The Hong Kong Polytechnic University

Institute of Textiles and Clothing

Design Innovation of Functional Cycling Sportswear

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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

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______________________________ (Signed)

Luo Jie (Name of student)

TO MY FAMILY

For their constant love, support and encouragement

ABSTRACT

This research aims to develop an integrated design model and realize design innovation of functional cycling sportswear (FCS). Based on investigating the characteristics of cycling sport and the mechanisms involved in thermo-physiology, biomechanics and aesthetics, this design innovation model provides a novel design framework to achieve cycling sportswear with desirable functions for satisfying the aesthetic, thermal and biomechanical functional requirements of the cyclists during wear. The research work has been conducted by developing the theoretical framework, and then simultaneously carrying out aesthetic, thermal and biomechanical functional design, finally creating FCS prototypes with existing machines and technologies.

The cycling sportswear by meeting the multi-functional requirements in terms of thermal comfort, biomechanical protection and aesthetics, is highly demanded by cyclists. These multi-functional requirements lead to the design innovation of FCS with application of multi-disciplinary knowledge integration. A theoretical framework for the FCS design has been developed to model the design process by systematically integrating different knowledge and identifying the relationships between them, which demonstrates that the design innovation of FCS is the fusion of aesthetic design with thermal and biomechanical functional design.

With this theoretical framework, the aesthetical design, thermal functional design and

biomechanical functional design of cycling sportswear have been carried out and reported in individual chapters. Based on the fusion of the design in these three aspects, the final fused functional cycling sportswear design was realized through illustrating the design inspiration and design brief. Three collections of FCS prototypes were created according to the different applications, including Collection I for the 5th Qiaodan Cup International Sport Equipment Design Contest, Collection II for the exhibition of the SMART Convention 2008, and Collection III for the 2012 London Olympic Games.

In summary, with these achievements in this study, a model of multi-functional design innovations has been developed scientifically and systematically, with which the high performance sportswear products with superior functional performance can be achieved for various applications.

RESEARCH OUTPUTS

Refereed Journal Articles:

1. **Luo, J.**, Mao, A. H., Li, Y., Au, J., Design innovation model for cross-functional cycling sportswear design, Textile Research Journal, 2012, **(SCI,** submitted**)**.

2. **Luo, J.**, Mao, A. H., Li, Y., An innovative engineering design framework of digital clothing for superior thermal performance, Journal of Information & Computational Science, 2011, Vol.8(3), pp. 422-430 **(EI)**.

3. Mao, A. H., **Luo, J.**, Li, Y., Multi-scale simulation and system architecture for thermal engineering design of digital clothing, Journal of Information & Computational Science, 2011, Vol.8(3), pp.570-578 **(EI)**.

4. Mao, A. H., **Luo, J.**, Li, Y., Luo, X. N., Wang, R. M., A multi-disciplinary strategy for computer-aided clothing thermal engineering design, Computer-Aided Design, 2010 **(SCI, Impact factor 1.67)**.

5. Mao, A. H., **Luo, J.**, Li, Y., Engineering design of thermal quality clothing on a simulation-based and lifestyle-oriented CAD system, Engineering with Computers, 2010 **(SCI, Impact factor 0.87)**.

Conference Presentations and Publications：

1. **Luo, J.**, Li, Y., Zhang, X., Wang, Y. J., Design and functional performance of cycling wear, The 1st Textile Bioengineering and Informatics Symposium, 2008, Hong Kong, pp. 766-772

2. **Luo, J.**, Yao, L., Au, J., Luximon, A., Hu, J. Y., Lv, R., Li, Y., Critical evaluation on design and function of cycling wear, WACBE World Congress on Bioengineering, 2009, Hong Kong, pp.554-559

3. **Luo, J.**, Guo, Y. P., Au, J., Mao, A. H., Li, Y., Yao, L., Thermal biologic analysis of the human body during cycling sports, The 3rd Textile Bioengineering and Informatics Symposium, 2010, Shanghai, pp.1431-1436

4. **Luo, J.**, Li, Y., Au, J., Zhang, X., The evolution of road cycling sportswear: A review and discussion, The 4th Textile Bioengineering and Informatics Symposium, 2011, Beijing, pp.1652-1658

5. **Luo, J.**, Mao, A. H., Li, Y., Au, J., Zhang, X., Aesthetic elements in functional cycling sportswear design, The 5th Textile Bioengineering and Informatics Symposium, 2012, Japan, (Accepted)

Books/Chapters in Books：

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Exhibitions：

1. Li, Y., Guo, Y. P., Yao, L., **Luo, J.**, Cao, X. Y., Chao, H., Wang, Y. J., Zhou, J. Y., Lv, R., Chen, C. M., Huang, S. H., Han X., "Glory" – The Brilliance of Olympic and Sportswear Innovation, Hong Kong, Jul., 2012
2. Li, Y., Yao, L., **Luo, J.**, Guo, Y. P., Cao, X. Y., Chao, H., Wang, Y. J., Zhou, J. Y., "Speed" – The Brilliance of Olympic and Sportswear Innovation, Hong Kong, Jul., 2012
3. Li, Y., Yao, L., **Luo, J.**, Guo, Y. P., Cao, X. Y., Chao, H., Wang, Y. J., Zhou, J.

Y., “Angle” – The Brilliance of Olympic and Sportswear Innovation, Hong Kong, Jul., 2012

4. HKRITA, Project PI.: Li Yi, **Luo, J.**, Innovation and Technology Commission – Exhibition of Interstoff Asia Essential, Hong Kong, Mar., 2012
5. **Luo, J.**, Li Y., Au, J., Zhang, X., – Exhibition of the Arts of Fashion Symposium, San Francisco Art Institute, U.S.A. Oct., 2011
6. HKRITA, Project PI.: Li Yi, **Luo, J.**, “Design Innovation of Functional Cycling Sportswear” – Exhibition of Innovation and Technology Symposium, Hong Kong, Apr., 2011
7. Li, Y., Yao, L., **Luo, J.**, Guo, Y. P., Cao, X. Y., Chao, H., Wang, Y. J., Zhou, J. Y., “Cycling Functional Sportswear” – 1st Textile Bioengineering and Informatics Society (TBIS) International Conference, Hong Kong, Aug., 2008

Patents and Copyright on Intellectual Property：

1. Li, Y., Hu, J. Y., Yao, L., **Luo, J.**, Cao, X. Y., Chao, H., Guo, Y. P., Zhou, J. Y., Wang, Y. J., 自行车运动服的制备方法以及自行车运动服, China Patent Office, Filing date: 22 Oct 2010（RIP-31A，Filing number 201010255317.1）.

Honours and Awards：

1. **Luo, J.**, Li, Y., Au, J., Zhang, X., Arts of Fashion International Student Design Competition, **Finalist**, the Arts of Fashion Foundation, San Francisco, USA, Oct., 2011

2. **Luo, J.**, Li, Y., Au, J., Zhang, X., Cao, X. Y., “ComMax”, **Golden Award** in the 5th Qiao Dan Cup International Sport Equipment Design Competition, Beijing, China, Oct, 2010

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CHAPTER 1 INTRODUCTION

1.1 Research Background

The recent increase in people's interest in sports has developed into a cultural phenomenon. Sport is no longer just a simple activity: it is a business, media spectacle, culture, and a global industry (Andrew, 1998). Moreover, sportswear is no longer just sportswear: it has integrated art, design, and fashion. Sportswear has become increasingly friendlier, more comfortable, and high-tech (Salazar, 2008; Ma and Yan, 2004; O'Mahony and Braddock, 2002). With the greater attention being given to the research and development of sportswear, its design concept and method have been undergoing great changes as well. The majority of research has focused on sportswear design, especially in many European and American research centers (Wang, 2008). A sportswear designer should possess a diversified knowledge of the features of sportswear, and understand the factors of sports in terms of culture, technology, aesthetics, and functions during sportswear design, thus satisfying the diverse requirements of the wearer.

With the increase in the application of science and technology in sports, sportswear is becoming increasingly important as a high-tech performance factor (Ma and Yan, 2004; O'Mahony and Braddock, 2002; McKenzie, 1997; Shishoo, 2005). In sports, a slight difference can determine whether one becomes a winner or a loser. Athletes need to consider external factors more, such as training instruments and sportswear, which may possibly influence their performance, aside from continuous and insistent physical training (Ma and Yan, 2004; O'Mahony and Braddock, 2002; Wang, 2008). An increasing number of athletes believe they can perform better in sports not only by being in top physical condition, but also by choosing the right garment or equipment during sporting events (Andrew, 1998).

Sportswear design benefits immensely from new developments in textile technologies (Andrew, 1998; Shishoo, 2005). Advanced textile technologies enable sportswear to provide more thermal comfort and to meet biomechanical requirements (Bramel, 2005; McCann, 2005; Stegmaier et al., 2005). Sportswear with superior functional performance may help athletes rapidly transport sweat generated during movement away from the skin and decrease skin temperature, thus removing the athlete's discomfort due to the wet clothing (Wong et al., 2005). Meanwhile, functional sportswear protects athletes from muscle injuries, relieves exercise load (Doan et al., 2003), and increases muscle power output (Bringard et al., 2006; Gill et al., 2006). To seize the market, famous brands, such as Nike and Adidas, are dedicated to developing innovative textile materials and including functional sportswear design according to the micro-requirements of various sports with the support of high technology (Braddock, 1998; François, 1999).

Given the strong impact of sportswear on athletic performance, sportswear is being customized and designed for particular kinds of sports, in accordance with the characteristics of the event and the biological features of the athletes, to improve wearer's performance to the greatest extent (O'Mahony and Braddock, 2002). Cycling sportswear is one of the most commonly customized functional sportswear. In 1898, the world's fastest cycling record of 17.4 km/h was achieved by Taylor, a famous professional cyclist (Ritchie, 1996). However, with the aid of new equipment and training methods, this speed record was continuously broken by the athletes who came after him. In a bicycle race, when the ride velocity reaches 32 km/h, more than 90% of the athlete's energy is consumed by his or her clothing's friction with the atmosphere (Ma and Yan, 2004). Even wrinkles on sportswear can decrease the ride velocity of a cyclist. Hopefully, high-tech cycling sportswear will relieve the friction from the atmosphere and strengthen the ability of the clothing to wrap around the wearer's muscles and generate more power (O'Mahony and Braddock, 2002; Xu and Tao, 2002; Zhang and Qiao, 1997). The above are just a few examples of how high technology is widely applied in the design of functional cycling sportswear (FCS).

Cycling has become a very popular sport and an important component in various sporting events; hence, the design of cycling sportswear is attracting much interest among athletes, designers, and manufacturers (McKenzie, 1997). The presence of innovative materials and special fabric structures, such as moisture management material, UV-protection material, and less flexible material, enables cycling wear design to include additional requirements for thermal comfort and biomechanical needs, and thus design and produce comfort and protective high-tech sportswear (Bramel, 2005; Li, 2001; Shishoo, 2005). The design of cycling sportswear should be a fusion of art and technology, which will offer the human body better functional performance, such as thermal comfort, muscle injury prevention, fatigue release, and increased power output, rather than only fulfilling aesthetic needs.

In this research, an innovative multi-disciplinary design of cycling sportswear is carried out with the fusion of aesthetic design, thermal functional design, and biomechanical functional design. This design was based on a systematic investigation of thermal physiological, biomechanical, and aesthetic mechanisms, and a scientific identification of thermal functional requirements, biomechanical functional requirements, and aesthetic requirements. The approach to achieve functional cycling sportswear design was established to satisfy these multi-aspect requirements.

1.2 Research Aim and Objectives

The fundamental knowledge acquired for this study can be obtained by literature review, which is reported in detail in Chapter 2. The related fields include 1) the history, evolution and market of cycling sportswear; 2) the thermal and biomechanical functional design of sportswear, as well as materials for sportswear functional design; 3) the aesthetic effect in sportswear design; 4) the design process in garment industry.

The observations from the literature review suggest that there is still a long distance to go for realizing the design innovation of cycling sportswear with the fusion of aesthetic and functional design for desired functions. Thus, the aim of this research is to achieve a design innovation of functional cycling sportswear (FCS) that satisfies the multi-aspect functional requirements of thermo-physiological, biomechanical, and aesthetic aspects.

