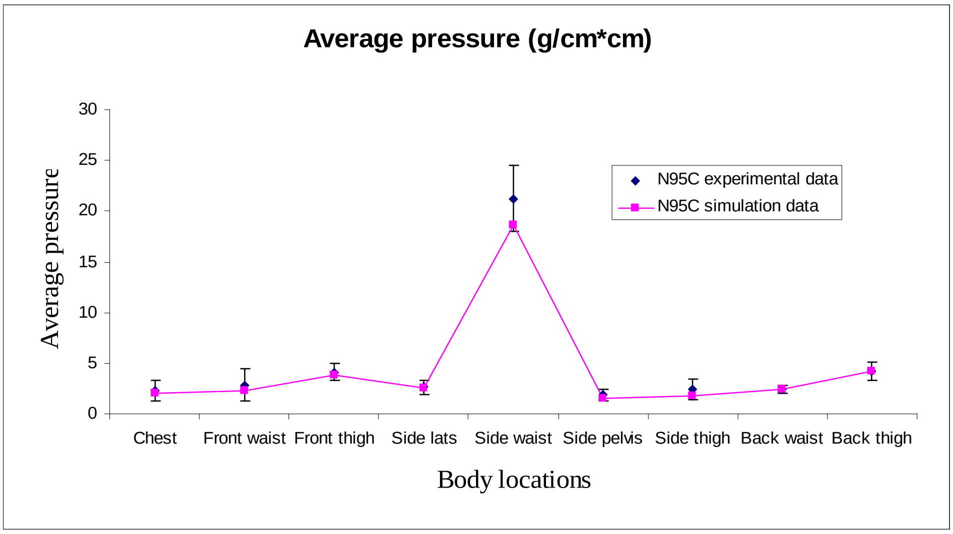
Given predicted dynamic individual pressure sensations, the dynamic pressure comfort during the process of the physical activity can be deduced by using the established fuzzy logic system. The dynamic pressure comfort sensation R_p can then be obtained through the deduction process characterized by the inference rules shown in Table 5.4.

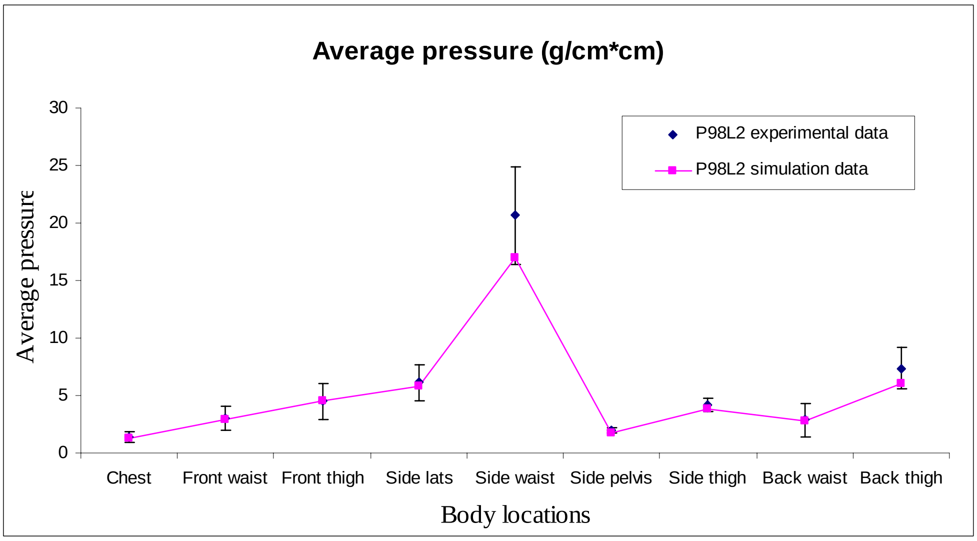
When the calculation of each rule is completed, an output function is generated. These output functions are then combined into a single aggregate output. By calculating the centroid of the area of aggregate output using the centroid calculation method, the location of the centroid in the x-axis represents the predicted comfort score.

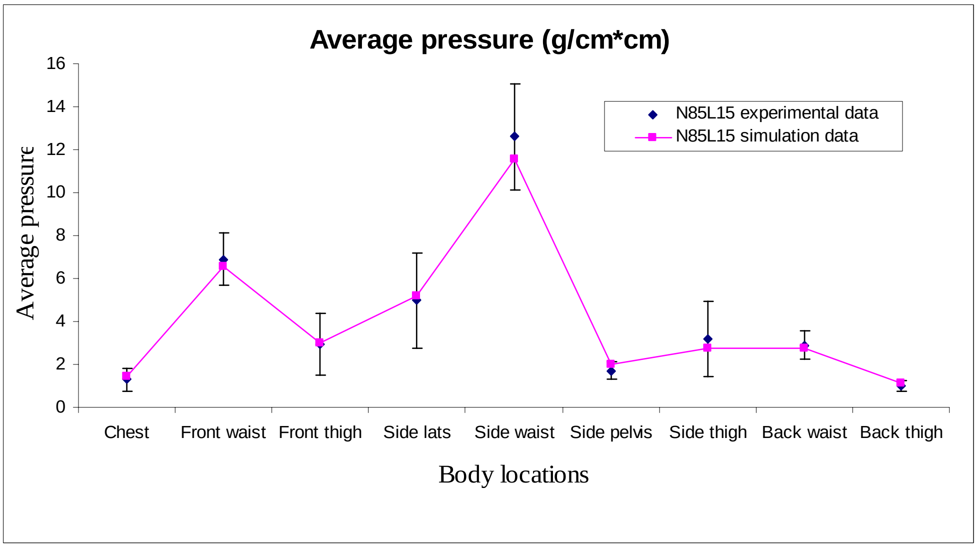
5.3 VALIDATION OF SKIN PRESSURE PREDICTION

5.3.1 Skin pressure distribution validation

During the simulation process, the garment fabric parameters in Table 5.2 were used as input data. After simulation by using the simulation model reported in Chapter 4, the skin pressures on the nine locations of human body were recorded. The predicted skin pressures are compared with the experimental measurements in Figure 5.8.


Average pressure (g/cm*cm)
Average pressure
30
25
20
15
10
5
0
N95C experimental data
N95C simulation data
Chest
Front waist
Front thigh
Side lats
Side waist
Side pelvis
Side thigh
Back waist
Back thigh
Body locations


Average pressure (g/cm*cm)
Average pressure
30
25
20
15
10
5
0
P98L2 experimental data
P98L2 simulation data
Chest
Front waist
Front thigh
Side lats
Side waist
Side pelvis
Side thigh
Back waist
Back thigh
Body locations


Average pressure (g/cm*cm)
Average pressure
16
14
12
10
8
6
4
2
0
N85L15 experimental data
N85L15 simulation data
Chest
Front waist
Front thigh
Side lats
Side waist
Side pelvis
Side thigh
Back waist
Back thigh
Body locations

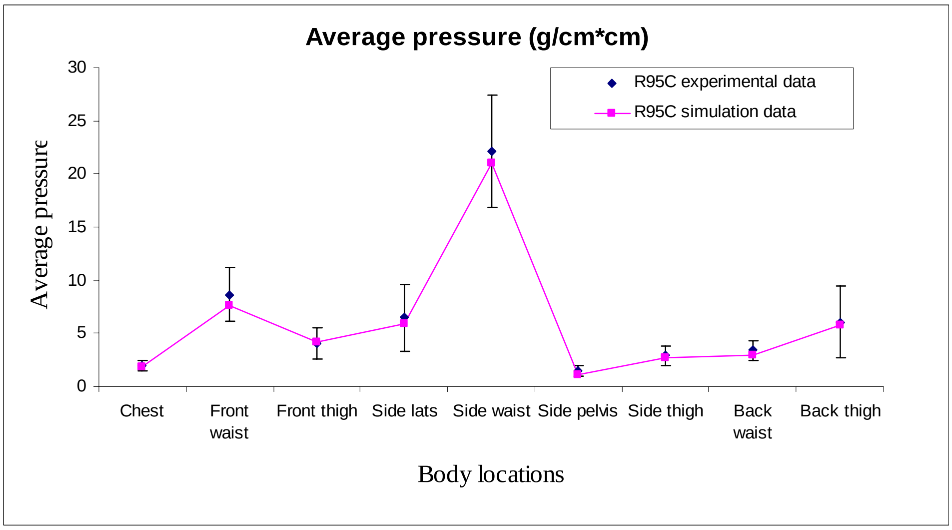


Figure 5. 8 Comparison between the experimental data and simulation data

As Figure 5.8 shows, the numerical simulation predicts the same trends of skin pressure distributions as the experimental measurements. The skin pressure at the side waist is significantly greater than those at other body locations, while the skin pressure on chest is the smallest among all the body locations. All the predicted skin pressure is falling within the error bars of the experimental measurements, showing excellent agreement between them.

5.3.2 Prediction of overall pressure comfort

During the simulation process, the pressures of body locations can be recorded. According to the empirical in section 5.2.2, each pressure can be transferred into pressure sensation rating. Table 5.5 shows the transfer results of nine pressures about 4 garments.

Table 5.5 Pressures and pressure sensations

	Chest	**Front waist**	**Front thigh**	**Side lats**	**Side waist**	**Side pelvis**	**Side thigh**	**Back waist**	**Back thigh**
Garment 1									
Sensation rating	0.66	0.63	0.71	0.45	0.79	0.88	0.79	0.77	1.00
Pressure	1.98	2.24	3.89	2.51	18.68	1.47	1.75	2.39	4.23
Garment 2									
Sensation rating	0.43	0.64	0.76	0.58	0.78	0.89	0.90	0.77	1.11
Pressure	1.27	2.86	4.53	5.77	17.02	1.79	3.89	2.78	6.04
Garment 3									
Sensation rating	0.48	0.69	0.64	0.56	0.74	0.90	0.84	0.77	1.20
Pressure	1.42	6.56	3.02	5.17	11.56	1.98	2.78	2.75	1.11
Garment 4									
Sensation rating	0.63	0.71	0.74	0.59	0.81	0.87	0.84	0.78	1.00
Pressure	1.89	7.67	4.21	5.91	21.08	1.13	2.76	2.99	5.80
Garment 5									
Sensation rating	0.60	0.67	0.63	0.63	0.77	0.87	0.77	0.78	0.90
Pressure	1.81	4.84	2.96	6.93	15.27	1.12	1.43	3.21	2.19
Garment 6									
Sensation rating	0.37	0.62	0.61	0.50	0.74	0.89	0.91	0.80	0.89
Pressure	1.09	1.24	2.72	3.76	11.57	1.76	3.98	4.03	4.02
Garment 7									
Sensation rating	0.79	0.64	0.77	0.43	0.79	0.94	0.88	0.81	1.20
Pressure	2.41	2.77	4.55	2.12	18.86	3.08	3.55	4.45	2.37
Garment 8									
Sensation rating	0.36	0.63	0.57	0.47	0.82	0.87	0.81	0.77	1.10
Pressure	1.06	1.99	2.19	2.99	21.87	1.09	2.10	2.56	1.14

Based on the fuzzy logic system developed in section 5.2.3, the pressure sensation ratings of the body locations are used drive the pressure sensation distribution according to the membership functions for corresponding body locations. Then, the influence rules are used to deduce the overall pressure comfort for each garment.

The predicted pressure comfort for the garments are then compared with the comfort ratings obtained from the wear trial, as shown in Figure 5.9. The result shows that there is a linear relationship between the predicted and the actual comfort ratings with r ≈ 0.888.

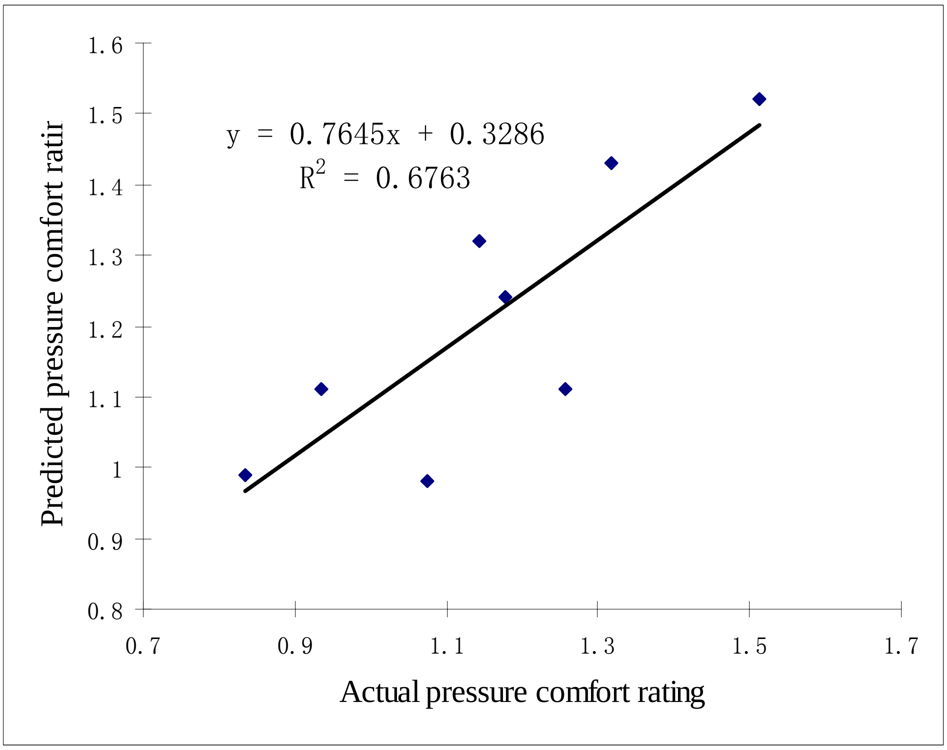


Figure 5.9 Actual comfort rating against predicted comfort rating score

5.4 CONCLUSION

In this chapter, a theoretical framework to model and simulate the perception of pressure comfort is developed by reviewing the research in human neurophysiology. During wear, the brain receives neural signals from various body locations and interprets them into individual pressure sensations for individual location. The pressure sensation sensitivity for individual human body location is different. The overall perception of pressure comfort is dependent on the individual pressure sensations perceived.

According the theoretical framework, a numerical simulation model is developed on the basis of the experimental results reported early to establish the psychophysical relationships between skin pressure and pressure sensations for different body locations, which are used to transfer the pressure into pressure sensation ratings. In order to predict overall pressure comfort, a fuzzy inference system for the dynamic pressure comfort prediction based on the individual pressure sensations is developed to predict overall clothing pressure comfort on the basis of individual pressure sensations of nine body locations.

The predicted skin pressure results were validated by experimental results, showing that fabric mechanical properties have significant influences on skin pressures. The predicted skin pressures are input into the psychophysical relations to derive pressure sensations of individual body locations, which then input into the fuzzy logical model to predict the overall pressure comfort of eight garments. The predicted pressure comfort scores are compared with the actual comfort scores derived from the experiments. Good agreement is observed between the two, indicating the model is able to produce predictions in linguistic form and fuzzy logic is an effective tool for modeling the process of the human psychological perception of clothing pressure comfort.

CHAPTER 6 SIMULATION VISUALIZATION

6.1 INTRODUCTION

So far a range of data has been presented. It is now essential to discuss the ways in which the data can be visualized. Visualization in scientific computing and engineering design is getting more and more attention from many people. Especially in relation with the fast increase of computing power, graphic tools are required in many cases for interpreting and presenting the results of various simulations, or for analyzing physical phenomena [20]. Visualization of scientific data has become a very important topic for many researchers. Scientists, engineers, medical personnel, business analysis, and others often need to either analyze large amounts of information or study the behavior of certain processes. Numerical simulations carried out on supercomputers frequently produce data files containing thousands and even millions of data values. Similarly, satellite cameras and other sources are amassing large data files faster than they can be interpreted. Scanning these large set of numbers to determine trends and relationships is a tedious and ineffective process.

The appropriate way to analyze and understand these results is to visualize the data. If the data are converted to a visual form, the trends and patterns are often immediately apparent. Visualization is not just a simple graphic presentation, which itself has the power to present large amounts of numerical information in an efficient and effective way so we can gain insight into the numbers. Visualization is rather an exploration of data and information graphically, as a means of gaining understanding as well as insight into data. Visualization of data is an emerging visual computing technology that uses intuitionist and innovative graphical user interface and visualization techniques. This technology helps engineers, scientists, and technicians to access, analyze, manage, visualize, and present large and diverse quantities of data to get information from raw technical data. The technology has evolved from the combination of powerful desktop computers, statistical and other analytical tools, graphics and visualization, as well as sophisticated interaction tools. The data visualized enable scientists to explore their research data, to gain new scientific insight, and to communicate their discoveries to others. Visualization allows the conversion of information, which cannot be perceived by the human eye, into forms suitable for this most highly developed human sense.

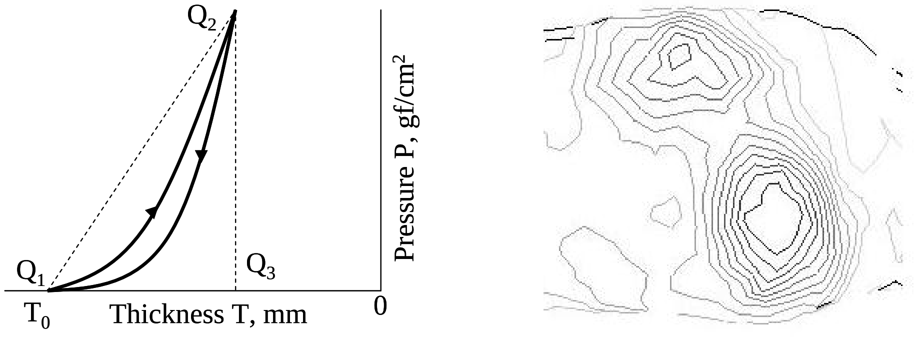
The visualization technique is to transform experimental data into graphical primitives. There are many different kinds of data sets, and effective visualization schemes depend on the characteristics of the data. A collection of data can contain scalar values, vectors, high-order tensors, or any combination of these data types. Data sets can also be two or three dimensional. Graphing and visualization techniques can vary from simple charting to volume visualization. Several academic visualization classification schemes have been proposed. Basic techniques include the familiar types of graphs such as scatter, line, and contour, as well as 3D surfaces, and various combinations of these. Advanced visualization methods may also comprise 3D geometric rendering, volume visualization, multidimensional visualization, vector fields, and animation.

Clothing engineering design refers to creating new clothing by enhancing existing designs or by altering existing ones to perform new functions. It is a complex iterative-decision–making competitive process. The clothing engineering design process generates and uses a large volume of dynamic data. The biomechanical engineering design for textile and clothing products is typical of the kind of human-clothing engineering in which the biological human body interacts dynamically with a garment on the large areas of contact surface. The main simulation results are garment pressure distribution and biomechanical performance of the human body. The designer needs to quantitatively investigate and evaluate the relationship between the mechanical performance of textile and clothing products and human sensory factors, including physiological and psychological aspects. Indeed visualizing and analyzing the results of the mechanical simulation using a broad range of interaction techniques is crucial to the effectiveness of product development in the clothing biomechanical engineering design system. In this chapter, the main research exploits visualization technology to transform the pressure data to colour; and to map the various deformations and sensory perception.

6.2 MECHANICAL VISUALIZATION

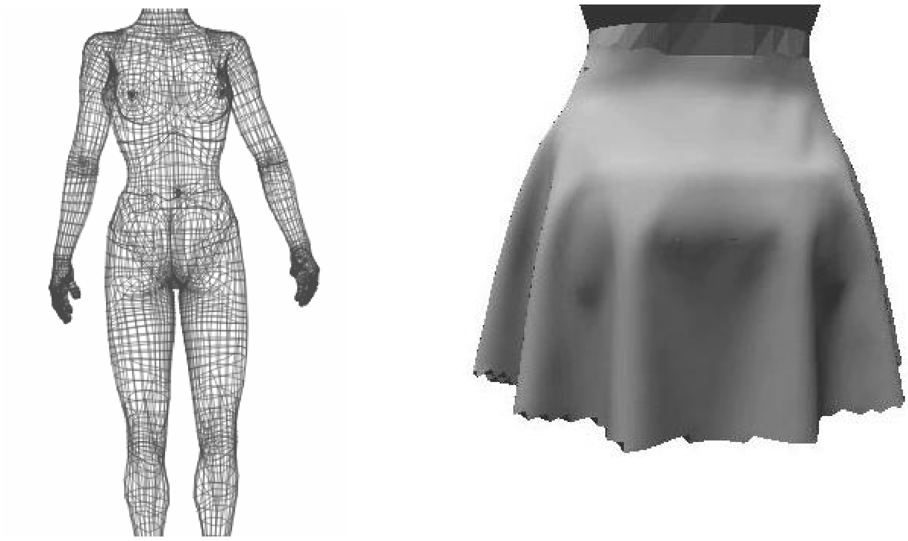
Visualization of data includes a well-defined set of graphics and visualization tools for visually interpreting the data and producing a hard copy of the results. The environment of data visualization includes analysis tools for a better understanding of the data, data management tools for generating, reducing, saving, and restoring the data, and data access techniques to help get the data in to and out of the visual data analysis environment. As visualization environments mature, they focus largely on integrating the analytical and visual technologies into more complete data interpretation systems. Some applications of visualization integrated into CAD, GIS, and spreadsheet software have already been developed. The idea behind visualization data is to put the user in the center of the analysis process, using visualization as a tool to navigate through data.

Figure 6.1 shows examples of various visualization methods.

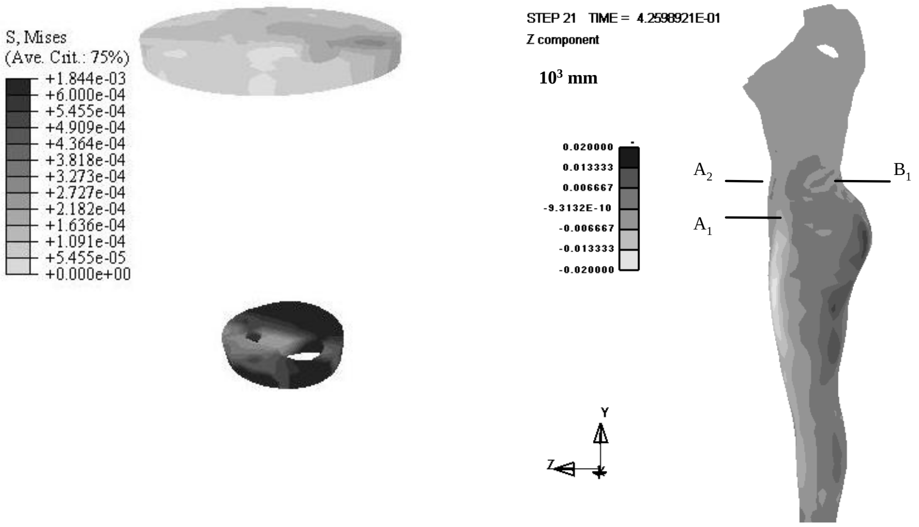


(a) Chart and graph

(b) Contouring



(c) 3D surfaces (d) Rendering



(e) Volume (f) Multidimensional visualization

Figure 6.1 Various methods of visualization

In Figure 6.1, we can see: (a) the pressure curves on the clothing, (b) the distribution of pressure on the human body, (c) the 3D mesh body, (d) the deformation of clothing, (e) the deformation of human body, and (f) the pressure distribution on the human body. All these methods can be used to clothing biomechanical engineering design to visualize and analyze the interaction force generated during the dynamic interactions between the clothing and the human body induces the perception of various mechanical sensations. Therefore, the engineering design of clothing mechanical performance needs to predicate and visualize the simulation results mainly in human physiologic and psychology, i.e. clothing mechanics behavior.