Meanwhile, the literature review can also identify the knowledge gaps to achieve this design innovation, which was described in detail in section 2.10, including 1) the systematical design model for cycling sportswear functional design is not available; 2) the aesthetic elements in cycling sportswear design are still not identified and investigated; 3) The thermal functional design of cycling sportswear to provide superior thermal comfort has not been achieved; 4) The biomechanical functional design of cycling sportswear to prevent the muscle injury and fatigue has not been achieved; 5) The realization of functional cycling sportswear design with prototypes for various applications is still not available.

In order to fill in these knowledge gaps and achieve the aim of this study, the key factors deciding the multi-functions of the cycling sportswear were investigated and analyzed; the multi-aspect functional requirements were identified and expressed in detail; and then the aesthetic and functional design were explored and performed to meet these multi-aspect requirements. Specifically, the objectives of this study can be described as follows:

- To build a multi-disciplinary framework of FCS design, which is the application of a multi-disciplinary knowledge of thermal biological, biomechanical, and aesthetic science, textile material, and art of design. The design innovation of FCS represents the fusion of aesthetic design with thermal and biomechanical functional design. This multi-disciplinary framework illustrates the knowledge, techniques, and logic relationships involved in achieving the final FCS products.

- To achieve the aesthetic design of FCS. The aesthetic elements in FCS design can be identified and illustrated by investigating the effects of aesthetic elements such as fabric, color, and cut and fit on athletic sport performance, as well as by identifying the detail design preference of professional cyclists.

- To achieve thermal functional design of FCS. Thermal functional requirements may be accurately identified by studying thermal mechanisms and conducting experimental analysis. Based on this, the FCS can be designed and achieved with desired thermal functions to offer thermal comfort to cyclists during cycling.

- To achieve the biomechanical functional design of FCS. Biomechanical functional requirements may be accurately identified by investigating the biomechanical mechanisms of cycling anatomy, muscle fatigue, and muscle injuries, as well as by analyzing the questionnaire survey data. The FCS designed with compression effect may be achieved to offer biomechanical protection for individual muscle groups to reduce fatigue and prevent injuries.

- To realize FCS design with prototypes for different applications. FCS design can be realized with prototypes by using existing machines, technologies, and fabrics, and by fusing aesthetic, thermal, and biomechanical functional design. With this design innovation model, different collections of FCS may also be designed and created based on specific design inspirations for different applications.

1.3 Research Methodology

In order to achieve the objectives of this study, the following research methodologies were employed:

I) Multidisciplinary framework development for FCS design

a) Theoretically describe the functional requirements of cycling sportswear, including the multi-aspect needs of the body during cycling and the multi-functions of cycling sportswear;

b) Identify the functional requirements of FCS by analyzing the data of a questionnaire survey from professional cyclists, which also provide information on detailed biomechanical and aesthetic requirements;

c) Present a multi-disciplinary framework that addresses the knowledge and technologies involved in aesthetic, thermal physiological, and biomechanical fields as well as their relationships; and

d) Identify the key parts of knowledge, techniques, and procedure involved in the proposed multidisciplinary framework.

II) Aesthetic design of FCS

a) Investigate the aesthetic elements in sportswear in terms of fabric, cut and fit, and color, and illustrate how these aesthetic elements influence the functions of sportswear and even game performance;

b) Build a theoretical model of fusing the aesthetic and functional design in cycling sportswear to demonstrate the relationships and processes involved;

c) Identify the aesthetic preference of professional cyclists for FCS design through analysis of data from a questionnaire survey; and

d) Identify and illustrate the aesthetic design elements in FCS design.

III) Thermal functional design of FCS

a) Set up the theoretical knowledge through literature review, including the mechanisms of thermal behaviours in cycling and the factors of thermal comfort for cyclists;

b) Identify the thermal functional requirements by conducting a cycling exercise experiment, which was carried out, as follows:

- A group of athletes were employed to perform a cycling exercise wearing short pants in a controlled chamber according to the specified protocol.

- The front skin temperatures were measured by an infrared thermographic system and the back skin temperature were measured by digital sensors.

- The sweat volume of the skin in terms of stratum corneum water content (SCWC) and transepidermal water loss (TEWL) were measured by digital devices.

- The measured data was collected and analyzed and presented in charts and color mapping diagrams.

- Analyze the thermal distributions of the individual body parts and identify the thermal biological requirements of cyclists during cycling.

c) Create thermal zones of the human body to express the thermal biological requirements of cyclists pertaining to each body part;

d) Perform thermal functional design of cycling sportswear using functional materials and treatment on the different parts to achieve thermal comfort; and

e) Measure the thermal properties of fabrics and then illustrate the fabric selection for thermal functional design of FCS through the numerical design and simulation of FCS in specified cycling scenarios.

IV) Biomechanical functional design of FCS

a) Determine the theoretical knowledge through literature review, including the biomechanical mechanisms of skeletal muscles, muscle fatigue and muscle injuries, sport injuries, and the effect of compression garments;

b) Illustrate the muscle group recruitments in cycling for FCS design, identify injuries in cycling, and determine the body parts covered by clothing that require injury prevention;

c) Identify details of the biomechanical need of cyclists for FCS by analyzing the questionnaire data;

d) Create biomechanical zones of the human body for expressing the biomechanical requirements of cyclists pertaining to each muscle group;

e) Identify the appropriate pressure range for each muscle group to achieve optimal compression effect on the muscles;

f) Perform biomechanical functional design of FCS by adopting the compression design with functional textile and tape coating technology to produce desired pressure on individual muscles, which reduces muscle fatigue and muscle injuries, and to increases muscle performance; and

g) Measure the mechanical properties of the fabric and then illustrate the fabric selection for the biomechanical functional design of FCS through numerical simulation of the compression effects of fabrics.

V) Realization of the functional cycling sportswear design

a) Introduce the process, technology, and machinery involved in the creation of FCS prototypes;

b) Illustrate the realization process in detail by introducing the design and creation of an FCS collection in terms of design inspiration, design scheme, fabric, garment pattern, and design demonstration; and

c) Create more FCS collections for a design contest, an exhibition and 2012 Olympic Games.

1.4 Research Significance and Value

To achieve desired multi-functional performance, this research explores the design innovation of FCS with the fusion of thermal functional design, biomechanical functional design, and aesthetic design. This design innovation was carried out beginning from the study of aesthetics, thermal physiological and biomechanical mechanisms. Then, the functional requirements of cycling sportswear in the aesthetic, thermal physiological and biomechanical aspects were identified through a series of analyses from a questionnaire survey, literature review, and experimental observation. During the creation process of the FCS prototypes, knitting technology was adopted to make multi-structural fabrics, and existing seaming machines, functional treatment, and new tape coating technology were used to achieve the desirable functions. Professional computer-aided design tools were used to validate and optimize the functional performance of fabrics and the designed FCS.

The FCS products achieved by applying this design innovation are intended to have superior thermal, biomechanical, and aesthetic functions. These products can help wearers obtain thermal comfort by quickly releasing generated sweat on skin and decreasing the skin temperature during movement, reducing muscle fatigue and injury by exerting appropriate pressure on the muscles by the compression effect of FCS, and producing an aesthetic influence on the performance through related aesthetic elements. These benefits obtained from this design innovation can greatly improve the performance of professional athletes in cycling competitions, offer functional comfort for common consumers engaged in fitness and recreational cycling, and increase the brand value of sportswear manufacturers in the cycling sportswear market.

1.5 Thesis Outline

This thesis consists of eight chapters to report on the research findings of this study. The structure of these chapters is shown in Fig. 1, which demonstrates the flow and relationships among the chapters.

Chapter 1 introduces the research background, research aim and objectives, research significance and value, and the research methodology adopted for this study.

Chapter 2 presents an extensive literature review in relevant disciplinary areas to both provide knowledge involved and identify the knowledge gaps for this study.

Chapter 3 presents a multidisciplinary framework of FCS design. The functional requirements of cycling sportswear are first described through the multifunctional requirement analysis and questionnaire analysis. Based on the review of current factor models for cycling, a multidisciplinary framework of FCS design is proposed and explained.

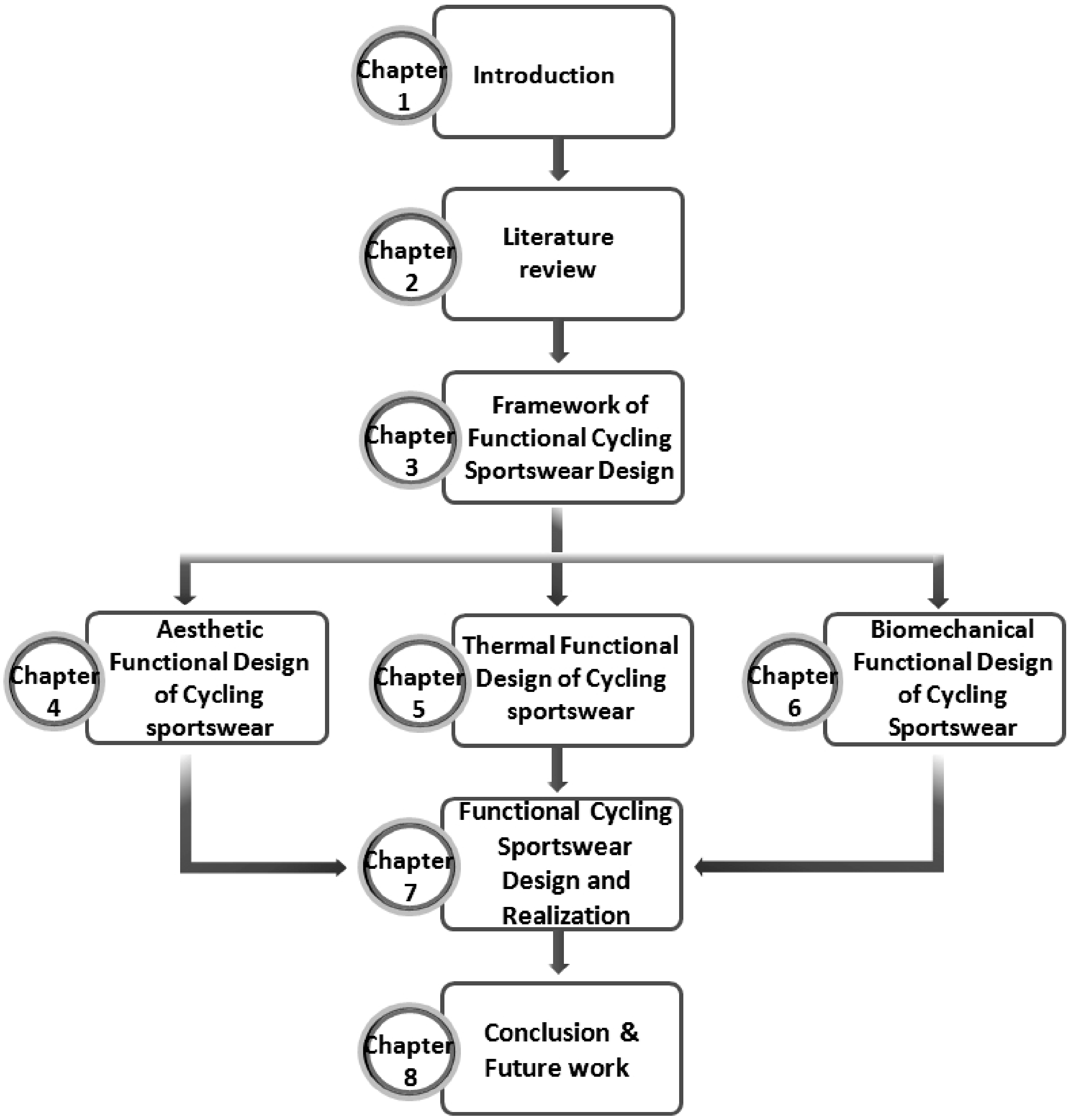


Fig. 1.1 The structure of the thesis content

Chapters 4 to 7 elaborate the theoretical framework proposed in Chapter 3.

Chapter 4 describes the aesthetic design of FCS, which is the medium to fuse thermal and biomechanical functional designs. The functional mechanisms of aesthetic elements in terms of fabric, color, cut and fit are investigated, and the preferences of professional cyclists on aesthetic design of cycling sportswear are surveyed and analyzed. The aesthetic elements in the FCS design are identified and illustrated.