6.3 MECHANICAL PERFORMANCE OF CLOTHING

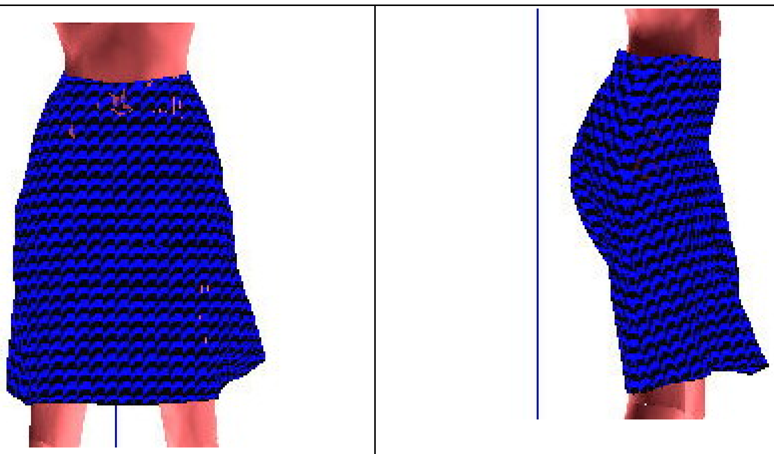
6.3.1 The simulated clothing deformation

The clothing will become deformed because of a fabric’s mechanical property. The clothing deformation can be recorded during a simulation process and it can be visualized by color, form, plot and animation. To ensure that the reproduction of the illustrations is of a reasonable quality, it is advised to avoid the use of shading. The contrast should be as pronounced as possible.

To visualize and analyze the results of the mechanical simulation effectively, the features were used in this study were: linear and logarithmic axis scales, axis annotation, simultaneous display of data and visualization, diverse range of plotting modes, diverse range of 3D display modes, superimposition of mathematical functions, intuitive user interface [41]. Most FE packages have their own visualization modules to view the results of the mechanical analysis. .

Following is an example, using the M-smart software package [73] [72] to illustrate the clothing deformation analysis used for a clothing biomechanical engineering design. The simulation scheme is a hybrid model (geometric model and particle model).

The visualization process consists of three parts: processing simulation results, according to the simulation data to construct the 3D geometric model, graphics process and animation. Figure 6.2 shows the outlook of skirt when it is fitted to the body with two views: (a) the front view of the skirt fitted to the body, and (b) the side view of the skirt fitted to the body. The simulation indicates the skirt stretch and recovery during the wearing process.



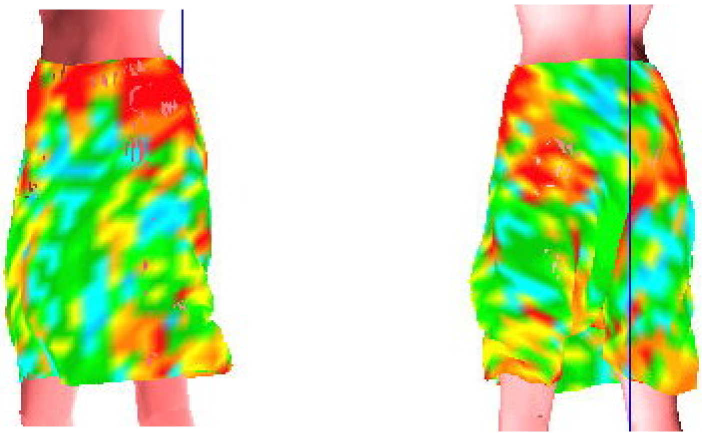
(a) Front view of the skirt fitted to the body

(b) Back view of the skirt fitted to the body

Figure 6.2 Deformation of skirt in the fitting process

6.3.2 The simulated clothing pressure distributions

With the numerical results of the simulation, various force deformations of garment can be visualized. There is three types forces that are generated during simulation process: compression, shearing and bending. Figure 6.3 shows the simulation results of forces distributions on the garment.



(a) Front (b) Back

Figure 6.3 Pressure distribution of skirt

Figure 6.3 illustrates that the forces distribution on the garment are consistent with deformation of garment. The bigger the curvature on the garment, the bigger is the tensile force. In Figure 6.3(a), we see that the bigger tensile force on the garment is the area of breast. In the Figure 6.3(e), the bigger bending force on the garment is the area of waist. The visualization of garment deformation can help the designer to evaluate the design concept in a virtual platform.

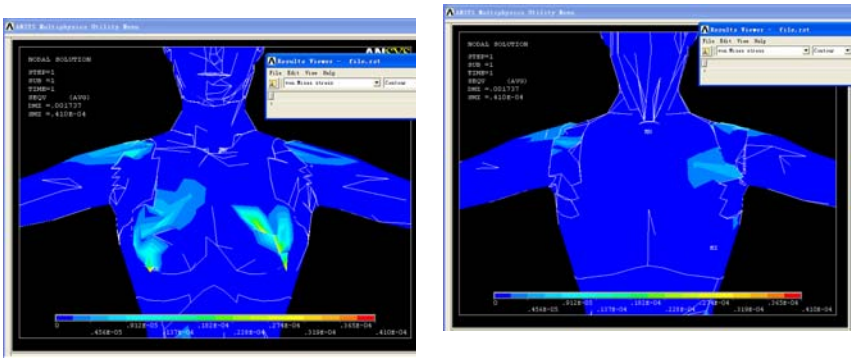
6.4 PRESSURE SENSORY VISUALIZATION

6.4.1 Mechanical behavior of the human body

Clothing comfort is very subjective. Evaluation of pressure comfort must combine the predicted pressure and the sensation index from a large volume of experiments involving wear trials. It needs much work on psychological evaluation of garment pressure, from which a series of psychophysical models can be developed based on the investigation of the relationship between objective stimuli and psychological perceptions as well as the investigation of the relationship between the predictions and the objective measurements. For medical clothing items, there are often criteria of specific physical parameters to be met. The evaluation of medical effects is much complicated, and needs more co-operations with clinical practice within a long term.

To visualize the sensory perception in the CAD environment, a series of psychophysical experiments have to be carried out to study mechanical comfort of the garment in different wear situations by conducting mechanical sensory comfort perception trials and objective measurement of dynamic pressure distribution. Further, psychophysical models of mechanical comfort have to be developed in different wearing situations, by using statistical methods, neural networks and etc [92].

The clothing biomechanical engineering design has to take into account the clothing deformation and human body deformation. Especially, the researcher wants to simulate the clothing biomechanical performances to predict the human body physiology and psychological comfort performance. In this study, the software Ansys and M-smart are used to simulate the clothing biomechanical performance and human body biomechanical performances. The core technology includes the programming and the data transfer between software packages. The simulation can be divided into two steps: the first one is to generate the forces that act upon the human body doe to the garment deformation. Then these forces data are transformed into the Ansys's data format. The second step is to define the human biology parameters and import the forces data to simulate the human body deformation using Ansys software.



(a) Front (b) Back

Figure 6.4 Skin pressure distribution

Figure 6.4 shows the distributions of the skin pressure during the wearing process. In this simulation process, a high skin pressure of 6.8gf/cm2 is observed as wearing vest, and a lower skin pressure of 2.7gf/cm2 is observed, while the garment pressure shows similar values of 6.1gf/cm2 and 6.2gf/cm2 for the vest respectively.

6.4.2 Pressure animation

In order to visualize the change of clothing pressure during the wear, the animation technology can be used [35]. In animation processing, key frame technology often is used to strut all pressure change processes. Those key frames have great influence upon the pressure distribution and other in-between frames in animation can be generated from key frames. Linear interpolation and higher order spline interpolation are the regular methods to build in-between frames.

Compared with normal method such as linear interpolation and higher order spline interpolation, 4-Point subdivision scheme has some advantages in building in-between frames. 4-Point subdivision technology can generate blander vision effect than linear interpolation method and display more efficiency than higher order spline interpolation method.

4-Point subdivision scheme is proposed by N. Dyn, J. Gregory and D. Levin in [66].

$$\begin{cases} P_{2i,2j}^{k+1} & -1 \le i \le 2^k n+1, -1 \le j \le 2^k m+1 \\ P_{2i+1,2j}^{k+1} = (\frac{1}{2}+\omega)(P_{i,j}^{k} + P_{i+1,j}^{k}) - \omega(P_{i-1,j}^{k} + P_{i-2,j}^{k}) & -1 \le i \le 2^k n, -1 \le j \le 2^k m+1 \\ P_{2i,2j+1}^{k+1} (\frac{1}{2}+\omega)(P_{i,2j}^{k+1} + P_{i,2j+2}^{k+1}) - \omega(P_{i,2j-2}^{k+1} + P_{i,2j+4}^{k+1}) & -1 \le i \le 2^k n+1, -1 \le j \le 2^k m \end{cases} \tag{6.1}$$

In the equation (6.1), P_i^k is a given control vertex sequence and w is a real number. The choice w = 1/16 is of interest since for this value the scheme coincides with the cubic Lagrange-based scheme proposed in [66].

Here, an adaptive pressure distribution animation algorithm based on 4-Point subdivision scheme is presented to generate in-between frames in the animation for pressure change process.

The algorithm can be described in four steps:

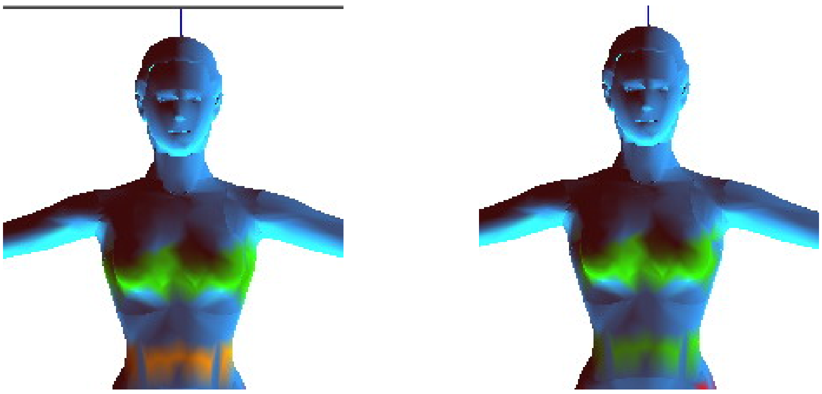
(1) Construct the key frame. The primary variable is the pressure distribution value on the body between the different parts in the body. Given any frame in the state, it contains the pressure dynamic simulation.

(2) Generate boundary frame of the animation. The initial sequence of frames is generated.

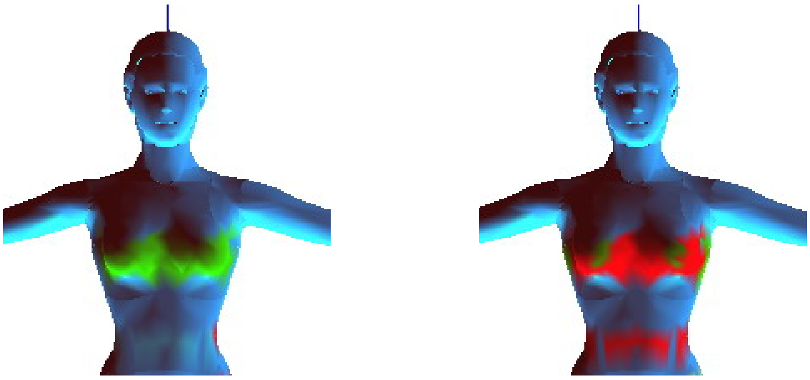
(3) Evaluate and check the space displacement factor in successive frames: Using 4-Point subdivision scheme to generate a set of new frames for this in-between frame.

(4) Repeat step 4 until the space displacement factor satisfies the requirement of continuity.

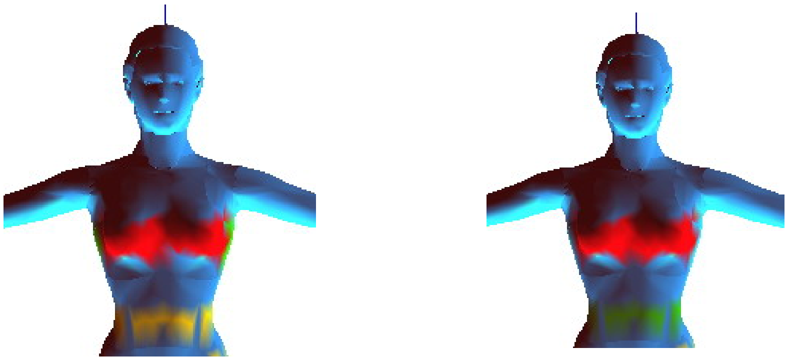
Figure 6.5 shows the in-between frames according to the key frame result using the 4-point subdivision scheme.