Chapter 5 is concerned with the thermal functional design of FCS. The work includes studying the thermal mechanisms and thermal comfort involved in cycling, identifying the thermal requirements of each body part cyclists use during cycling, carrying out thermal functional design with functional textile materials and treatments, measuring the thermal properties of fabric, and illustrating the fabric selection for thermal functional design through CAD simulation.

Chapter 6 reports on the biomechanical functional design of FCS. It begins with studying the biomechanical mechanisms of the human body in terms of cycling anatomy, muscle injury and fatigue, and the effects of compression garments, then identifying the biomechanical requirements of cyclists during cycling in relation to each muscle group used, subsequently carrying out the biomechanical functional design with functional textile material and special compression technology, and finally, measuring the mechanical properties of the fabric and illustrating the fabric selection for mechanical functional design through CAD simulation.

In Chapter 7, the functional cycling sportswear design is realized by producing prototypes for different applications. First, a typical creation process for FCS prototypes is introduced. Then, the realization process is illustrated by introducing the creation of FCS prototypes for competition and training, including design inspiration, design scheme, fabric, garment pattern, and design demonstration. By applying this design innovation method, more collections of FCS prototypes are produced for international design contests, exhibitions, and the 2012 Olympic Games.

Finally, Chapter 8 concludes this study and makes recommendations for future research directions.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

In order to determine the research objectives and the methodologies adopted for this study, which was described in Chapter 1, the relevant knowledge was reviewed in this Chapter to provide the background knowledge involved in this thesis.

The literature review is conducted through the following aspects, namely: 1) the history of road cycling, evolution of road cycling sportswear and cycling wear market; 2) the thermal and biomechanical functional design of sportswear and materials for sportswear functional design, as well as the materials on current market available for sportswear functional design; 3) the aesthetics in sportswear design; 4) the design process in garment industry.

2.2 History of Road Cycling

In order to learn about development of road cycling sportswear, it is important to review the evolution of bicycles and follow the history of road cycling races. The invention of the bicycle has brought a fascinating impact on society rather than a transportation tool. The advances in materials and innovations in techniques which were made before the start of the last century are the driving force behind the developments of bicycle (Cushing, 1896). As the bicycle is becoming an important tool in the social life of the modern era, cycling has also become a very popular for the people. Road cycling in recent years has been the most widespread form of cycling and has appeared in the Olympic games as a competitive event (Kristine, 2007).

The first version of bicycle in the world was invented by M. de Sivrac in 1791 with two wheels joined by a wooden frame resembling the body of a horse (Smith, 1972). However, it could not run without power from the leg of the rider. In 1836, Kirkpatrick McMillan of Scotland made a vehicle which, for the first time, the man on the draisine could lift his feet entirely off the ground and still propel himself. But the bicycle did not get the general public to accept until 1881 when a American bicycler named Pope offered prizes to doctors who published the best articles defending bicycle riding as a positive aid to good health. In 1884, the 'Rover' had been produced by J. K. Starley (Benedict, 1987), and the vehicle had two wheels of approximately the same size and was propelled by an endless chain running over the pedal-driven sprocket and then over the gears at the axle of the rear wheel (Marx, 1897). The design of the bicycle with a diamond frame and equal-sized wheels has basically remained to be the same form from 1890 until recent times (Herlihy, 2004).

Bicycles became a popular transportation tool from the early 1930's when the production costs finally fell and made bicycles affordable for ordinary people. With the increasing popularity of bicycle, the cycling sport has emerged in the people's life and become a popular form of sport. In 1868, the road cycling race was for the first time held in the world in France, in which the cycling distance was just two kilometers (Gideon, 1895). The first international extracurricular road cycling race was held in 1893 in the United States, and the first international professional road cycling race was held in the summer of 1896 (Ritchie, 1975). And in 1896, for the first time the cycling sport was adopted in the Olympic Games as an important item (Guttmann, 1992).

Since then, the road cycling race has developed in diverse forms and the number reaches the level of several hundred. In these diverse cycling races, the ‘Le Tour de France’ was the world’s biggest and the most famous international road cycling sporting event, which was started as a result of competition of two rival from news publishers beteween l'Auto and le Vélo (Daffern, 1974) in 1903. And hold in every July in France, except twice of the War of the Worlds. Fig. 2.1 shows the history of road cycling race.

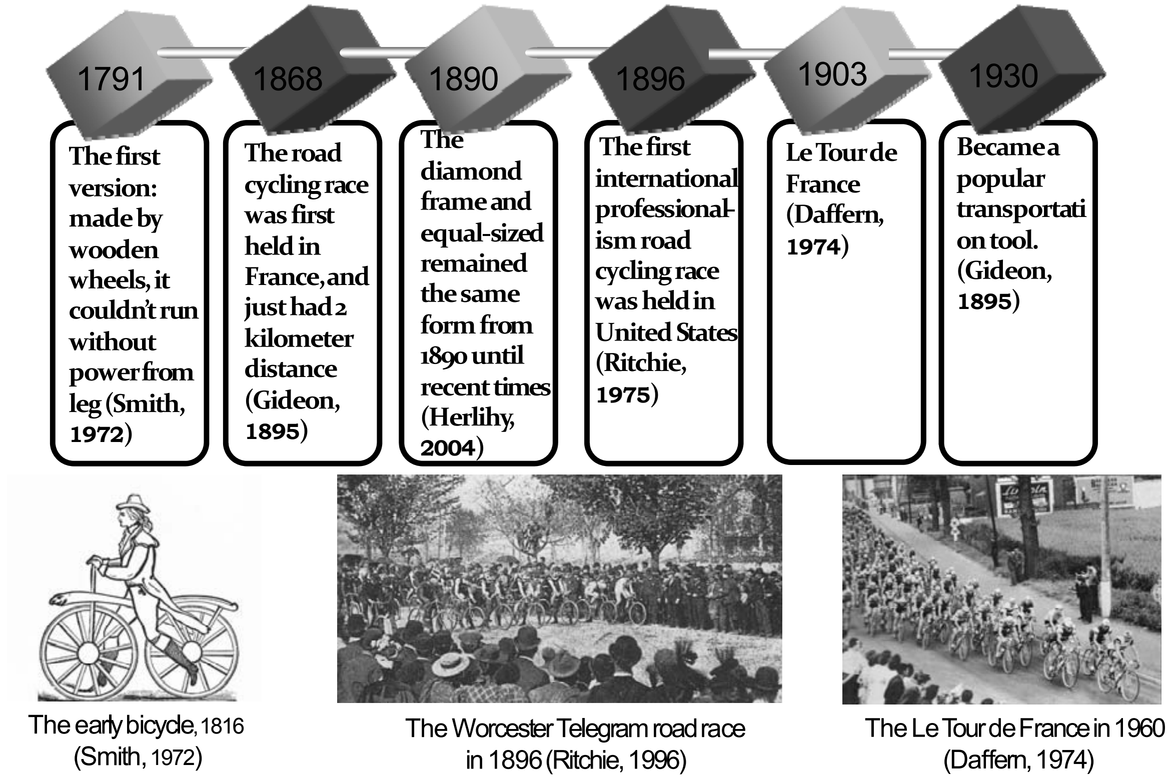


Fig. 2.1 The history of road cycling race

2.3 Evolution of Road Cycling Sportswear

With regard to the sporting garment, the early 'riding clothes' have evolved from being made of wool in the muted colors of the countryside and worn by the landed gentry of the eighteenth century into the suits worn by nineteenth century city men, and has replaced the fine laces, satins and velvets that had once been essential to the fashion industry (Braddock, 2001).

Those different from other ordinary people, bicycle riders, were extended to wear distinctive clothing. At first, many cyclists who were the members of the same club have the same uniform of the club (Smith, 1972). For instance, the Boston cycling club included the descriptions of its uniform in its rules saying that the color of the uniform shall be dark seal-brown and it shall consist of a jacket, shirt, breeches and stockings, and a cap (Horton et al., 2007).

Charles Pratt, the first president of the League of American Wheelmen and cycling's elder statesman, who recommended fine cotton corduroy to be the material for uniform, laid down the prescribed dress code for wheelmen in the American Bicycler (Alderson, 1972). He recommended that the uniform should be simple and light, and for free action, and should be in drab colors for the purpose of hiding the dust. The advice of Pratt was adopted by most male cyclists. The Pennsylvania Bicycle Club chose black cheviot suits with a high-standing collar, a black cap with silver cord and white shirts piped in black. Some other clubs added epaulets and some others gave up the short jacket for the heavy sweater (Norcliffe, 2006).

Most parts of uniforms were severely utilitarian. The dull colors of brown and gray concealed the dust; the short-tailed coat did not interfere with the seat in the saddle; and the long-visored cap was much better than a hat, which tended to blow off at the moment the cyclist was about to win an impromptu race (Smith, 1972).

The properly dressed cyclist was depicted in Overland Magazine in November 1895, New York Times, the article described the body of the rider as lightly enclosed in a woolen sweater with a loose-fitting coat, well-fit heavy woolen stockings, a pair of low shoes and a cap. Actually, the men's cycling style began to be improved since this year (Smith, 1972): the knickerbockers would be worn fuller at the knee and the cycle shoes would be sturdier.

In the late nineteenth century, gender started to be a concern in the shaping of sporting experience and in the development of sports clothing (Wang, 2008). Due to the determination to enjoy the freedom of movement offered by cycling, the women cycling bloomers at last emerged in the late nineteenth century (Dickinson, 1896), which was quite possibly the most important sporting activity in affecting women's fashion (Leach, 1984). Leach depicted how the presence of women wearing bloomers and riding bicycles in the 1890s undermined the concept that clothing was designed for the purpose of distinguishing the sexes and also rose the questions of whether bloomers were proper for lady and whether it was proper for a lady to ride bicycle. But it is also a big advancement in the function of women's cycling garments.

In the 1920s, the most fashionable women began to wear trousers for a range of sporting activities, including riding bicycles and hiking, while a few of the bravest wore beach pajamas at the fashionable coastal resorts of Biarritz or Monte Carlo (Leach, 1984). Once the bloomers had evolved into divided skirts and knickerbockers suits and became acceptable clothing, the road clothing had paved the way for trousers for women.

The first evolution of road cycling sportswear was initiated by Charles Pratt, the first president of the League of American Wheelmen and cycling's elder statesman, who raised a point of order stating that cycling garments should be light and free, and for free action (Smith, 1972). And with the development of cycling garments, club uniforms disappeared toward the mid-nineties, when cycling became a sport of the general public and not only for groups of people (Norcliffe, 2006). By 1896, sweaters were seen only on fast riders and professional racers, and most people who rode bicycles were shifting toward the double-breasted coat (Howland, 1896). It was the short trousers that represented the most radical departure for the men's clothing. Although his ancestors wore knee breeches, and although riding breeches had long been common, the ordinary American male scoffed at short pants, short pants just did not look right to men. The uniform for bicycle riders should be for ease, wrote Pratt (Horton, 2007).