In-between frame(1) In-between frame(2)



In-between frame(3) In-between frame(4)



In-between frame(5) In-between frame(6)

Figure 6.5 Frame sequences about Pressure change

6.5 CONCLUSION

The computer aided design for clothing biomechanical engineering design is a simulation process to analyze and evaluate the functional performance of clothing. The aim of the biomechanical simulation is the virtual reproduction of the mechanical behavior of a textile object subjected to various geometrical and mechanical conditions, or of the interaction between clothing object and a human body object. In order to analyze and understand the results of the mechanical simulation effectively, it is necessary to transform simulation numerical data into various graphical expressions to help the engineering designer analyze and evaluate the design process for visually interpreting the data. In this chapter, the graphs and charts, contour plots, surface modeling and rendering, as well as color-coding are used as tools for clothing biomechanical engineering design simulation. In addition, the animation techniques are used to generate the rich virtual description for design process. In this chapter, a 4-Point subdivision technology is introduced which is to be used for simulation animation. 4-Point subdivision scheme has some advantages in building in-between frames. 4-Point subdivision technology is used to generate blander vision effect to animal the dynamic simulation process.

CHAPTER 7 INTEGRATION FRAMEWORK

7.1 INTRODUCTION

It is clear from the thesis so far that development of an understanding of clothing biomechanical engineering design system is considered important. This chapter focuses on the investigation of an integration CAD clothing biomechanical engineering design system, which is the fundamental research that establishes the theoretical framework of the science of clothing engineering.

As mentioned in previous chapters the clothing biomechanical engineering design means creating new clothing by enhancing existing designs or by altering existing ones to perform new functions, and it presents the relationship between clothing mechanical performance and the human factors [99] in terms of: (1) physical factors (such as the body size and the shape); (2) biomechanics of human body (such as the deformation of the muscles); (3) neurophysiology (formulating sensory signals from the interactions of the body with the clothing); and (4) psychology (subjective perception of sensory sensation from the neurophysiological sensory signals and then formulated subjective overall perception and preferences). The study of the clothing mechanical behavior makes it possible to predict and evaluate mechanical effect objectively, and to meet the needs of various requirements of human biological and psychological needs in life, protection, healthcare, medicine surgery and sensory comfort during wear.

Clothing biomechanical engineering design, a complex iterative-decision –making competitive process, requires, as a realistic possibility, computer graphics and computer display technology in order to provide a visual environment for design, analysis, evaluation, and visualization. All the knowledge together can systematically predict the performance of clothing during wear.

Clothing design task consists of selecting the style, color and materials to meet specified functional requirements for the clothing. This design process is largely based on experience and intuition of the designer, which has several disadvantages [99]. Firstly, too much reliance is placed upon the individual designer but not on knowledge-based design models. It is difficult to require a designer to communicate with interdisciplinary professionals in order to apply the concepts developed through research. Furthermore, the training of new design 'apprentices' is a lengthy, tedious, and costly process. Secondly, it is difficult to achieve iterative decision-making process in a short design time. Thirdly, the designer does not have the means to make a parametric analysis of the mechanical performance of clothing before it is produced. Finally, it is difficult to maintain a consistently updated information system involving multiple sets of data at several locations within an organization.

The integration of CAD is a logical way to realize such a concept of clothing biomechanical design [36] [100]. The aim of an integrated CAD system is to combine all product data in one well structured flowchart, support all design necessary, and facilitate maximum efficiency by integrating the processes for various stages in the development cycle.

As mention above, integration technology can support the management, control, communication, and information share for design process. Integration technology can be used to provide a fluent data flow for clothing biomechanical engineering design that supports design efficiently. Up to now, there are very few integration technology applications in textile and clothing design systems.

In this chapter, an integration CAD system for Clothing Biomechanical Engineering Design (CBED for short) is presented. The development of this system will be largely based on the computer aided design technology, computer graphics, basic sciences, mathematical models, material sciences, and experimental methodology [55].

This system can provide an integration environment from function specification, data management, design process simulation, and design evaluation for CBED.

The main characteristics of this system combine the design, simulation, analysis, and evaluation together to support the design process efficiently.

7.2 SYSTEM ARCHITECTURE

CAD technology for clothing biomechanical engineering design can be divided into four phases: design, modeling, simulation and evaluation. This design process involves rich mathematical models; different models have different requirements for clothing engineering design. To establish the relationship between these models and share the data, it is important to develop an interface for different data format. Knowledge of how to manage these mathematical models and data files is very important during clothing biomechanical engineering design. Integration CAD system can support all design steps from problem formulation to problem solution.

Figure 7.1 shows the main objects in clothing biomechanical functional engineering design.

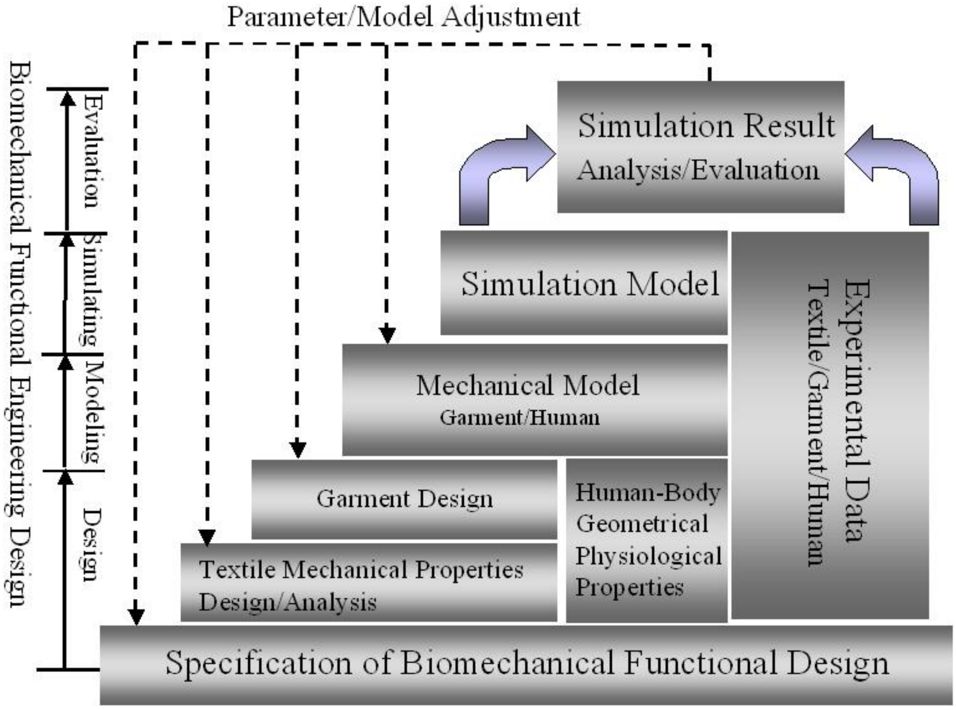


Figure 7.1 Main objects in clothing biomechanical functional engineering design

As shown in Figure 7.1, clothing biomechanical engineering design needs to integrate material science, engineering design, mathematical models, and information technologies. CBED is a complex iterative-decision-making process. It involves a number of aspects such as, analysis of the mechanical properties of textile, garment design, measurement and description of human body's geometrical/physiological properties, mechanical modeling for the contact system between human body and clothing, simulation model for biomechanical design, and the analysis as well as evaluation of the psychophysical relationship between mechanical stimulation and psychological comfort perception.

So this system integrates clothing design process, clothing-body biomechanical models, numerical solutions, analysis and evaluation of clothing mechanical performance into a CAD environment based on a collection of well-integrated software tools. As illustrated in Figure 7.2, there are eight working components in the system namely: (1) user interface; (2) Engineering design processing; (3) geometrical model of garment and human body; (4) preprocessors; (5) mechanical analyzers (special and commercial software); (6) result visualization; (7) sensory evaluation; (8) engineering database.

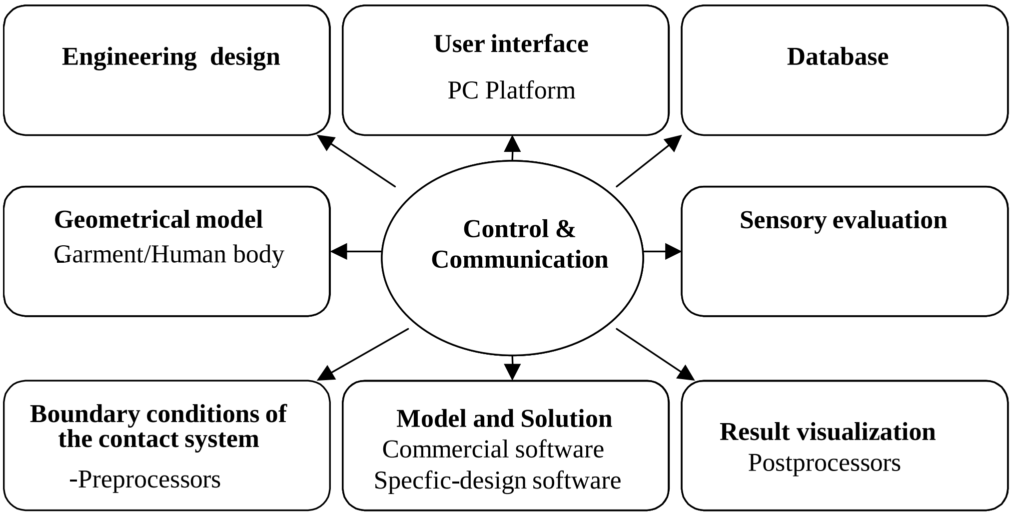


Figure 7.2 Components of integration system

7.2.1 System architecture

The fundamental research to achieve the integration CAD system of clothing biomechanical design involves a number of areas as listed below: 1) To develop a comprehensive engineering design database to support design, analysis and evaluation for clothing biomechanical engineering design; 2) To study and develop mathematical model and algorithm for constructing 3D garment from 2D apparel patterns, with specification of material property, motion and dynamic mechanical properties; 3) To establish a software platform of clothing biomechanical engineering design with mechanical analysis and visualization; and 4) To study and develop a software to visualize biomechanical sensory perceptions according to the quantitative relationship between mechanical performance of clothing and human sensory perceptions.

Based on the components of integration CAD system for CBED, Figure 7.3 shows the system architecture of the clothing biomechanical engineering design reported in this study.

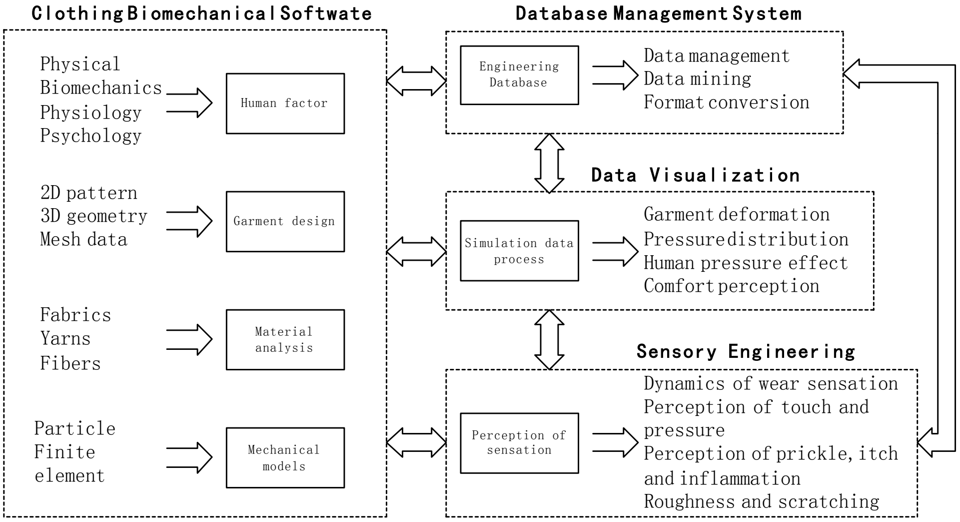


Figure 7.3 System architecture

7.2.2 Engineering database

The engineering database aims to: (i) create the communication between researchers, technologists, designers, customers, manufacturers and other related sectors; (ii) provide scientific data on clothing performance; (iii) increase design automation in textile and clothing industry; and (iv)provide other management for (a) product development; (b) design process control; (c) quality assurance and (d) performance evaluation [72].

An important characteristic that must be considered in the development of a clothing engineering database is that the clothing design process communicates frequently with the information from the hierarchical construction of a fiber-yarn-fabric-garment and a 3D human body. The structural geometry of textiles is central to all aspects of the computer-aided design and prediction, which should be presented to the designer during the design process. Therefore, the clothing engineering database should support user-friendly program packages that are quick and efficient in time and space to input, store and display the information of fiber-yarn-fabric-garment.