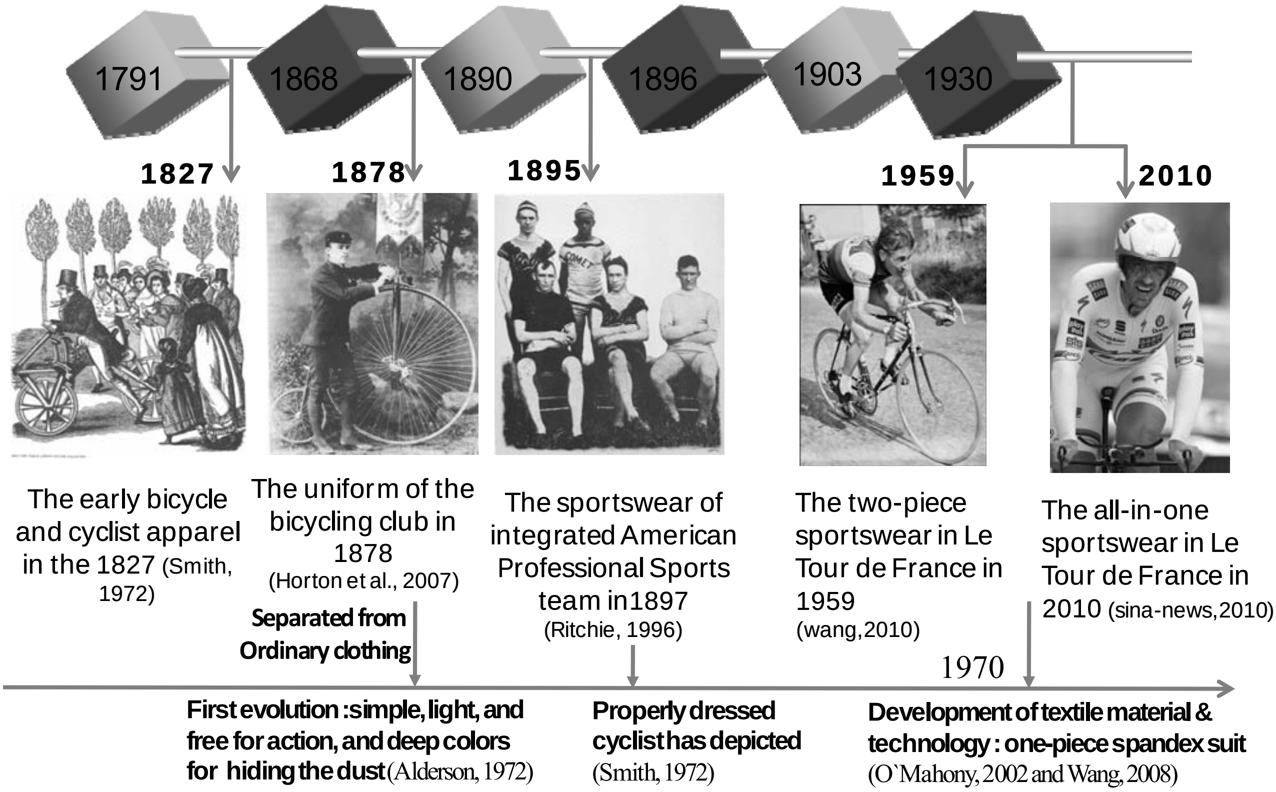


Fig. 2.2 The representative developments in the evolution of road cycling sportswear

With the trend of fitness in the 1970s, the fashion industry adopted fabric technology and cycling clothing with the idea of sportswear (O'Mahony and Braddock, 2002). With a growing number of runners, athletes have adopted the one-piece spandex suit, which could reduce wind resistance (Wang, 2008). The concept of loose-fit clothing to reduce air interference with sports' equipment has grown. And more and more athletes who were champions also worn with one-piece suit. In 1973, the East German women's professional suits for cycling sport were two-piece outfit which included one jersey and one pair of shorts (McCann, 2005). With the development of fabric material and technology, the cycling sportswear appears now to be all-in-one suits, which borrowed the concepts from the swimsuits offered to the Olympic swimming team (McKenzie, 1997). With the increased demand for increased cycling speed, it is very important to know how to reduce air resistance. The fresh all-in-one cycling sportswear which can cut down wind resistance replaced the baggy cotton cycling sportswear which can only be worn for non-sporting activities. Fig. 2.2 shows the representative developments in the evolution of road cycling sportswear.

2.4 Cycling Sportswear Markets

With the popularity of cycling sport in people's life, the cycling wear has also gradually become a commercial product and finds its way into the clothing store (Horton et al., 2007). The review of the change of the cycling wear market and the main brands of cycling wear products on the current market, it is necessary to reveal the situation with cycling sportswear design.

The first sweaters which were provided to professional riders appeared in 1896 in the Unite States, and the cycling markets for the general people who rode bicycles were shifting toward the double-breasted coat (Smith, 1972). When people could pay only US$ 1 for their suits of cycling, both cycling costumes and cycling suits for men began to be more popular in the clothing stores. A complete outfit of sack coat, trousers, and wool 'cassimere' cap could be bought for as little as US$ 4.95. If a sedate outfit had little appeal, the prospective buyer was encouraged to buy the cycling pants separately for about US$ 1.50 and add a heavy wool 'bike' sweater which cost the same as the pants. Those were attractive in 1896 (Smith, 1972).

With increasing expansion, in 2003 the worldwide sportswear market was valued at US$ 92 billion, and it was recorded that the cycling participants aged 6 and above were 17.5 million in the United States alone (Shishoo, 2005). With the trend toward outdoor sport activities, there are more than 2,000 companies in the cycling industry in American alone, having a six billion dollar business in 2007, according to the most recent National Sporting Goods Association study (Xiao, 2009). As the healthy, environmental and economic benefits of cycling are continuously enjoyed by the general public, many companies and brands emerged and thrived, attempting to combine functionality with high-tech fabric innovations and produce highly covetable collections (Andreff, 2006). The following reviews the main brands of cycling wear manufacturers on the current market.

Nike

Nike is primarily devoted to the design and development of sportswear and sport equipments. The company has its own retail stores, distributors and licensees worldwide. The popularity of all-in-one suits for swimming encouraged the design of specific suits for specific sports. Seven different fabrics developed by Nike created Nike's speed skating suits and appeared at the 2002 Salt Lake City Winter Olympics

(Bramel, 2005). Nike was also the sponsor of ‘Discovery’ which is a famous professional cycling team in the world.

Adidas

As one of the largest sport industry companies in the world, Adidas also designed the cycling sportswear for professional cyclists. The Adi-star Body Mapping Jersey designed and developed by Adidas aims to keep the body dry and comfortable meanwhile allow cyclists to achieve optimal performance levels (Braddock, 1998). This Adidas’s cycling wear appeared in the 2008 Olympic Games.

Moa Sport and Nalini

Moa Sport, also known as Nalini, is the famous cycling sportswear sponsors in the world with a leading position on the international market, and has been producing cycling sportswear for more than 30 years. Currently, Moa Sport also provides the sponsorship for most famous professional teams, clubs and manufactures, which require high quality products for both competition and training (Nalini®, 2010).

Craft

The Craft Company, which initially is known for producing temperature-regulating base layer, also offers specialty lines for cyclists. The athletes of Le Tour de France have adopted Craft of Sweden for many years, and the winner of the Le Tour de France in 2009 wore the suit produced by Craft (Tao, 2009).

Through reviewing the literature on the development of the cycling sportswear market and the main brands of cycling sportswear on the current market, we can find that cycling sportswear has become popular for both athletes and general consumers, and there is a huge market with great potential for the functional garment manufacturers and designers. There are many different styles and functions of cycling sportswear in the market from different manufacturers. However, no cycling sportswear products are available on the market that are designed with consideration of aesthetics and thermal physiological and biomechanical functions at the same time to improve the performance of the cyclists and to provide protection for them .

2.5 Thermal Functional Design

Thermal functional design is a new trend of clothing design based on style and pattern design, which places the focus on creating clothing with desired thermal functions to offer thermal comfort. The thermal functions may include water vapor permeability, moisture management, thermal insulation, air breathability, waterproof and UV protection. These functions are not only required by the professional athletes, but also wanted by the general consumers. In this section, the relevant knowledge and research studies of thermal functional design of sportswear are reviewed in terms of thermal transfer processes in clothing wearing situations, the factors of thermal comfort, CAD technology in sportswear, and sportswear design concerning thermal comfort.

2.5.1 Thermal Transfer Processes

Clothes protect the human body from hot or cold external environments, in which people may feel uncomfortable, get disease or even be hurt by the extreme bad climatic conditions. The thermal functions of clothing, such as thermal insulation, dryness, moisture management, and air breathability, can help people to ease themselves from these negative influences of the environment. From the view of physical science, performances of thermal functions are based on the thermal transfer processes in the clothing wearing situations. The investigation of the thermal transfer processes involved in the clothing wearing situations is very helpful for the designers to analyze the thermal functions of clothing and design functional sportswear.

The thermal transfer processes in clothing wearing situations mainly include the heat and moisture transfer processes in clothing material, the thermo-regulations of the human body, and the heat and moisture exchange among clothing, human body and external environments.

Heat and Moisture Transfer Process in Clothing Material

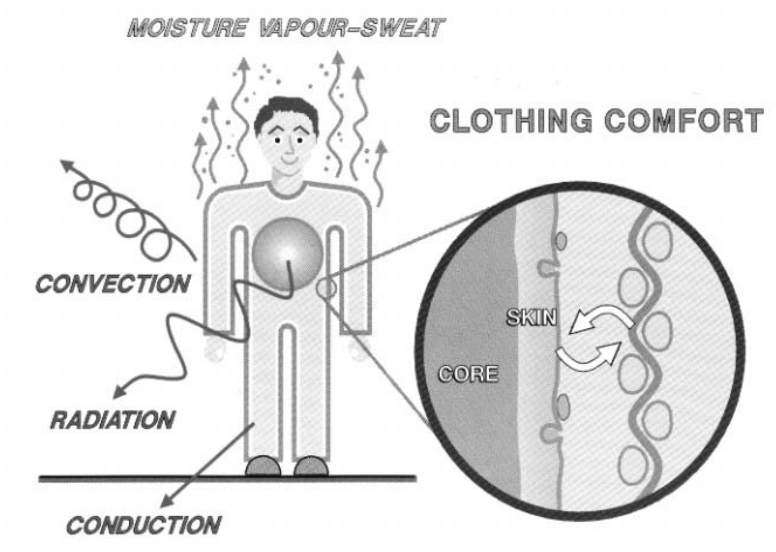


Fig. 2.3 Heat and moisture transfer process (Li et al., 2006)

Heat and moisture transfer process in clothing is the main physical behaviour theoretically influences the thermal functions of clothing, as shown in Fig. 2.3.

- ***The heat transfer process***

The heat transfer process in textile material includes multiple transfer mechanisms in terms of conduction, convection and radiation. In theory, conduction heat transfer always takes place through the solid fibers in the textiles material with the condition of temperature gradient, which is the most dominant mechanism of heat transfer in textiles. Convection heat transfer occurs when there is fluid in contact with a different temperature of the textile surface. The heat flows from the object with high temperature to the one with low temperature. If the inter-fiber space is large enough, the convection will be clearly observed. Thus, stronger convection will happen with more porous textile materials. Radiation heat transfer takes place due to large temperature difference between different objects. Thermal radiation is one of the forms of electromagnetic radiation and can transfer at the speed of light. When the temperature gradient is small, thermal radiation can be ignored.

- ***Moisture transfer process***

The vapor moisture transfer process happens by means of diffusion and convection as a result of a water vapor concentration gradient that exists in the textile materials, where the interstices between fibers provide space for moisture to flow away (Pause, 1996). There are many similarities between heat conduction and moisture diffusion in the textile material. Mecheels (1971) reported that there are four ways of moisture (in the phase of water vapor or liquid) transfer occurring in textile materials, namely: a) diffusion through the space between the fibers, b) absorption/desorption by the fiber materials, c) transfer of moisture through capillary interstices in yarns/fibers, and d) migration of moisture on the fiber surface. The fiber will keep absorbing moisture until it reaches the saturated status decided by the absorption rate. The property of hygroscopicity (also called moisture regain) is used to indicate the moisture absorption capacity of fibers (Nordon and David, 1967).

- ***Liquid transfer process***

The liquid transfer process in the textile material experiences two stages of wetting and wicking, and the wetting stage is prior to the wicking stage (Kissa, 1996). Both wetting and wicking are determined by surface tension at the solid-vapor-liquid interfaces. In view of the physical mechanism, the surface tension is the energy supplied to increase the surface/interface area by one unit. When the liquid water is in contact with the fibrous material, an equilibrium state will be reached with minimization of interfacial free energy on the surface. The wicking process will be suppressed with the decreased number of fibers in the textiles (Ito and Muraoka, 1993). The greater number of fibers will lead to sufficient pores to fasten the wicking process.

- ***Condensation/Evaporation***

Moisture condensation/evaporation is an important form of phase change processes, which may result in the coupled heat and moisture transfer processes. Condensation is a common physical phenomenon which occurs when the textile is exposed to an environment with a high temperature gradient and a high humidity source, which cause the local relative humidity to reach 100% or full saturation (Vafai, K. and Tien, 1989). If there is still extra moisture diffusing into the textiles, condensation will happen and continue until the condition is broken. When the relative humidity of air in the surrounding microclimate is less than 100%, evaporation occurs. During the phase change process of condensation/evaporation, the heat also needs to be released or absorbed to realize the physical state change (Murata, 1995). Thus the moisture condensation/evaporation is a common physical mechanism to dissipate or generate heat during wearing conditions.