To reinforce the design, analysis and evaluation phases in a systematic design process with various types of information, an engineering database will support an iterative-decision process with analysis and synthesis based on knowledge of basic sciences, mathematics, and engineering sciences. The database considerably enriched with the extensive data sources of the design environment (rules, methods, standard elements etc.) and flexible data types (text, numbers, equations, diagrams, graphical, photographic images etc.) that are not known previously but defined during the design process. The development of clothing biomechanical engineering database has been reported in Chapter 2.

7.2.3 Mechanical design software

Clothing biomechanical design software is the core in the design phase. The researcher can use this software to finish their design and analysis. The performances of clothing mechanics during wear and the effects on the human body can be simulated through mathematical model. There are some commercial CAD packages such as Exceed (Hummingbird Ltd., Toronto, Canada), ABAQUS (version 6.4, Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, USA) [32] [1], and LS-DYNA (ANSYS, Inc. USA) [29] that enable numerical analysis of mechanical performances of different types of fabric. There is some self-development software to simulate the mechanical performance of clothing. In this chapter, the software that is named M-smart will be used to illustrate the design process. This software is developed using C++ language and OpenGL. The operating system is Windows 200X/Xp. The development of simulation software has been discussed in chapter 4.

7.2.4 Data visualization

Visualization is concerned with exploring data and information graphically, as a means of gaining understanding and insight into data. Visualization of data is an emerging visual computing technology that uses intuitionist and innovative graphical user interface and visualization techniques. This technology helps engineers, scientists, and technicians to access, analyze, manage, visualize, and present large and diverse quantities of data to get information from raw technical data. The technology has evolved from the combination of powerful desktop computers, statistical and analytical tools, graphics and visualization methods, and sophisticated interaction tools. The data visualized enable scientists to explore their research data, to gain new scientific insight, and to communicate their discoveries to others.

To visualize and analyze the results of the mechanical simulation effectively, the following features were considered essential for the post-processors: linear and logarithmic axis scales, axis annotation, simultaneous display of data and visualization, diverse range of plotting modes, diverse range of 3D display modes, superimposition of mathematical functions, intuitive user interface. Most software packages have their own visualization modules to view the results of the mechanical analysis. Please note that the development of simulation visualization was reported in Chapter 6.

7.2.5 Sensory engineering

Sensory engineering of mechanical performance of clothing should be based on quantitative investigations of the relationship between clothing mechanical performance and human sensory (physiological and psychological) factors. Zhang et al. [103] reported a systematic study carried out to investigate the bagging behavior of woven fabric in terms of the psychophysical relationship between subjective perception and objective stimuli from fabric residual bagging deformation, fabric fatigue behavior during bagging process and its theological mechanism, as well as the stress distribution of bagged fabric. The development of pressure sensations has been discussed in Chapter 5.

7.3 INTEGRATION DESIGN SYSTEM

7.3.1 System function

The main system function of clothing biomechanical engineering design been developed in the study can be described in Figure 7.4.

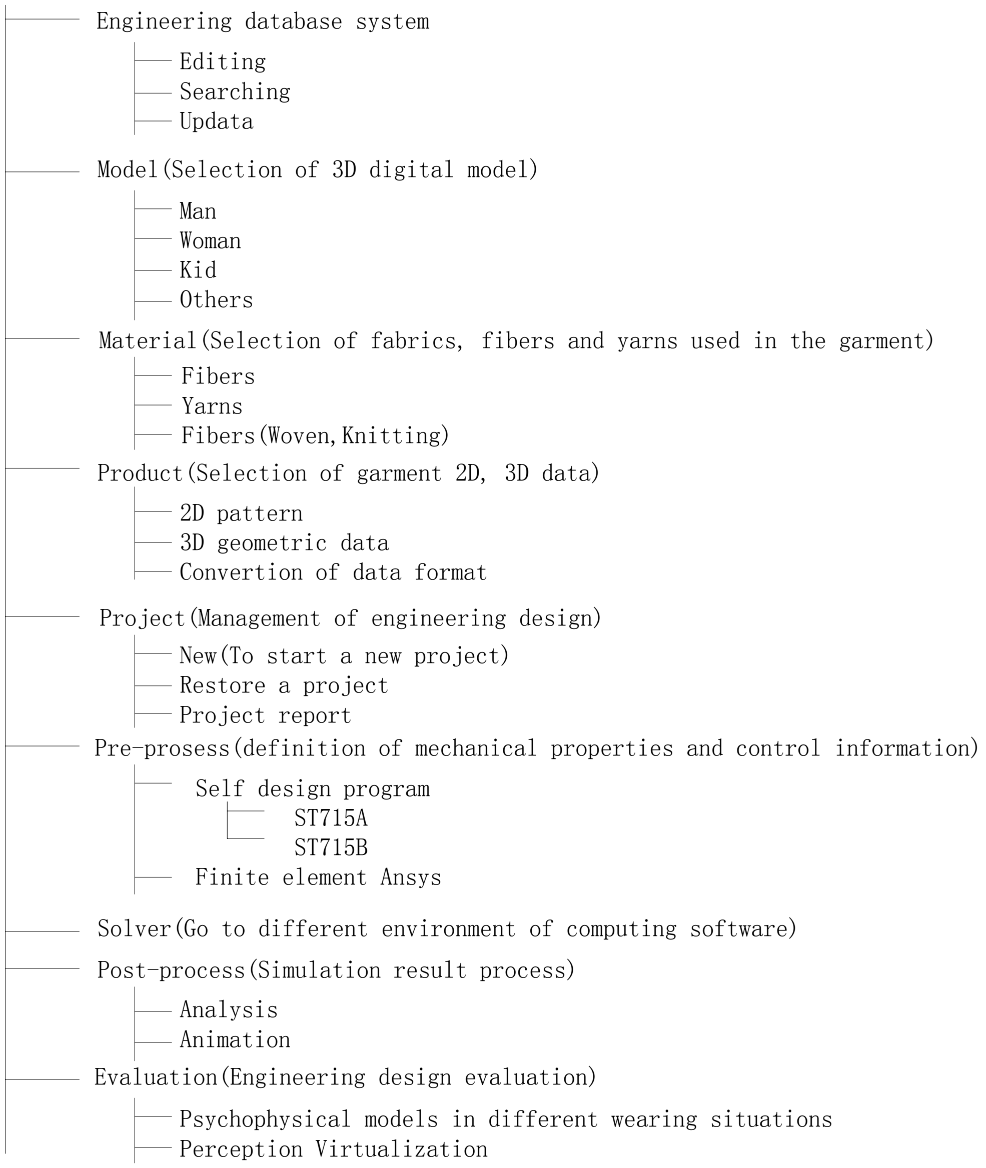


Figure 7.4 System function

This system can support the engineering database management system. It can be used to share and manage the data used during engineering design process. The menu item “Model”, “Material”, and “Product” are the preprocessing part. The main function is support the designer to prepare the parameters used in the design process. The menu item “Project” refers to the project management. It can provide the trace of design process. The system is provided with a Graphical

User Interface to create a unique environment from which both the modeler and the simulation are executed. The ST715A and ST715B are the self-copyright software, the commercial software is Ansys.

7.3.2 Computational simulation

Clothing is made of fabric, which is a kind of flexible material and behaves with complicated deformation. Due to the complicated deformation of fabric and different pattern assembly, garments show aesthetic appearance of infinite variations. It is also important to understand the relationship between mechanical performance of clothing and mechanical properties of fabric in simple deformations, such as tension, shearing, bending and compression, because these fabric properties are the basic parameters used in mechanical models of clothing. As mentioned in the literature review in Chapter 1, these properties can be measured through experiment.

The mechanical interaction between human body and a garment varies significantly for different wearing situations, depending on four factors: (1) garment style; (2) garment space allowance; (3) dynamic wearing or pattern assembling processing; and (4) posture of the human body. These factors have to be approached by providing different boundary conditions in the development of contact models. The mechanical system of the contact, which is often non-linear due to the large deformation and complicated contact condition, is usually solved numerically using a finite element method and other discretized methods.

The dataflow chart for the simulation computation of clothing mechanical design is described in Figure 7.5.

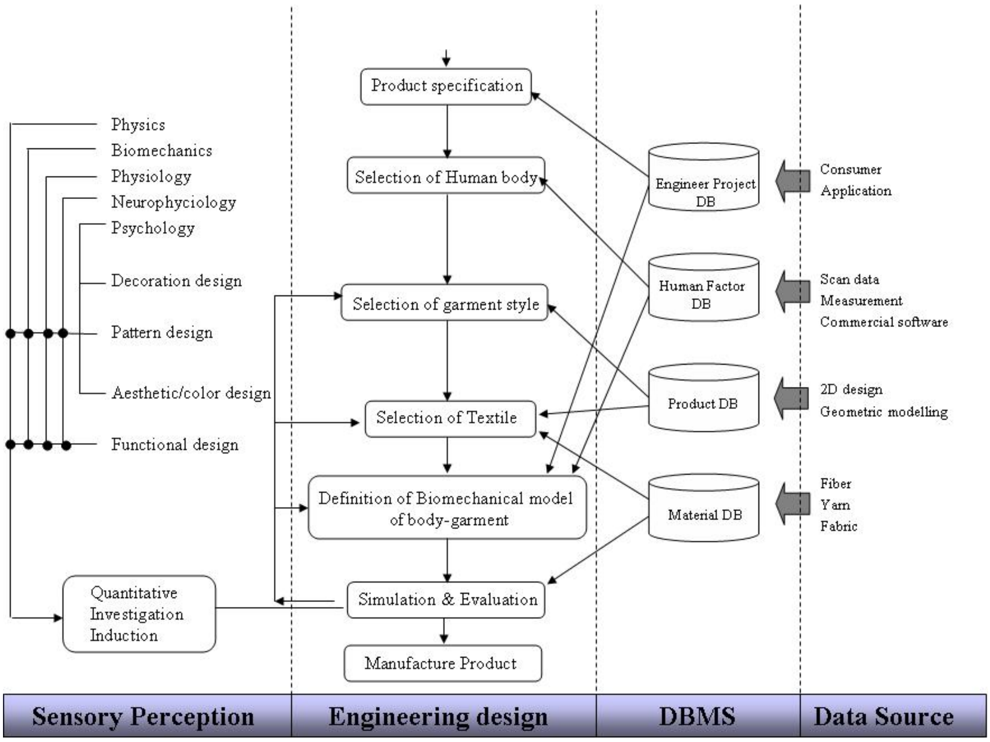


Figure 7.5 Simulation dataflow Chart

7.3.3 Analysis and evaluation

The design phase determines feasible style and materials parameters, the analysis phase is used to calculate and visualize the mechanical performance of the textile and clothing system. Such as distributions of stresses and strains in the garment, the deformation of the skin and soft tissues, and the garment pressure distributions on the skin. This analysis involves computational experiments of the design to test whether it meets the desired functional criteria of clothing. To analyze clothing mechanical performance based on 3D virtual prototypes requires the development of the 3D mechanical models of clothing and human body that can simulate the mechanical interactions between them in different wear situations. The saying of “A picture is worth a thousand words” is indeed still true. Visualization of the 3D prototypes deformed, and various mechanical parameters, such as various strains and stresses and pressure, can give the designer immediate feedback on design decisions. Based on the visible simulation results, various functional analyses can be carried out. For some special garment items, biomechanical prediction can be obtained.

Pressure comfort should be one of criteria to decide which design is optimal among several alternatives in the design process. The designer can judge whether the product meets the comfort requirements by comparing the predictions with desirable values, such as desirable pressure distributions and psychological perceptions of comfort pressure. Therefore, in addition to the design and the analysis functions, the system should ideally provide the function of sensory evaluation of pressure comfort.

7.4 A DESIGN CASE

7.4.1 Product design specification and pre-processing

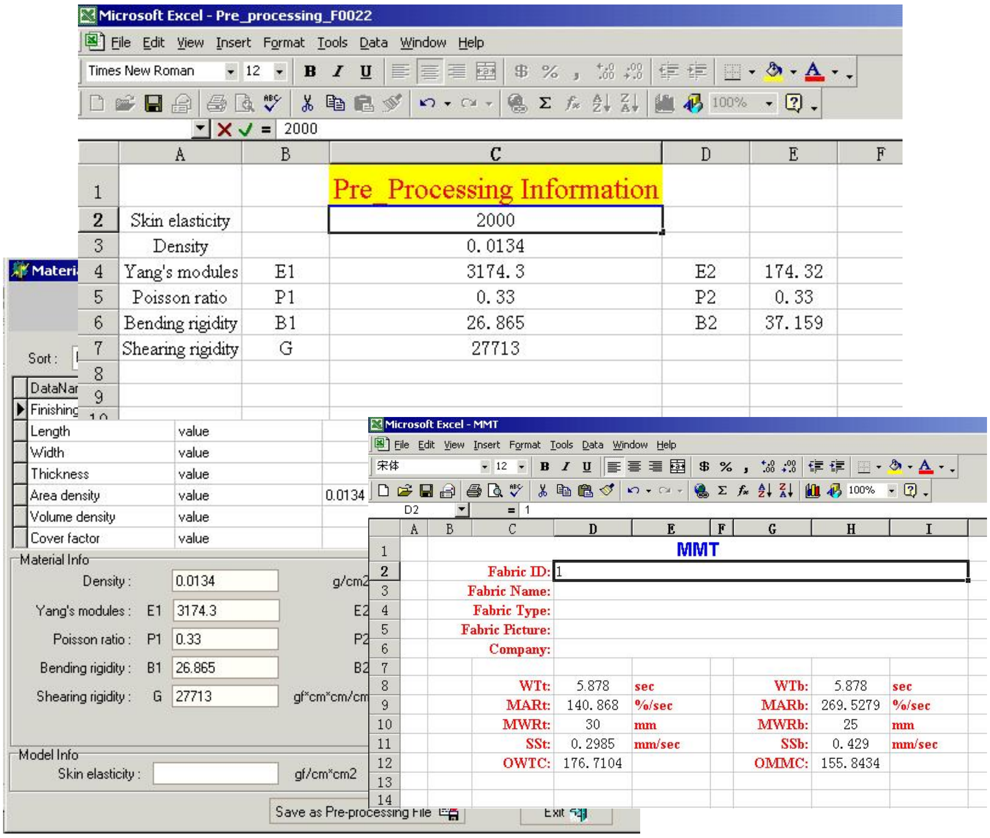
Clothing biomechanical engineering is defined as the application of a systematic and quantitative way of designing and engineering apparel products to meet the biomechanical needs of human body and to maintain an appropriate pressure and stress distributions on the skin and in the tissues for the performance, health and comfort of the wearer. Let us take an example

The product specification: a female's vest. The material is shown in the Table 7.1.

Table 7.1 Physical and mechanical properties of selected garment

	Garment		
	C98L2	N85L15	P98L2
Fiber content(%)	C(98)L(2)	N(85)L(15)	P(98)L(2)
Thickness(mm)	0.73	0.57	1.27
Weight(g/m*m)	179.00	215.00	220.00
Tensile			
LT	0.83±0.15	1.00±0.11	0.78±0.11
WT(gf/cm.cm*cm)	3.76±1.62	10.02±8.23	6.27±1.58
RT(%)	57.26±12.17	72.89±17.77	54.01±15.11
EMT(%)	24.56±6.12	43.26±23.77	56.39±37.89
Shear			
G(gf/cm.degree)	0.77±0.02	0.65±0.13	0.46±0.10
2HG(gf/cm)	2.21±0.14	1.57±0.49	1.47±0.18
2HG5(gf/cm)	2.47±0.22	1.70±0.50	1.57±0.19
Bending			
B(gf.cm/cm)	0.02±0.01	0.02±0.01	0.04±0.04
2B(gf.cm/cm)	0.03±0.01	0.04±0.01	0.06±0.05

Design aims: to design the clothing and simulation the deformations of clothing and human skin deformations during the wear. Figure 7.6 shows the main parameters selected from the database.



= 2000

	A	B	C	D	E	F
1			Pre_Processing Information			
2	Skin elasticity		2000			
3	Density		0.0134			
4	Yang's modules	E1	3174.3	E2	174.32	
5	Poisson ratio	P1	0.33	P2	0.33	
6	Bending rigidity	B1	26.865	B2	37.159	
7	Shearing rigidity	G	27713			
8						
9						

DataNar		
Finishing		
Length	value	
Width	value	
Thickness	value	
Area density	value	0.0134
Volume density	value	
Cover factor	value	

Material Info
Density : 0.0134 g/cm2
Yang's modules : E1 3174.3 E2
Poisson ratio : P1 0.33 P2
Bending rigidity : B1 26.865 B2
Shearing rigidity : G 27713 gf*cm*cm/cm

Model Info
Skin elasticity : gf/cm*cm2

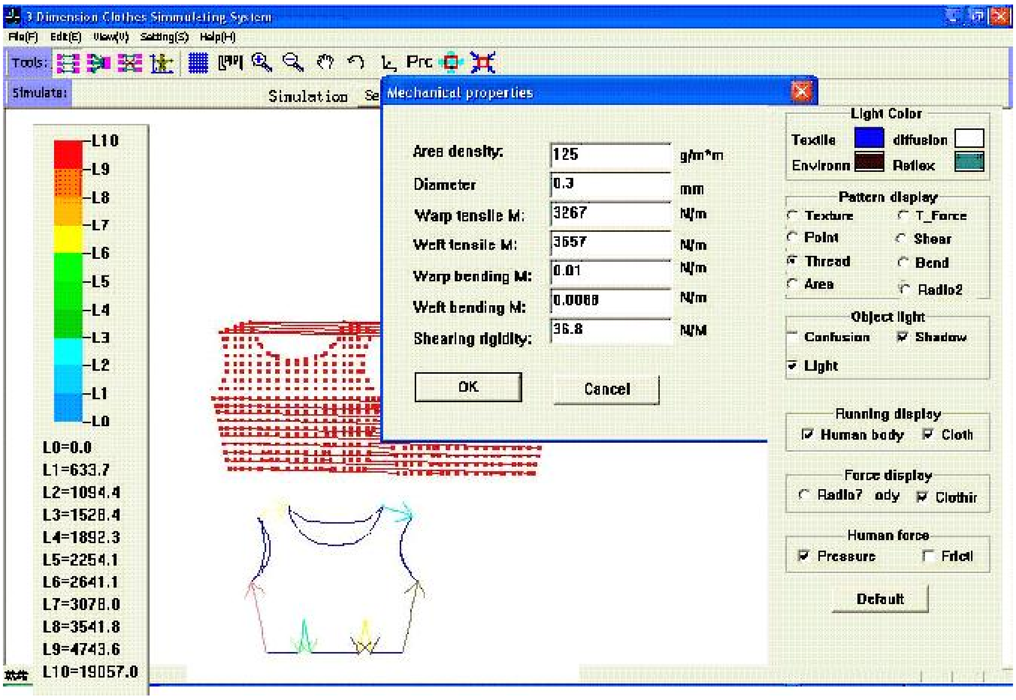
D2 = 1

	A	B	C	D	E	F	G	H	I
1				MMT					
2			Fabric ID:	1					
3			Fabric Name:						
4			Fabric Type:						
5			Fabric Picture:						
6			Company:						
7									
8			WTt:	5.878	sec		WTb:	5.878	sec
9			MARt:	140.868	%/sec		MARb:	269.5279	%/sec
10			MWRt:	30	mm		MWRb:	25	mm
11			SSt:	0.2985	mm/sec		SSb:	0.429	mm/sec
12			OWTC:	176.7104			OMMC:	155.8434	
13									
14									

Figure 7.6 The interface of pre-processing

7.4.2 Computational simulation

After completing the product specification and parameters preparation, the key step is simulation. Figure 7.7 shows the computational simulation part. Various parameters of fabric, human body are listed as outputs of the simulation results.



L0=0.0
L1=633.7
L2=1094.4
L3=1528.4
L4=1892.3
L5=2254.1
L6=2641.1
L7=3078.0
L8=3541.8
L9=4743.6
L10=19057.0

Area density:	125	g/m*m
Diameter	0.3	mm
Warp tensile M:	3267	N/m
Weft tensile M:	3557	N/m
Warp bending M:	0.01	N/m
Weft bending M:	0.0088	N/m
Shearing rigidity:	36.8	N/M

Light Color
Textile 🟦 diffusion ☐
Environn 🟫 Reflex 🟩

Pattern display
○ Texture ○ T_Force
○ Point ○ Shear
● Thread ○ Bend
○ Area ○ Radio2

Object light
☐ Confusion ☑ Shadow
☑ Light

Running display
☑ Human body ☑ Cloth

Force display
○ Radio7 ody ☑ Clothir

Human force
☑ Pressure ☐ Frictl

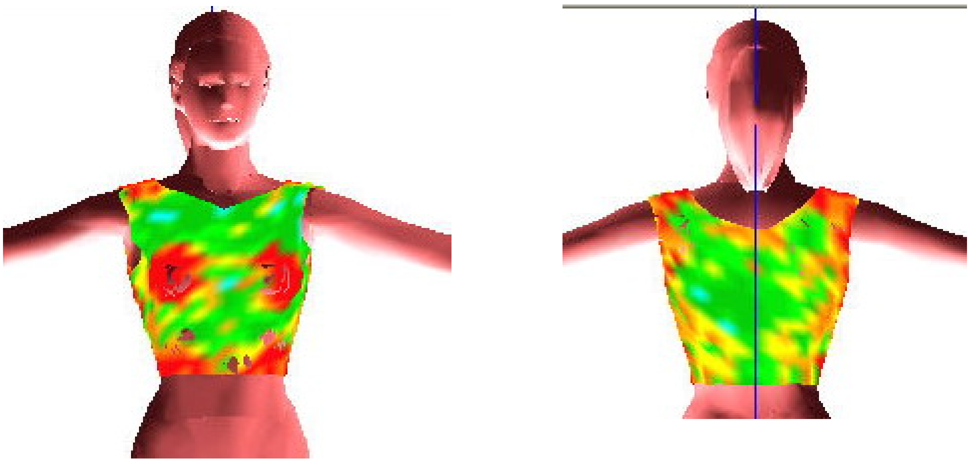
Figure 7.7 The interface of computational simulation

In the Figure 7.7, the designer can define the parameters used in the simulation. The different simulation results, for examples, the different types of forces that act on the clothing and human body, can be selected to be used to visualize the force distribution.

7.4.3 Post-processing

7.4.3.1 The simulated clothing pressure distributions

In order to present the mechanical simulation result of clothing and human body, the main forces acted on the clothing and skin deformation on the human body are shown in the graphics windows. Figure 7.8 and 7.9 show the simulation results.



C98L2 Front C98L2 Back

Figure 7.8 The Pressure forces on the clothing

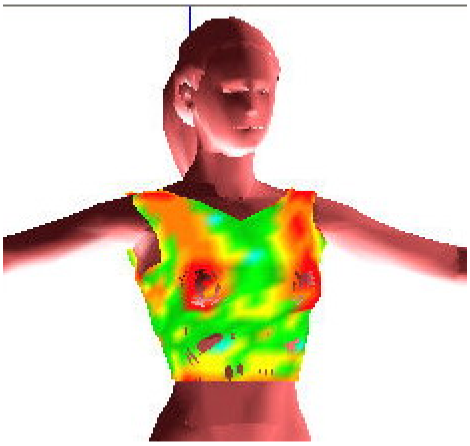


Figure 7.9 The tensile forces on the clothing

As shown in the design case, the integration system can help a designer to preview the mechanical performance of clothing and human body. Such mechanical performance is designed for intended wearing situations before the garment is made to test the design concept. Based on the simulation results, the designer is able to identify which design is better for special function application.

7.4.3.2 Skin pressure distributions

In the wearing process, the human body is deformed under pressure from the garment.

Figure7.10 shows the distributions of the skin pressure in wearing the vests.