Thermoregulatory Behaviours of the Human Body

To sustain life in various environments, the human body must have the ability to keep the temperature of core and skin at a reasonable range under a variety of external conditions, that is, the core body temperature should be maintained at 37.0±0.5°C, and the skin temperature should be managed at approximately 33°C. In the human body, when the body core temperature drops, the thermoregulation system will regulate the body temperature by producing heat, and when the body core temperature rises, the thermoregulation system will regulate the body temperature by dissipating heat (Grosbie et al., 1963; Guyton, 1981). The basic mechanisms of the body thermoregulation system include two processes: a) when the body feels warm, vasodilatation of blood vessels is activated to increase the blood flow, and the sweating mechanisms will function to dissipate heat by sweat evaporation; b) when the body feels cold, vasoconstriction of blood vessels is activated to reduce the blood flow and increase the heating production by muscle shivering (Polk and Elliot, 1995).

Thermal Exchange between the Clothing, Human Body and Environment

Similar to the heat and moisture transfer in the clothing material, heat and moisture exchange between the clothing, human body and environment leads to heat or moisture gradient between the three of them. When there are temperature gradients among the clothing surface, body skin and external environment, the heat flux will flow from the region with a high temperature to the region with a low temperature through conduction, convection and radiation. The heat generated by the human body will be directly transferred to the clothing due to the close contact between them. The heat loss by radiation usually occurs when there is a large temperature difference between the clothing, human body and environment (such as ground, building and sun). Compared with the mechanisms of conduction and convection, the radioactive heat transfer does not require any medium. Bertucci et al. (2005) observed that when the air velocity exceeds 0.2m/s, forced convection occurs.

The air velocity is an important factor that contributes to the heat loss from the body and clothing. Besides the direct heat exchange between the clothing, body and environment, the sweat on the body skin will be directly diffused to the fabric of clothing and be absorbed by the fibers when the clothing contacts with the skin. The good thermal functions of fabric can quickly absorb the sweat on the skin and offer a dry feeling to the body. Meanwhile, the evaporation action of the sweat occurs with these diffusion processes. The heat loss by the sweat evaporation is an important means to decrease the skin temperature. The thermal exchange in the clothing wearing system is shown in Fig. 2.4.

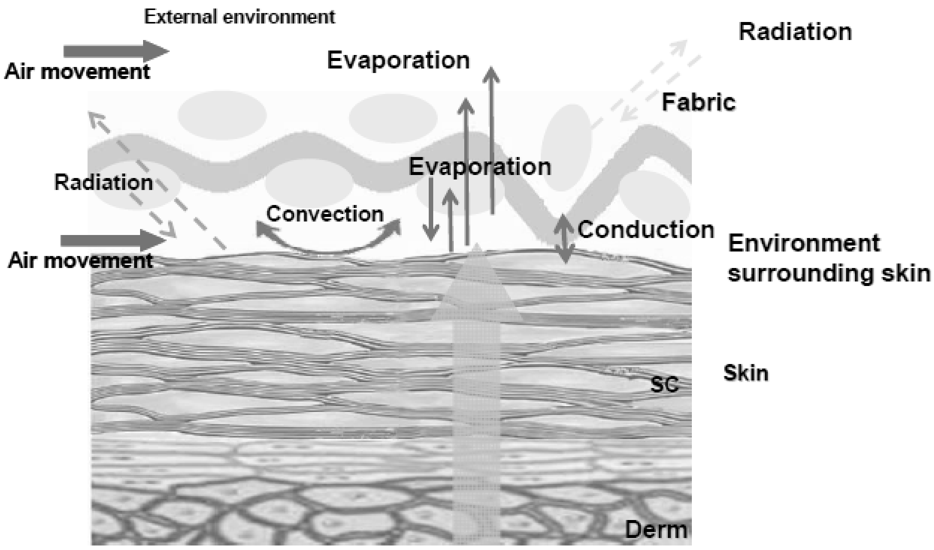


Fig. 2.4 Thermal exchanges between the clothing, skin and environment (Yao, 2008)

2.5.2 Definition the Factors on Thermal Comfort

According to ASHRAE standard 55-66 (later adapted by ISO 7730), thermal comfort is defined as 'That condition of mind which expresses satisfaction with the surrounding thermal environment'(Atlanta, 2005). Thermal environment here is regarded as those characteristics of the environment which affect the heat and moisture loss from the human body. Theoretically, people will obtain thermal comfort when the energy exchange between the human body and surrounding environment reaches a thermal equilibrium. And the thermal comfort will be maintained if the heat generated by the human metabolism system will be dissipated to keep such a thermal equilibrium.

However, the thermal comfort as defined by ASHRAE standard is a subjective concept. Thus for different people with different race, different physical, physiological and psychological conditions may result in different perceptions.

In order to investigate the physical, physiological and psychological mechanisms of thermal comfort, many researchers have made efforts in studying the mechanisms and even developing description models for thermal comfort. Fanger (1972) summarized that the heat balance of the human body is the first requirement of thermal comfort under steady state conditions. Gagge et al. (1967) carried out the research on the thermal sensation and comfort of the unclothed human body in the resting and sitting situations, and through comparison with the associated physiological response found that the thermal comfort will be obtained when the temperature of the environment is between 28 to 30^{o}C. In later research, Gagge pointed out that the thermal comfort and thermal sensations at the start of exercise are related to the initial transient rise of body temperature. Hensen (1981) developed some empirical models for describing the partial effects on thermal comfort with the factors of air velocity, air temperature and partial vapour pressure. Fanger (1972) proposed a general steady thermal comfort model based on the experimental analysis, in which the indices PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) were suggested to predict the subjective rating of thermal comfort in a specified thermal environment, and the given parameters in this model including the physical environment conditions (temperature, relative humidity and wind velocity), clothing thermal insulation and physiological activity of human body (Metabolic rate). Havenith (2002) in the macroscopic view categorized the factors of thermal comfort as climatic conditions, physical activity levels and clothing insulation.

Actually, the human body detects dynamic internal and external temperature changes through thermoreceptors distributed in tissues and organs, and the signals from those thermoreceptors will be transferred to the brain to generate the thermal sensations, which are the main physiological correlations to the thermal comfort (Hensel, 1981). Wang (2002) systematically proposed a numerical method by systematic integration of the previous models to simulate the perception of thermal comfort, in which the thermal and moisture sensations act as input parameters. The moisture sensation (dampness) and the dampness sensation and thermal sensations (warmth and coolness) were considered as the key factors of thermal comfort.

From the study of these researches, we can find that the physical mechanisms of thermal and moisture sensations play an important role in the perception of thermal comfort. Since the perceptions of coolness, warmth and dampness change with different environment temperature and the activities of the wearer, thus, the physical properties of temperature and humidity should be taken into account when investigating these sensations and evaluating the thermal comfort perception.

2.5.3 Sportswear Design on Thermal Comfort

Clothing is such an intimate object to us that it plays a very important role in our biological health and psychological happiness. With concerning the high added values of products, the common consumers more and more desire the superior functions of the clothing to improve the wearing comfort feeling during various activities (Li, 2007). The requirement of high functional performance of clothing also is demanded by designers/manufacturers to improve the value of their products and thus seize the market. Thus, with these increasingly requirements, the design of sportswear now focuses more on the thermal functional performance, which strongly impacts on the wearing feeling even the sport performance.

Currently, the sportswear, importantly, is customized and designed for the special kind of games with accordant to the characteristics of the game and the biological response of the human body during the sport (Li, 2001). The schematic representation of the human-clothing-environment thermal system during sports is illustrated in Fig. 2.5.

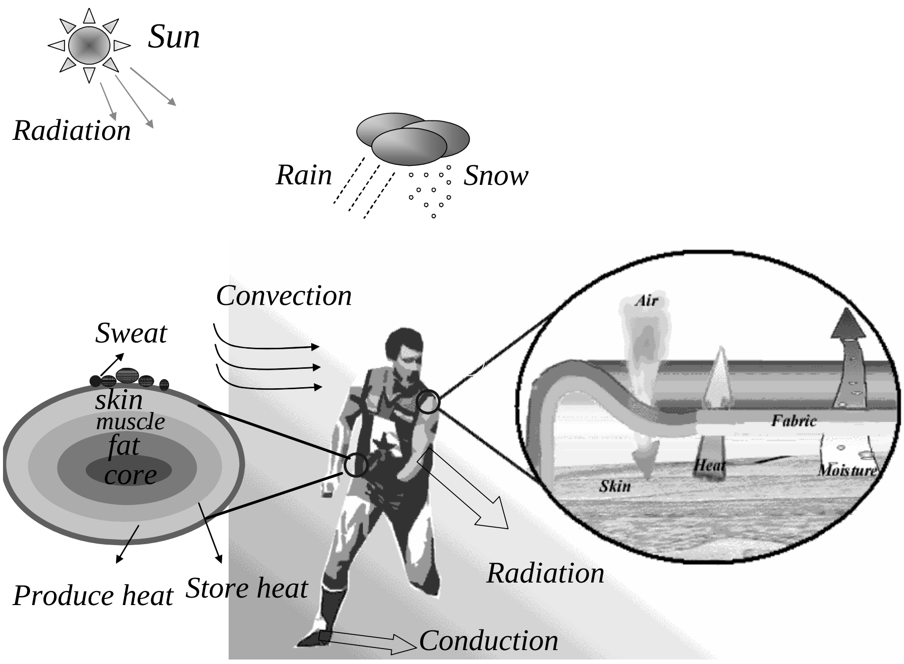


Fig. 2.5 Human-clothing-environment thermal system during sports (Mao et al., 2008)

Until now, there have some researches carried out on the thermal comfort of various sportswear. Wong and Li (2004) studied the relationships among human physiological and psychological thermal and moisture responses in tight-fit aerobic wear by experimental analysis and pointed out that overall clothing comfort may be best described with thermal sensation at the outer thigh, and humidity at the inner thigh. Wong et al. (2005) conducted a series of psychological sensory experiments to investigate the influence of thermal comfort perception in young adult consumer's preference to sportswear, Twenty-eight females and ten males aged between 18 and 35 participated in the experiments, and there were nine individual sensations and overall clothing comfort were evaluated by the subjects before, during and after a period of running. Huang (2006) summarized the thermal parameters of clothing for accessing the thermal comfort property during dynamic conditions based on moisture vapour pressure alteration within the clothing, surface temperature of the clothing and heat loss from the body. Ho et al. (2008) reported on an experimental investigation of the effects of T-shirt design on clothing thermal comfort measured in terms of clothing thermal insulation and moisture vapour resistance. These researches mainly focused on the investigation of the relationships between the physical properties and thermal comfort of sportswear, and still do not probe the functional design of the sportswear. However, they laid good foundation for the functional design of sportswear.

For the design of the functional cycling sportswear, though the relevant research is just at the beginning phase, it is quite important to investigate and identify the thermal physiological response of the human body during the cycling sport. It is reported that in each year there is approximately 30,000 to 35,000km cycled by professional cyclists (PC) in both training and competition, with in excess of 90 days of competition and participation in at least one of the major 3 week tours (Black and Cloud, 2008). In contrast, the amateur cyclist would normally cover no more than 25,000 km in a year, having less than 50 competitive days and no more than two consecutive days. To investigate the physiology of cycling which determines the success in good performance, much research on the physical characteristics of the body during cycling, specially road cycling, has been carried out (Fernández-García et al., 2000; Padilla et al., 2000). The most outstanding characteristics are the high aerobic capacity, as shown by the maximal power output (Wmax) and maximal oxygen uptake (VO2max) , whose value range during the cycling and relationship with the cycling performance has been identified in wide range of literatures (Chicharro et al., 2000; Lucía et al., 2000). Some other physiological variables, such as heart rate, pulmonary response, metabolic rate, also have been investigated in the study of cycling physiology (Alejandro et al., 2001). However, there has still no focus on the thermal physiological response of the body during cycling, such as the temperature and relative humidity of the skin, which are the key consideration in identifying the thermal requirements for functional cycling wear design.

2.5.4 CAD Technology in Sportswear

The application of computer-aided design (CAD) technology for clothing design is a significant advancement in the development of computerization in the clothing industry. The clothing CAD system enables the designers/engineers to achieve their design with short design cycle and low design cost by the aid of computers in their products design. Currently, there have been many CAD systems applied in the textile product design, such as the style and pattern design, fitting simulation and animation (Fairhurst, 2008).

The CAD system for sportswear thermal functional design is a pioneer research, which offers the capacity to help the designers to conceive their product using an engineering method by simulating the thermal behaviours of the human body, clothing and environment system in specified scenarios. Sportswear thermal functional design with

CAD systems and tools is an effective and economical solution of designing sportswear with superior thermal performance for wearing in various environments with a feeling of comfort (Li, 2007). To achieve desirable thermal functions, the sportswear design process does not following the traditional trial and error method, but is a functional engineering process which integrated multi-disciplinary knowledge and transferred the knowledge into user-friendly design tools by applying CAD technologies. With these CAD tools, the designers can investigate, simulate and preview the physical thermal behaviours in the sportswear, and iteratively improve their design until achieve the ideal design.

To help the designers to quickly achieve thermal functional clothing design, Mao et al., (2008) have developed two CAD systems respectively for multi-layer and multi-style thermal functional clothing design. With these CAD tools, the designers may design thermal functional clothing using various textile materials and construction methods, quickly preview the thermal performance of designed clothing, make optimization and improvement. The thermal performance of the sportswear can be quickly simulated and validated with the CAD system before the physical pattern making to reduce the design cycle and lower the design cost.

2.5.5 Summary

In this section, the thermal functional design of sportswear has been review from the aspects of thermal transfer processes in clothing wearing situations, the factors of thermal comfort, sportswear design on thermal comfort and CAD technology in sportswear. The thermal transfer processes involved in the clothing wearing situations include the heat and moisture transfer processes in clothing material, the thermo-regulations of human body, and the heat and moisture exchanges among the clothing, human body and external environments. The investigation of these thermal behaviours is very helpful to understand analyze the thermal functions of clothing. The research of the thermal comfort has been reviewed, which indicates that the physical properties of temperature and humidity should be considered when investigating the thermal and moisture sensations and evaluating the thermal comfort perception. Though there have some researches touched the thermal comfort property of sportswear, the research on the thermal functional design of the cycling sportswear is just at the beginning phase. There has CAD systems reported for thermal functional clothing design, which can help the designers quickly validate and optimize their design before the physical pattern making to reduce the design cycle and lower the design cost.

2.6 Biomechanical Functional Design

During actions and activities, the muscles of the body need to perform a huge amount activity through both aerobic and anaerobic energy conversion. All of those works will generate energy and be regulated by the body skin and respirations. However, on the other hand, the biomechanical characteristics and performance of the muscles are the basis of the body to finish the actions and activities. The entire kinetic system contains both physiologic and biomechanical foundation during sport exercise (Faria and Cavanagh, 1978). The working mechanisms of this system provide scientific base for the biomechanical functional design of sportswear. In this section, the biomechanical functional design of sportswear is reviewed from the aspects of muscle anatomy, cycling injury and fatigue and Effect of garment compression in sport.

2.6.1 Muscle Contraction and Cycling Action in the Movement

Muscle Contraction

Tension generation by muscle fiber is through the cross-bridge cycling action of actin and myosin. During the action, the muscle may shorten, lengthen or remain the same under tension. For the muscular system, the term ‘contraction’ means muscle fibers generate tension under the control of motor neurons (Brooks et al., 1996).

DeGroot et al. (1994) indicated that muscular work depends on the length–tension, force–velocity power relationships of the involved muscles. In order to understand how the muscle works under tension, the action of a muscle fiber can be compared to a rock climber with a rope. In this analogy, the rope is analogized as muscle actin, and the climber analogized as muscle myosin. When the climber pulls himself up with his arms, the myosin also pulls itself along the actin. During the climbing activity, the climber repeats the action of locking legs, outstretches arm and pulls clinging to a rope to move upward. Similarly, the myosin also climbs repeatedly clinging to the actin. Thus during the myosin movement process, the muscle fiber may lengthen or shorten (also called contractions), which creates tension and allows the muscle to perform work. Shannon (2009) imagined the muscle fibers working like a ratchet system composed of actin filaments and myosin filaments and illustrated the schematics of muscle fibers as Fig. 2.6. In this theoretical hypothesis, each muscle has an optimal resting length under tension. In physiology, this optimal length means the perfect compromise between having a large number of cross-linked actin and myosin while still leaving enough 'spare rope' for the myosin to climb up.

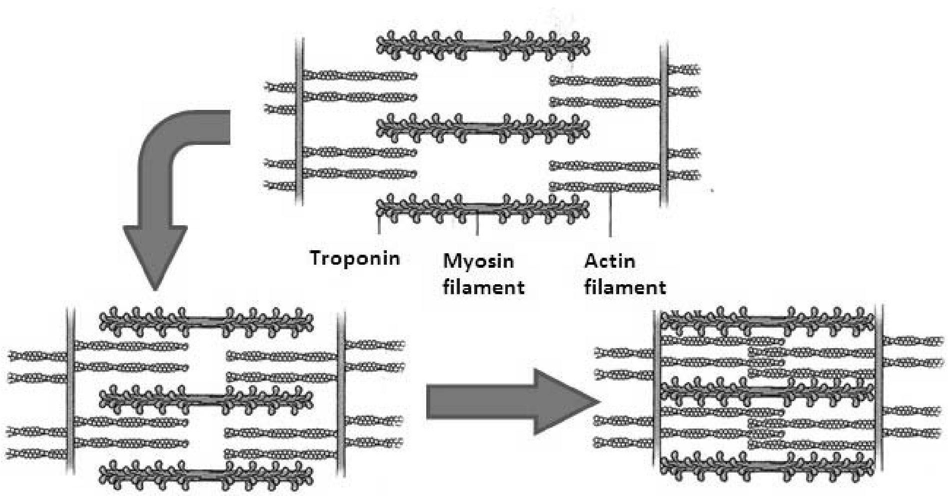


Fig. 2.6 Actin and myosin filaments in the muscle fiber (Shannon, 2009)

Muscle Action during Cycling Movement

In order to enhance the performance of the muscle and meanwhile to prevent the muscle from injury during cycling, it is essential to have a scientific understanding of the muscle recruitment pattern during cycling sport, which lays a substantial foundation for developing specific and functional cycling sportswear. However, the initial purpose of many researches carried out about the muscle action and pattern during cycling was to develop an effective training program of muscle for cyclists to enhance performance and prevent injury.

The kinetic chain of cycling is commonly viewed as a closed chain. The power of force production during cycling is influenced by muscle lengths and joint angles, as well as the variation of them in the different seat height, body orientation and rate of pedaling. The muscular work is dependent on the force–velocity, length–tension, relationships of the muscles involved (DeGroot et al., 1994)

When the cyclist rides the bicycle, the buttocks act as the main holding point, the trunk bows forward and the upper arm bend at the joint to fix the ride gesture, and lower limbs provide power for cycling exercise (MacIntosh et al., 2000). During this action, a necessary force needs to be imposed to the pedal in order to overcome the friction between the wheel and the ground and also the friction between the cyclist and the atmosphere to drive the bicycle running ahead. For a more detail investigation of the muscle involvement, the ride action can be regarded to be divided into sub-actions from upper limbs and lower limbs (Gregor and Rugg, 1986). Muscles in the upper limbs and trunk produce a counterbalancing force to the lower limbs during the pedaling motion.

The hand, shoulder, neck, back, arm and abdomen form a muscular sling in supporting the movement of the trunk and pelvis (Schmidt, 1994). And the muscle in the low limbs by concerted contraction in turn is the fundament muscle to generate maximum force to perform pedaling. The cycling action is repeated by the coordination of muscles in both the upper limbs and lower limbers cycle by cycle, Fig. 2.7 shows the pedaling action in a cycle. Thus the action of pedaling by the lower limbs is the key point in driving the bicycle and achieving a high riding speed (Raymond et al., 2005).

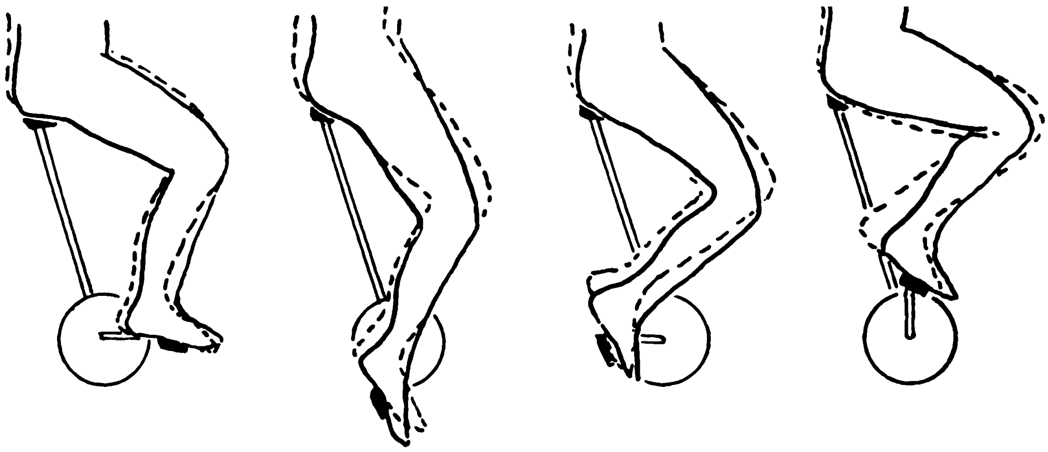


Fig. 2.7 The pedaling action in a cycle (Houtz and Fischer,1959)

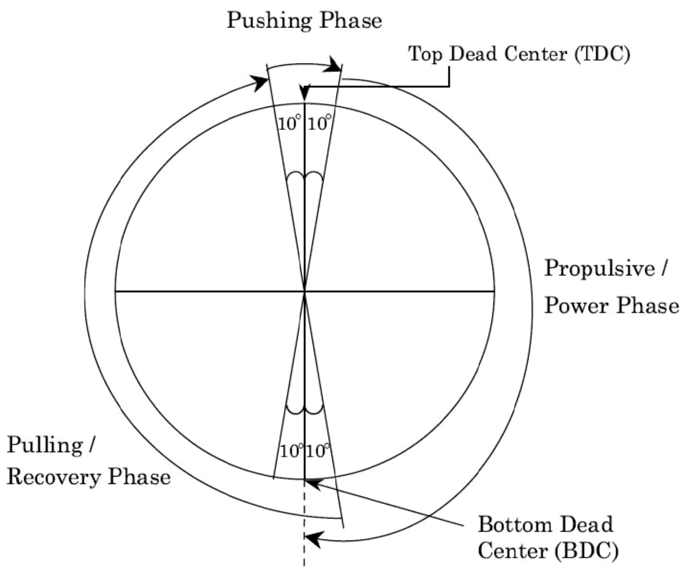


Fig. 2.8 Three phases of the cycling crank (Gregor and Rugg, 1986)

For understanding the muscle recruitment in cycling, the crank cycle was broken into three phases by Gregor and Rugg (1986) as shown in Fig. 2.8, namely, power (down stroke) phase, recover (upstroke) phase, pushing phase. Based on this effort, Ryan and Gregor studied and summarized the activity pattern of muscles during cycling, as presented in Table 2.1.

Muscles	**Function**	**Approximate range of action (°)**
Gluteus maximus	Hip extension	340–130
Vastus lateralis	Knee extension	300–130
Vastus medialis	Knee extension	300–130

Rectus femoris	Knee extension/Hip flexion	200–110
Soleus	Ankle stabilizer	340–270
Gastrocnemius	Ankle stabilizer/Knee flexion	350–270
Tibialis anterior	Ankle stabilizer/Ankle flexion	All the range
Hamstrings (without biceps femoris)	Knee flexion	10–230
Biceps femoris	Knee flexion/Hip extension	350–230

Table 2.1 Summary of muscle activity pattern of the pedaling cycling (Ryan, 1992)

As summarized by Houtz and Fischer (1959), during bicycling muscles contract in a pattern which is orderly and coordinated, and the pattern muscle activity is highly reproducible. Generally, varying the height of the bicycle seat does not influence the timing of muscle activity, but the exercise is performed with less effort. According to the research output of muscle activity pattern in cycling, optimal cycling equipment including cycling sportswear could provide effective force on the pedals during both the propulsive and recovery phases.