Health and disease prevention have been a major concern of human beings, particularly for consumers in the new century in purchase decisions of their apparel products. Biological health and psychological happiness are critical indices reflecting quality of our lives, in which clothing plays very important roles. Clothing is one of the most intimate objects associated with the daily life of individual human beings, as it covers most part our body most of the time. Consciously or unconsciously, our physiological/biological status and psychological/emotional feelings are closely associated with the clothing we wear. Significant proportion of modern consumers understands the importance of clothing and demands apparel products with higher added values in terms of functional performance to satisfy various aspects of their biological and psychological needs in terms of communication, protection, healthcare, medicine and sensory comfort during wear. The main purpose of clothing biomechanical engineering design is just to design the special function clothing product for different area. The simulation results can show the pressure distribution on the human body. In the Figure 7.10, the skin pressure is towards the normal direction of the skin in the interface or against the garment pressure on the skin. The pressure value shows the areas subject to the pressure from the garment as well as the areas not subject to pressure. The pressure distributions are similar to the distribution of skin displacement respectively, suggesting that the skin deformation induces pressure on the soft tissues, which is defined as the skin pressure.

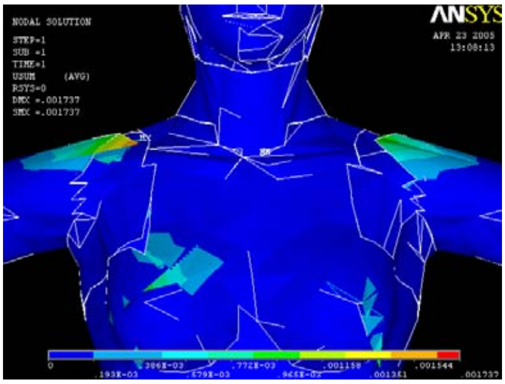


Figure 7.10 Skin pressure distribution

7.5 CONCLUSION

In this chapter, the CAD technology for clothing biomechanical engineering design integration platform is presented. The development of this platform will be based on the computer technology, mathematical model, textile and clothing science, and experimental methodology. The function of this system integrates design, analysis and evaluation together to support clothing biomechanical engineering design, and it can be applied to establish scientific principles for the development of new functional products with superior performance to meet the requirements from both consumers and doctors. In this chapter a design case is reported to illustrate the functions and design flow in integration environment.

This integration system has two features. The first one is that this system is integrated CAD system. The engineering database, the simulation software package, and visualization tool set are integrated together to support the design process. The second one pertains to the integration system; a function design platform is developed systematically according to the requirement of function design procedures with friendly interfaces.

The limitation of this system is data format conversion. With more software packages integrated into the integration system, different software may have special data description format. It is necessary to create a united in data conversion format to ensure efficient communication between the software packages.

CHAPTER 8 CONCLUSIONS AND FUTURE WORK

In this thesis, a theoretical framework has been studied and developed for establishing a clothing biomechanical design platform. This thesis focuses on development of an integrated computer aided design system for clothing biomechanical engineering design, including development of clothing engineering database, clothing geometric model, biomechanical simulation model, mechanical sensory perception model, visualization interfaces, which has been integrated to form a CAD platform. The achievement of this study is summarized as follows.

8.1 CONCLUSIONS

In Chapter 1, comprehensive literature review was conducted in a number of areas: integration technology, engineering database, clothing biomechanical design, clothing biomechanics and sensory engineering. The progresses in each area were surveyed and knowledge gaps were identified to ensure the originality of the study. Computational models and simulation techniques have been developed in textile and clothing biomechanics. However, a number of knowledge gaps for establishing a CAD software platform for clothing biomechanical engineering design were identified, including: development of engineering database, hybrid geometry model to determine the shape of clothing, user-friendly software for constructing 3D garment from 2D patterns, clothing biomechanical models, simulation model for predicting mechanical sensory perception, and software platform to integrate them all together to support the engineering design process. On basis of literature review, the objectives of the study were derived to fill the knowledge gaps. To achieve the objectives, extensive researches were carried out and reported in Chapter 2, Chapter 3, Chapter 4, Chapter 5, Chapter 6 and Chapter 7.

Chapter 2 reported the development of an engineering database system for clothing biomechanical engineering design. The special requirements of textile and clothing function engineering on databases were studied by detailed examination of the complex and dynamic design process in comparison with business database, including different types of data and flexible data formats. An engineering database was designed and developed accordingly to store various complex structure data and various forms of data values, and to meet the special need of the complex iterative-decision-making design process, design description, design management and integration of multidisciplinary knowledge and data. It provides a communication environment for different users and supports product development, design process control, quality assurance, and product performance evaluation.

Chapter 3 reported the development of a hybrid simulation model by integrating mathematical models with computation algorithms to derive 3D garment data from a garment’s 2D pattern and to specify human body-garment contacting conditions for computational simulations. In this process, we are required to construct a surface that not only satisfies interpolating conditions or preserves shape, but also has C^1 or C^2 continuity or exact conformity regardless of whether the geometric distribution of characteristic vertices is uniform or not. To achieve this, a model with rational recurrence curves and recurrence surfaces in multivariate B-Form on some regions was developed to overcome the limitation of the bicubic spline interpolating method and Coons surface method for finding a suitable parameter domain and its partition on a space mesh.

In Chapter 4, a biomechanical engineering of clothing design systems using different methods was developed. The main methods include an improved particle method for textile mechanical modeling, hybrid method for 3D clothing modeling and mechanical simulation, and finite element model with the hybrid method for simulation of biomechanical behavior of human body. These methods cover four major aspects: (1) the consideration of human factors in engineering design of clothing products; (2) the simulation and visualization of the wearing performance of clothing and human body deformation; (3) integration finite element software packages into the system to simulate the human body biomechanical behaviors; (4) integration of the engineering design database into the system for inputting, storing and displaying the information during the design process.

In Chapter 5, the prediction of the models was validated against the skin pressure measurements collected in wear trials. Good agreements between theoretical predictions and experimental observations were observed. Further, a fuzzy logic model was developed by investigating the psychophysical relationships between the data on pressure sensory comfort and skin pressure measurements. A fuzzy inference system was developed and employed to predict overall dynamic pressure comfort on the basis of individual pressure sensations at nine body locations. Good agreement was obtained between predicted and actual overall perception of clothing pressure comfort. By integrating this fuzzy logic model with the clothing biomechanical model, fabric mechanical properties can be used to predict skin pressures, which then can be used to predict the pressure sensations at different body locations and overall pressure comfort.

In Chapter 6, visualization and analysis interfaces were developed for clothing biomechanical engineering design to analyze and evaluate the functional performance of clothing. In order to analyze and understand the results of the mechanical simulation effectively, numerical data from the simulations on skin pressure distributions, stress and strain distributions and pressure sensations were transformed into various graphical expressions to help engineers and designers to analyze and evaluate their designs. To generate good animations, 4-Point subdivision scheme was employed in building in-between frames, which can generate blander vision effect than linear interpolation method and gain more efficiency than higher order spline interpolation method. With these interfaces, the numerical simulation results can be presented visually as dynamic animation movies, which can be easily understood by designers and consumers with little scientific and engineering knowledge.

Chapter 7 presents an integration CAD platform to provide an integrated design environment for clothing biomechanical engineering design, which was developed by integrating all the models, databases and computer interfaces developed in previous chapters. This integration platform has two features: (1) this platform is an integrated CAD system, in which the engineering database, the simulation software package, and visualization tool set are integrated together to support the design process; (2) the system is developed systematically according to the requirement of functional engineering design procedures with friendly interfaces. This platform integrates design with mathematical simulations, analysis and evaluation together to support and guide the complex iterative-decision-making design process, which can be applied to establish scientific design principles for the development of new functional products with superior biomechanical performance. A design case was reported to illustrate the functions and design flow in the integrated CAD system.

8.2 FUTURE WORKS

The objectives of this study have been achieved. However, further research needs to be conducted to develop the system into a system for industrial applications. The limitation of this system is data format conversion. As a number of software packages are integrated into the CAD platform, and the different software has its own special data format, which is normally not recognized by other software packages. There is an urgent need to create the standardized data conversion format that can be recognized by different software packages to facilitate effective communications between the software packages. For accelerate design innovations, data mining function needs to be built in the engineering database. Simulation system efficiency is another area to be further improved in the future work. Finally, systematical experimental studies need to be carried out to establish more comprehensive psychophysical relationships between skin pressure distributions and psychological pressure sensations.

References

1. ABAQUS, I., *ABAQUS/CAE Users' manual.* 2004: Pawtucket, USA: ABAQUS, Inc.
2. Baraff, D., *Rigid Body Simulation.* Course Notes of SIGGRAPH, 1998: p. D1-D68.
3. Baraff, D. and A. Witkin., *Large Steps in Cloth Simulation.* SIGGRAPH, 1998.
4. Breen, et al., *A Physically Based Particle Model of Woven Cloth.* The Visual Computer, 1992. **8**(6): p. 264-277.
5. Breen, et al., *A Particle-Based Model for Simulating the Draping Behavior of Woven Cloth.* Textile Res. J., 1994. **64**(11): p. 663-685.
6. Breen, D.E., *Clothing Modeling and animation*. 2000: A K Peters, Lid.
7. Carignan, M., et al, *Dressing Animated Synthetic Actors with Complex Deformable Clothes.* in ACM SIGGRAPH,New York, 1992.
8. Charlie C.L. Wang, Yu Wang, and M.M.F. YUen, *Design Automation for Customized Apparel Products.* Computer Aided Design, 2005. **37**: p. 675-691.
9. Charlie C.L. Wang, Yu Wang, and M.M.F. Yuen, *Feature Based 3D Garment Design through 2D Sketches.* Computer Aided Design, 2003. **35**: p. 659-672.
10. Chen, W.J. and S.T. Tan T. N. Wong, *A constrained Finite Element Method for Modeling CLoth Deformation.* The Visual Computer, 1999. **15**(90-99).
11. Chorafas, Dimitris N., *The engineering database*. 1988, London, Boston: Butterworths.
12. Collier, J.R., et al., *Drape Prediction by Means of Finite-Element Analysis.* Journal of the Textile Institute, 1991. **82**(1): p. 96-107.
13. Coquillart, S., *Extended Free-Form Deformation: A Sculpturing Tool for 3D Geometric Modeling.* Computer Graphics, 1990. **24**.
14. Creig, I., *The Application of a New Generation of Consumer Research Techniques to Predicting and Maximising Market Share in the Fiber Market.* Journal of Textile and Institute, 1994. **85**: p. 231-243.
15. D. Sabin, M., *Behaviour of recursive division surfaces near extraordinary points.* Computer-Aided Design, 1978. **10**: p. 356~360.
16. Daley, R., *Integration Technologies Available,* in *Integration Technology for CASE*, R. Daley, Editor. 1993, Avebury Technical. p. 1-20.
17. Denton, M.J., *Fit, Stretch and comfort.* Journal of textile institute, 1972. **1**(1): p. 12-17.
18. DeSalvo, G.J., *ANASYS engineering analysis system example manual*. 1985: Houston, Pa.: Swanson Analysis System.
19. Dimitris A. and Kalogeropoulos, *Towards knowledge-based systems in clinical practice: Development of an integrated clinical information and*

knowledge management support system. Computer Methods and Programs in Biomedicine, 2003. **72**(1): p. 65-80.

20. Earnshaw, Rae A., *Visualization and modeling*. 1997: San Diego, Calif.: Academic Press.
21. Eischen, J.W., S. Deng, and T.G. Clapp, *Finite-Element Modeling and Control of Flexible Fabric Parts.* IEEE, Computer Graphics and Applications, 1996. **16**(5): p. 71-80.
22. G. Pahl, W. Beitz, *Engineering Design*. 1977: Spring Vwelag, Berlin Heidelberg New York Tokyo.
23. Gao, C., *Computer Simulation and Modeling Techniques for 3D Virtual Garment*, in *Computer Science*. 2004, ZHongshan University: Guangzhou.
24. Gerelly, C.S., *The Further Direction for Integration Technology*, in *Integration Technology for CASE*, R. Daley, Editor. 1993, Avebury Technical.
25. Ghaddar, N., *Integrated human-clothing system model for estimating the effect of walking on clothing insulation.* Journal of Thermal Sciences, 2003. **42**(6): p. 605-619.
26. Ghulam Mustafa, Falai CHen, and J. Deng, *Estimating error bounds for binary subdivision curves/surfaces.* Journal of Comoputational and Applied Mathematics, 2005.
27. H.J.Pels, *Integration in production management systems: An integrating perspective.* Integration in production management systems, 1992.
28. H.N. Ng, R.L. Grimsdale, and W.G. Allen, *A System for Modeling and Visualization of CLoth Material.* Computer & Graphics, 1995. **19**: p. 423-430.
29. Hallquist, J.Q., *LS-DYNA Theoretical Manual*. 1998: Livermore Software Technology Corporation.
30. Hatch, K.L., *Textile Science*. 1993, USA: West Publishing Company, New York.
31. Hearle, J.W.S., *Fabric mechanics as design tool.* Indian Journal of fibre and textile research, 1994. **19**(3): p. 107-113.
32. Hibbitt and K.S., *Chapter 2 ABAQUS Basics, in Getting Started with ABAQUS*. 2003.
33. Hollies, N.R.S., *Clothing Comfort*. 1977, Michigan: Ann Arbor Science Publishers, Inc.
34. Hollies, N.R.S., et al., *A human perception analysis approach to clothing comfort.* Textile Research Journal, 1979. **49**: p. 557-564.
35. House, D., H., and D. Breen, E., eds, *Cloth Modeling and Animation*. 2000, Natick, Massachusetts: A. K. Paters,Ltd.
36. Hsu, T., *Computer-aided design: an integrated approach*. 1992: St. Paul, Minn.: West Pub. Co.