2.6.2 Muscle Injury and Fatigue Analysis in Cycling

Though the cycling action is soft and smooth, which may make possibly less injuries, there are a number of overuse injuries happening in cycling due to greater time spent in training and competition than many other sports. Meanwhile, the cycling race features intensive and fast speed, which causes the inevitable sport injury during the movement (MacAuley, 1995).

Wilber et al. (1995) surveyed the recreational cyclists and found that 85% had one or more overuse injuries, and 30% required medical treatment. The common site for overuse injury is the knee (41.7%). Holmes (1994) explained that knee pain is the most common overuse problem of cyclists, usually caused by strong knee extensors. This problem can lead to a negative influence on performance and enjoyment for cyclists.

According to the sports requirements on the body in cycling, through a series of surveys Yang and Yao (1999) summarized that sports injury happened in the individual parts of the body and the types of the injury, as well as the cause factors to find some facts. Acute cycling injuries can cause damage to any anatomical area, including the head, shoulder, neck, waist, upper and lower limbs. The surveyed data was obtained from three hundred and sixty five professional athletes located in different area of China during four years (average age is twenty five, training age is 5~6 years).

The injury frequency in all the parts of the body as shown in Fig. 2.9, where it can be seen the most of injury are the area covered by the clothing, such as waist, shoulder, knee, thigh, leg, wrist, back, neck, arm, chest, ankle, bottom, upper arm, elbow, abdomen and hip, and can be hopefully relieved by the functions of sportswear.

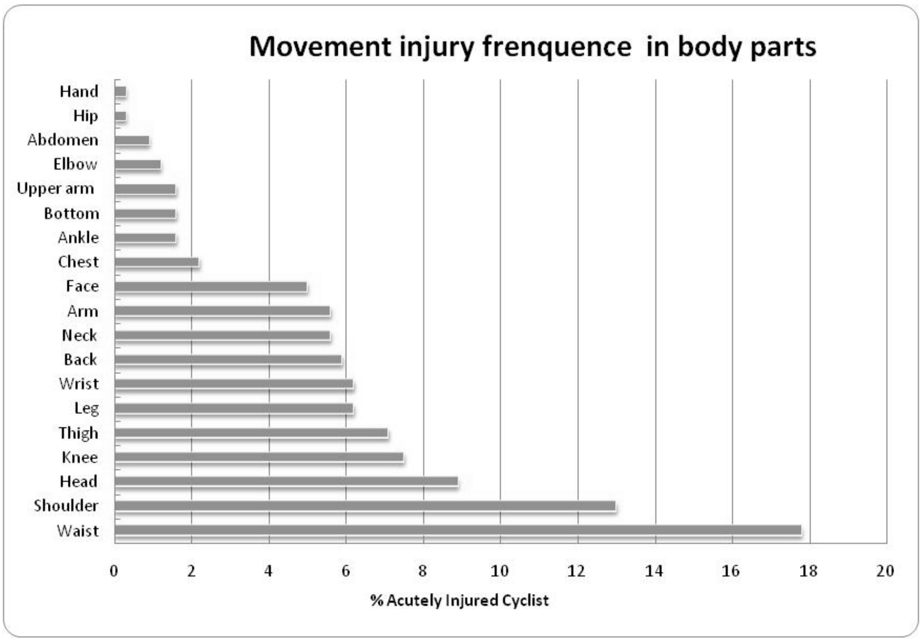


Fig. 2.9 The injury frequency happened in all the parts of the body (Yang and Yao, 1999)

The injury types in the cycling race is shown in Fig. 2.10. From this surveyed data, it can be seen that the type of injury during the cycling include soft tissue injuring, muscular strain, fracture, cerebral concussion and laceration.

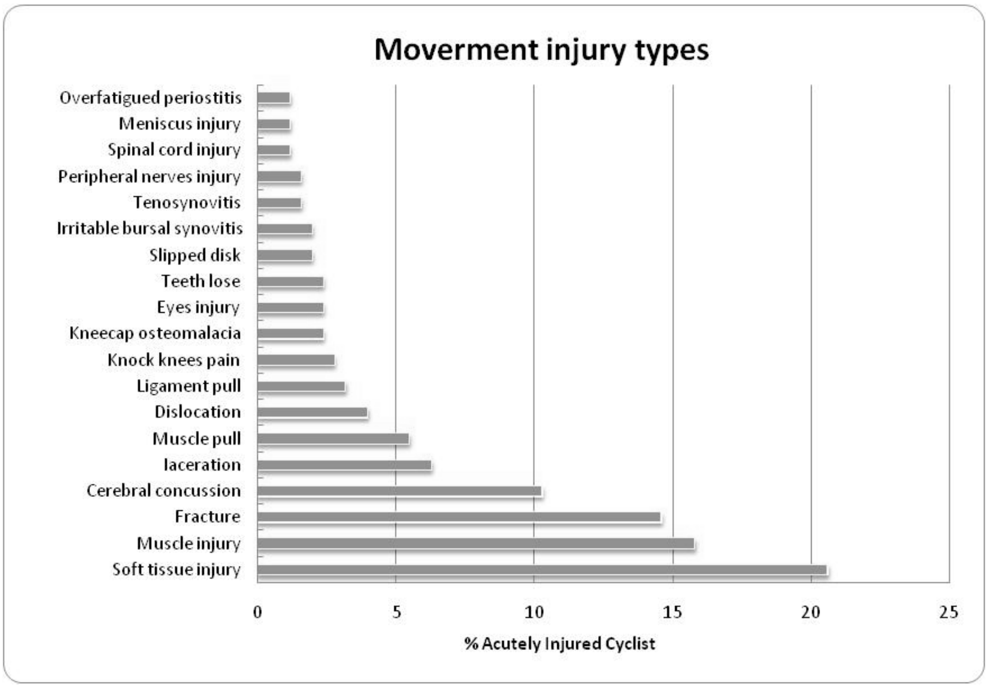


Fig. 2.10 The injury types in the cycling race(Yang and Yao, 1999)

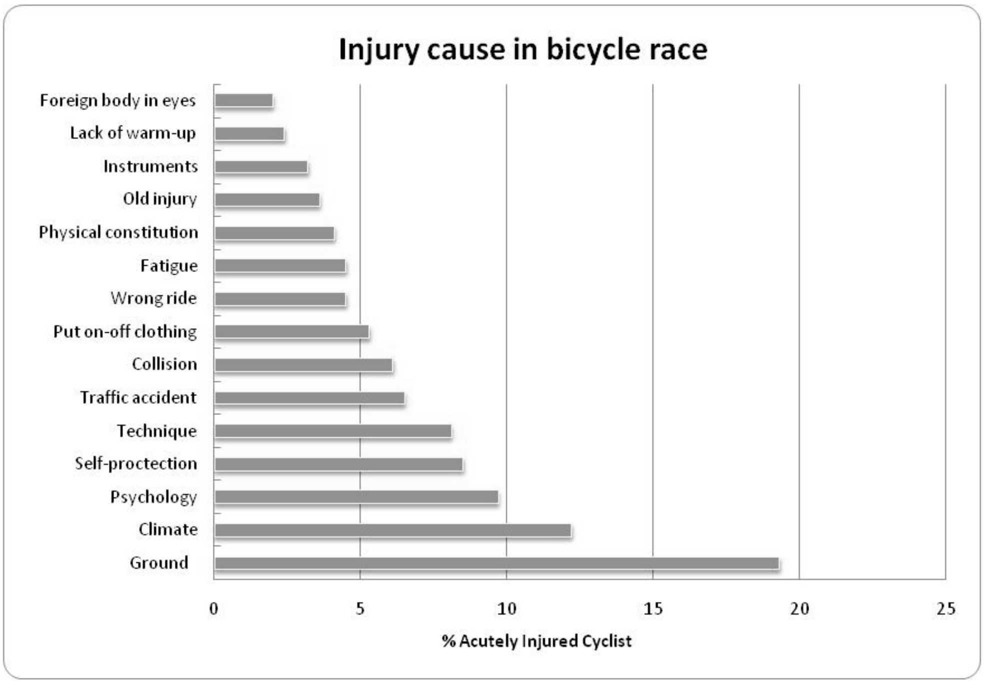


Fig. 2.11 The injury causing factors in cycling race(Yang and Yao, 1999)

The injury cause factors in cycling are shown in Fig. 2.11. It illustrates that the most injury of cyclists are caused by the ground, the climate condition, and psychology. The lack of self-protection, clothing putting on-off and fatigue also are the main causes for the cycling injury. How to avoid the injury from these causes is the key issue to improve the performance of the cyclists.

The analysis of these surveyed data shows the followings facts: a) most of muscle injuries during cycling happen in the body part covered by clothing, such as the waist, shoulder, back; b) The muscle involved in the pedaling action are easy to injure, including quadriceps femoris and tibialis anterior ; c) The most easy injury part of the lower limbs is the knee and the muscle injury area in the lower limbs mainly locate on the knee, thigh and leg.

Since the fatigue factor plays an important role in causing injury in cycling. Many researches also can be found about this physiological phenomenon during cycling movement. Muscles were regarded not only as effectors working under the control of the neural system but also as an integral network which mutually influences the nervous system. The nervous system may reduce the performance of a particular group of muscles due to fatigue. Fatigue also may result in the change of muscle recruitment in cycling.

In the studies of cycling, fatigue was generally caused by continuous decline rate of power output of pedalling during maximal workout of cycling. Edward (1981) recognized muscle fatigue as the failure factor of the muscle to maintain the target power output. Kay et al. (2001) observed that when the race proceeds for a period, the muscle fatigue is supposed to appear and the body will have many symptoms, such as short of breath or be nervous. Hautier et al. (2000) reported that due to that the trunk and the upper limbs work statically during the cycling race, these parts are easy to feel fatigue when experiencing a long distance race. The knowledge of muscle fatigue pattern during cycling from these studies proved a good foundation in developing muscle training programs and cycling equipment to reduce the risk of overuse injury.

2.6.3 Effect of Compression of Garment on Sport

With the improvement of textile material and technology, compression garments have became more and more popular in medical science (Ibegbuna et al., 2003) and being applied in various sport activity (Berry et al., 1987; Bringard et al., 2006; Duffield et al., 2007). In particular, the compression garments are used for athletes during training and racing to aid rapid recovery of performance.

It is reported that the compression garment functions to assist venous return and peripheral circulation in vascular patients, reduce muscle vibration, reduce accumulation of blood lactate following exercise, remove muscle damage markers in post-exercise (Duffield et al., 2010). Early research on compression garments focused on the influence of compression on increased venous blood flow and its positive role for venous thrombosis in patient’s recovery. Compressive stockings are good attempts in reducing venous stasis in the lower extremities (Gandhi et al., 1984; O'Donnell et al., 1979; Perlau et al., 1995; Sigel et al., 1975).

The concept of using compression garments for sports science grows as the compression of garments could reduce muscular fatigue and injuries, which can help the training for athletes to be more successful (Doan et al., 2003). The first exercise-related research on compression garments was conducted by Berry and McMurray in 1987, who found a decrease in venous and lower blood lactate concentrations after maximal exercise when wearing stockings during the exercise (Berry and McMurray, 1987). Through a series of investigations of Lycra-type compression shorts, Kraemer stated these compression shorts could enhance athletic performance, specifically enhance repetitive jump power (Kraemer et al., 1996; Kraemer et al., 1998). The possible physiological mechanisms contributing to the increased repetitive jump power include reduction in muscle oscillation, improved proprioception and increased resistance to fatigue. Compression garments also have been used to keep the working muscles warm in order to decrease musculoskeletal injuries (Doan et al., 2003; Sigel et al., 1975). There are many other benefits of compression garments for sport towards physiological performance and protection, illustrated by these experimental researches. Such as reduced post-exercise trauma and lactic acid buildup, reduced perceived muscle soreness and oscillation, promoted recovery of force production and improved proprioception and core stability (Manabu et al., 2001).

Actually, one of the most recognized usages of compression shorts in sports is found among professional cyclists. The tight fitting compression shorts provide separation between the groin and thigh muscles. This specific design is similar to other compression garments worn in other sports such as basketball, swimming and running (Sipes et al., 2011). Scanlan et al. (2008) pointed out that when subjects wore the lower body compression garments during cycling, their absolute and relative power output respectively increased by 4.2% and 5.7%. These studies show it is possible to design cycling wear considering compression function for the improvement of power output and injury prevention.