37. Hu, J.L., W.X. Chen, and A. Newton, *A psychophysical model for objective hand evaluation: an application of Steven's Law.* Journal of Textile Institute, 1993. **84**: p. 354-363.
38. Imaoka, H., et al., *Analysis of Deformations in Txtile Fabric.* SEN-I GAKKAISHI, 1988. **44**(5): p. 217-228.
39. Imaoka, H., et al., *Prediction of Three-Dimensional Shapes of Garments from Two-Dimensional Paper Patterns.* SEN-I GAKKAISHI, 1989. **45**(10): p. 420-426.
40. J.L. Hu and J.G. Teng, *Computational Cloth Mechanics: Present Status and Future Trends.* Finite Elements in Analysis and Design, 1996. **21**: p. 225-237.
41. Judith, R. and Brown, Rae Earnshaw,Mikael Jern, *Visualization: using computer graphics to explore data and present information*. c1995: New York: J. Wiley.
42. K. Hinds and J. Mccartney, *Interactive Garment Design.* The Visual Computer Graphics, 1990. **6**: p. 53-61.
43. K.R. Dittrich and J.L. Encarnacao, *Engineering databases*. 1990, Berlin: Spring Verlag.
44. Kang, T.J.a.S.M.K., *Development of Three-dimensional Apparel CAD System, Part II:Prediction of Garment Drape Shape.* International Journal of Clothing Science andTechnology, 2000. **12**(1): p. 39-39.
45. Kawabata, S., *The Standardization and Analysis of Hand Evaluation*, ed. T.T.M.S.o. Japan. 1980.
46. Kawabata, S., *The Standardization and Analysis of Hand Evaluation, Hand Eval. and Stand*. 1975, Osaka: Committee of the Textile Machinery Society of Japan.
47. Kawabata, S., NIWA, *Influence of fiber and process parameters on product performance.* 2000.
48. Klir, G.J.a.B.Y., *Fuzzy sets and Fuzzy logic, Theory and applications*. 1995: Prentice Hall P.T.R.
49. Kochan, D. and Jacobs, *Fundamental aspects on systems of integrated information processing for manufacturing*, in *Integration of CAD/CAM*, d. Kochan, Editor. 1984, North-holland.
50. Kozar, Z., *Integrated CAD/CAM systems as coming stage of machinery production automation process*, in *Integration of CAD/CAM*, d. Kochan, Editor. 1984, North-Holland.
51. Kunii, T.L., Gotoda, H., *Singularity THeoretical Modeking and Animation of Garment Wrinkle Formation Process.* Visual Computer, 1990. **6**: p. 326-336.
52. Kwan, T.J.T., *Integrated system simulation in X-ray radiography.* Computer Physics Communications, 2001. **142**: p. 263-269.
53. Kwork, Y.L., et al., *Subjective Evaluation of Jeans Pressure Comfort-Including Idearl Jeans.* 2001.

54. Li, Y., *Dimensions of Comfort Sensations During Wear in a Hot Condition.* Journal of Federation of Asian Textile Association, 1998.
55. Li, Y., *The Science of Clothing Comfort*. 2001, UK: Alden, Oxford.
56. Li, Y., *Wool Sensory Properties and Product Development.* 2nd China International Wool Conference, Xi'an, China, April, 1998: p. 15-16.
57. Luo, X., *Curves and surfaces in Computer Aided Geometric Design*. 1991, Dalian University of Technology.
58. Luo, X. and J. Yumin, *Bezier surfaces in multivariate B-form.* Chinese Sci. Bull, 1994. **9**.
59. Luo Xiaonan, L.N., Gao Chenyin, *Fairing geometry modeling based on 4-Point interpolatory subdivision scheme.* Journal of Computational and Applied Mathematics, 2004. **163(1)**: p. 189-197.
60. M. L. Boerstra, *Engineering databases: survey of existing engineering database management systems, criteria for selecting a database, and some practical experiences in applying a database system: report of the CIAD Project Group on Engineering Databases*. 1985: Amsterdam; New York: Elsevier.
61. M. Oshita and A. Makinouchi. *Real-Time Cloth Simulation with sparse Particles and Curved Faces*. in *THe Fourteenth Conference of Computer Animation*. 2001.
62. Minamitani, H.a.N.H., *A Neural Network Model of Pain Mechanisms: Computer Simulation of the Central Neural Activities Essential for the Pain and Touch Sensation.* IEEE transactions on systems, man, and cybernetic, SMC-11, 1981: p. 481-493.
63. Minamitani, H.a.N.H., *A Neural Network Model of Pain Mechanisms: Functional Properties of the Network Cells Providing the Power Law.* IEEE transactions on systems, man, and cybernetics, SMC-12, 1982: p. 907-913.
64. Mitsuno, T., et al., *Studies on the Clothing Pressure (Part 1) - Measurements by a Hydrostatic Pressure-Balanced Method.* Journal of the Japan Research Association for Textile End-Uses, 1991. **32**: p. 362-367.
65. Morooka, H., M. Nakahashi, and H. Morooka, *Compressive property of legs and clothing pressure of pantyhose from the view point of difference in age.* Journal of the Japan Research Association for Textile End-Uses, 997. **38**: p. 324-332.
66. N.Dyn, J.A.G. and D.Levin., *A 4-Point interpolatory subdivision scheme for curve design.* Computer-Aided Geometric Design, 1987(4): p. 257-268.
67. Ng H., N.a.G., R. L., *Computer Graphics Techniques for Modeling Cloth.* IEEE, Computer Graphics and Applications, 1996. **16**(5): p. 28-41.
68. Ng, K.C., *An integrated surveillance system-human tracking and view synthesis using multiple omni-directional vision sensors.* Image and Vision Computing, 2004. **22**(7): p. 551-561.

69. Nigg, B.M., and Herzog, *Biomechanics of the Musculo-skeletal System*. 1994, Singapore: John Willey $ Sons.
70. Provot, X., *Deformation Constraints in A Mass-Spring Model to Describe Rigid Cloth Behavior.* in Graphics Interface, 1995.
71. R.E. Barnhill and H.s. Ou, *Surfaces defined on surfaces.* Comouter Aided Geometrical Design, 1990. **7**: p. 323-336.
72. Ruomei Wang, et al. *A CAD system for clothing biomechanical sensory engineering*. in *17th IMACS World Congress Scientific Computation, Applied Mathematics and Simulation*. 2005. Paris, France.
73. Ruomei Wang, Y.L., *3D-Apparel CAD system - M-Smart*. 2005, 2005SR01691,China.
74. S.Coren, L.M.W., *Sensation and perception*. 1989, New York,NY,USA: Harcourt Brace Jovanovich.
75. S.F.Chen, J.L. Hu, and J.G. Teng, *A Finite Volume Method for Contact Drape Simulation of Woven Fabrics and Garments.* Finite Element in Analysis and Design, 2001. **37**: p. 513-531.
76. Segerlind and L. J., *Applied finite element analysis*. 1984: New York: Wiley.
77. Sifakis, et al., *Hybrid Simulation of Deformable Solids.* ACM SIGGRAPH/Eurographics Symposium on Computer Animation (SCA), 2007: p. 81-90.
78. Slater, K., *Human Comfort*. 1985, USA: Thomas Springfield.
79. Taillefer F., *Mixed Modeling.* Proc. Compugraphics, 1991: p. 467-478.
80. Tarfaoui, M.a.S.A., *Numerical Study of the Mechanical Behaviour of Textile Sturctures.* International Journal of Clothing Science and Technology, 2001. **13**(3/4): p. 166-175.
81. Terzopoulos, D., et al, *Elastically Deformable Models.* in SIGGRAPH, 1987.
82. Terzopoulos, D.a.K.F., *Deformable Models.* The Visual Computer, 1988: p. 306-331.
83. Turquin, E., *Sketching Garments for Virtual Characters.* Eurographics Workshop on Sketch-based Interfaces and Modeling, 2004.
84. Ullman, D. Jeffrey, *Principles of database systems, Second Edition*. 1982: Computer Science Press.
85. Usowicz, T.W., *Integrating reverse engineering into computer-aided software engineering*. 1991, University of California: San Francisco.
86. Volino, Pascal, *Virtual clothing: theory and practice*. 2000, Berlin: New York: Springer.
87. Volino, P., Courchesne, M., *Versatile and Efficient Techniques for Simulating Cloth and Other Deformation Objects.* SIGGRAPH, 1995: p. 137-144.
88. Volino, P., M. Courchesne, and N.M. Thalmann, *Versatile and Efficient Techniques for Simulating Cloth and Other Deformable Objects.* in SIGGRAPH, 1995.

89. W.J. Rasdorf and R.E. Fulton, *Engineering database management:leadership key for the 90's*. 1898, New York: American Society of Mechanical Engineers.

90. Wang, X. B., *Study of Pressure Comfort and Function of Sport-Guard Textiles.* Textiles Journal (China), 1989(5): p. 13-16.

91. Weil, J., *The Synthesis of Cloth Objects.* Computer Graphics, 1986: p. 49-54.

92. Wong, A., *Prediction of clothing sensory comfort using neural networks and fuzzy logic*, in *Textile and clothing*. 2003, Hong Kong Polythnic University.

93. Wong, A.S.W., et al., *Statistical Simulation of Psychological Perception of Clothing Sensory Comfort.* Journal of Textile Institute, 2001.

94. Woodson, T.T., *Introduction to Engineering Design*. 1966: New York: McGraw-Hill.

95. X.Q., D., *Numerical simulation of mechanical interaction between lower-limb and compression stocking.* Journal of Information and Computational Science, 2004(1).

96. Xiaonan Luo and H. Nie, *Recurrence surfaces on orbitrary quadrilateral mesh.* Journal of Comoputational and Applied Mathematics, 2002. **144**: p. 221-232.

97. Xiaoqun Dai, Tokao Furukawa, and S. Mitsur, *Drape Formation based On geometric Constraints and Its Application to Skirt Modeling.* Internal Journal of Clothing Science and Technology, 2001. **13**: p. 23-31.

98. Xiaoqun Dai, Y.L., and Xin Zhang, *Simulating Anisotropic Woven Fabric Deformation with a New Particle Model.* Textile Res. J., 2003. **73**(12): p. 1091-1099.

99. Y. Li and X. Zhang, *Mechanical Sensory Engineering Design System for Textile and Apparel Products.* Journal of Textile and Institute, 2005.

100. Y. Li, X.-Q.D., *Biomechanical engineering of textiles and clothing*. 2006, Cambridge CB1 6AH, England: Woodhead publishing limited.

101. Yeung, K.W., Li, Y., Zhang, X., *Finite Element Simulation of Body-Garment Dynamic Mechanical Interactions on the Knee Surface.* Finite Element in Analysis and Design, 2001.

102. Zhang, J., *A holonic architecture of the concurrent integrated process planning system.* Journal of Materials Processing Technology, 2003. **139**: p. 267-272.

103. Zhang, X., *Mechanism of Woven Fabric Bagging*. 1999, Hongkong Polythnic University.

104. Zhang, X., K.W. Yeung, and Y. Li, *Numerical simualtion of 3D dynamic garment pressure.* Textile Research Journal, 2002. **72**(3): p. 245-252.

105. Zhou, X., *ST715 particle system user manual*. 2003: Hong Kong Polytechnic University.