2.6.4 Summary

The discussion in this part is devoted to studying the biomechanical mechanisms of the body for biomechanical functional design of cycling. The literature has been reviewed from the aspects of cycling anatomy, cycling injury and fatigue and compression garments for the sport. The knowledge from cycling anatomy includes muscle contraction and muscle action during cycling movement, which are basic physiological mechanisms of the muscle involved in cycling sport. The cycling injury happening in the individual part, the types of the injury, as well as the cause factors of cycling injury have been reviewed to find out the pattern of cycling injury and fatigue. The research on compression garments' effect to increase venous blood flow to reduce muscular fatigue and injuries has been reviewed. Though there are some researches on the compression of stockings, the biomechanical functional design with compression concept for cycling wear to reduce the muscle injury and fatigue still need to be developed.

2.7 Materials for Sportswear Functional Design

The evolution and advances of sportswear is caused by the innovation of textile material for sportswear functional design (Stegmaier et al., 2005). This section reviews the main functional materials on the current market with its influence on sport.

The functional fabric for sportswear has greatly evolved due to functional requirements in the Second World War, and these developed fabrics were widely used for civil production in the apparel industry after the war. Synthesized fiber has rapidly replaced natural fibers, and the Nylon fiber has been adopted in the fabric design with fast speed due to its characteristics of low cost and endurance (Bramel, 2005). With the continuous innovation of fabric, sportswear is realized with more new functional performance, which offers more physiological influence on the body (Bartels, 2005). Table 2.2 summarizes the main functional materials on the current market for functional sportswear, addressing their influence of the sport.

Innovative material	Producer	Characteristics	Influence on the game
LYCRA®SPORT fiber (Lycra®, 2008)	DuPont company	• a kind of synthetic elastic fiber • stretch to 4~7 times the original length when undertaking pressures • recover to the original length when no pressure	• help to reduce the obstruction from the clothing for the game • obviously improve the physical strength and patience of the athletes • relief their vibration caused by the muscle fatigue
COOLMAX®EXTR-EME Performance fabric (Coolmax®, 2010)	DuPont company	• a kind of functional fiber • there is four grooves on the surface to effectively transport moisture • can rapidly transport the sweat on the skin to the clothing outer surface	• has good cooling effect and the skin temperature is decreased quickly • relief the uncomfortable feeling caused by the wetted clothing • good breathability increases the comfort feeling
GORE-TEX® fabric (Gore-tex®, 2009)	Gore	• is a kind of porous membrane • the diameters of of pores on the membrane are big than that of vapor but small than the liquid	• the athlete is comfort in the conditions of raining, winding, gale, and low temperature • and is thermally protected and

		• work as being pressed on a polyester fabric layer • is breathable, durable and water/windproof	improved the physical patience
Sphere React Dry (Stegmaier et al., 2005)	Nike	• a kind of smart fabric • automatically regulate the structure according to the wetness of the skin • the MRT fiber will change to be salient, when the skin is sweating	• Smartly change the structure to offer more space and speed the drying process to improve the comfort feeling • Keep dry-touch with the skin during the game
Clima TechFit (Sipes et al., 2011)	Adidas	• a high-tech suit made of synthetic polymer • designed to optimize the bodily efficiency • reduce the oxygen consumption • and muscle energy output	• an average 5.3% improvement in energy output • a 1.3% reduction in oxygen consumption on test subjects wearing the new suit • the onset of fatigue is delayed

Table 2.2 Summary of the materials used in functional sportswear design

As listed in the above table, most of the innovative functional materials in terms of fiber, membrane and fabric created by the famous brands of functional material and sportswear producers, are characterized by the innovative thermal and biomechanical functions, which can improve the comfort feeling of the body during the wearing time. For instance, the Lycra® fiber focuses on the improvements of biomechanical performance of the sportswear, which is helpful to reduce the obstruction of clothing, improve the physical patience of athletes and thus increase their game score; The CoolMax® aims to quickly transport away the sweat on the skin and relief the uncomfortable wetting feeling; and the Gore-tex® can increase the air breathability of the textile material to improve the comfort of wears in the conditions of raining, winding, gale, and low temperature.

These innovative characteristics of functional materials obviously can offer the designer to achieve more high-tech sportswear and improve both the wearing comfort and game performance of the athletes. However, they are developed by the commercial companies with high cost of copyright if adopted these material. On the other hand, in the design of specific sportswear, the designers should consider the match of these functional materials with their design concepts or specific functional requirements.

2.8 Aesthetics in Sportswear Design

The act of clothing to the body is to not only generate appearance of individuals also to offer aesthetic pleasure based on the past experience (Rudd and Lennon, 2001). In a social and climatic context, the appearance of a person is a perception of viewers, which involves interactions between the viewer, the wearer, clothing, and the environment (Fan, 2004). DeLong and Larntz (1998) reported that the appearance perception of clothing is influenced by Gestalt effect which includes line, shape, color, texture.

Thus, the process of designing often involves aesthetic, functional, economic and sociopolitical dimensions. Scientifically, aesthetics are more defined by the scholars as the study of sensory or sensori-emotional elements (Zangwill, 2007). Over the past years, sportswear design was going through changes in silhouette, construction, and technology that have improved the performance and aesthetic of sportswear. Many recent researches both through theoretical development and experimental observations have proofed that the emotion acts an important role in the activity of humans (Vallerand and Reid, 1984) and can influence the response of the body during sports (Roberts, 1992). Gauvin and Rejeski (1993) found out that the performance of activity has a close dependency on the psychological status of athletes in active time. The professional golfer Laura Baugh has strong notions about the look and the role of clothing in her active life. She pointed out that ‘function doesn’t have to mean drab, and how you look affects your game’ (Brooks et al., 1996). This section reviews the aesthetics in terms of color, cutting and fitting in sportswear design.

2.8.1 Color Impact

The colors in light are identified as red, orange, yellow, green, blue, indigo and violet.

Biologically, the retina of the human eye receives the light waves and transmits them to the brain through the optic nerves for decoding (Armstrong, 1991). It was concluded that the cones of the human eye are of three different types, each being capable of receiving one of the three primary color of light, i.e. red, green and blue (Diane and Cassidy, 2005).

For the body, color is perceived as a surface effect and can be defined several different and exciting ways. Actually, color works as interrelated visual sensations in color vision. Different colors setting together in harmony may produce a pleasing effect, which is a result of interaction between the external world and human's psyche (Gao, 2007). The sportswear color worn by athletes can affect the behaviour of the competitors (Frank and Gilovich, 1988). Even some research found out that the color of sportswear may also influence the outcome of contests (Hill, 2005).

However, in the early period, the impact of the color of functional sportswear on sport has not been cognized by most athletes. The cyclists in Boston cycling club wore dull and even deep cycling uniform which made them look drab (Smith, 1972). The first color innovation of sportswear happened in 1914 when American golf hero Walter Hagen won his first U.S. Open wearing colorful sportswear. However, it was not until the 1950s, men's golf sportswear turned into colorful fashion illustration when golfers like Jimmy Demaret wore combinations of chartreuse and orange. Until 1970s, the ladies' Professional Golf Association also joined the colorful revolution following the men golfers. And this strong color innovation storm continues to happen in the sportswear for hunting, tennis and also cycling (Time-Life Books, 1975).

Recently, scientists started research on the associations between the color and psychological functioning (Elliot, 2007). Maier et al. (2007) chose three color of red, green and black and conducted four experiments. Results indicated that participants wearing red had worse performance and evidenced more local processing (rigid constricting of attention) than those shown gray. This theory also been proved by Ioana et al., (2007), who pointed out that red sportswear has a psychological effect on the behaviours of the wearers and their opponents.

2.8.2 Cutting and Fitting Impact

Numerous researchers have focused on the complex interaction between aesthetics and attributes of clothing (DeLong, 1998; Kupfer, 1994). Since the body is designated as a key element in the aesthetics of clothing, the aesthetic criteria are consistently found to be central to consumers' evaluations of apparel (Eckman et al., 1990; Holbrook, 1986; Morganosky, 1984; Morganosky and Postlewait, 1989). Morganosky and Postlewait (1989) investigated the relative significance of form and expression in the aesthetic judgments of apparel, which are the two main theoreties in aesthetics. It was found that form, including elements such as lines and shapes, contribute more to the evaluation of aesthetic quality of a garment than the expression of garment.

Researchers also suggested that it might be a coping strategy to enhance appearance through selection of appropriate apparel, as it could help individuals by providing aesthetic pleasure (Feather et al., 1996; Rudd and Lennon, 1994). This psychological indication reported can result in higher performance in competition (Gauvin and Rejeski, 1993).

Generally, cutting in sportswear needs have more comfortable widths for a sense of freedom, which give generous allowance for movement. The characteristics of high-performance sportswear have significantly influenced the modern silhouette, and varying silhouettes and versatile detailing provide both function and comfort (O'Mahony and Braddock, 2002). Performance cutting means that the sportswear will follow the body contours but will not necessarily be figure-hugging, since ease of movement is essential; Curvilinear cutting allows unrestricted movement and curvaceous but lean forms; Ergonomic sportswear cutting is still a new technology in contemporary styling (O'Mahony and Braddock, 2002).

Clothing fit has been concerned as an important element of clothing appearance. However, fit is a complex issue which directly depends on the body anatomy (Cain, 1950). The issue of fit is not only an important feature of clothing appearance, but also has been regarded as an important factor for sportswear, as fitting in sportswear design has an influence on sports performance by the psychology of clothing aesthetics during competition.

Sportswear should have a smooth fit with the human body and has enough active room and adequate ease of movement (Chamber and Wiley, 1967). During body movement, even simple actions such as bending the elbows of knees stretches the skin by as much as 50% (Switzerland, 2005), while strenuous movements involved in active sports requires much more stretch (Ibrahim, 1966) (seen in Fig. 2.12). Especially, in cycling sport the position of the body is constantly changing and the competitor should be able to adopt the most ergonomic position at all times (O'Mahony and Braddock, 2002).

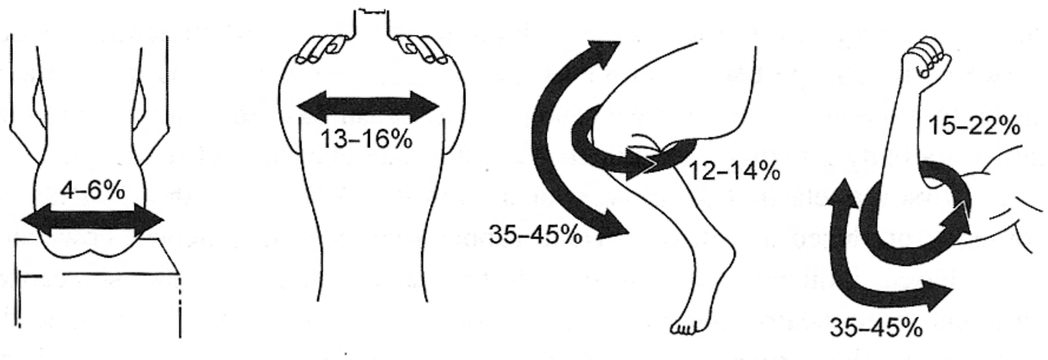


Fig. 2.12 Key stretch points on the body (Switzerland, 2005)

2.8.3 Summary

The act of clothing of the body is to not only generate an appearance of individuals but also to offer aesthetic pleasure. This section has reviewed the related researches on examining the relationship between the aesthetics in terms of color, cutting and fitting and the performance of sportswear. The design process of sportswear often involves the aesthetic, functional, economic and sociopolitical dimensions. Scientists have recently started to examine the associations between color and psychological functioning. Meanwhile, it was found that cutting and fitting is not only an important feature of clothing appearance, but also has been regarded as important factors for sportswear design. Elements such as lines and shapes greatly influence the evaluation of the aesthetic quality of garment, and fitting in sportswear design have influence on sports performance by the psychology of clothing aesthetics during competition.

2.9 Design Processes in Garment Industry

In order to understand and define the design process for the functional design of cycling wear in this research, we must review both the general fashion design process and sportswear design process that have been well defined in the garment industry. The design process involves studies in different contexts and diverse fields and generates a complex set of decision points for designers, since diverse elements are used in the garment design. The design issues in the garment design process should set the criterion for apparel attributes corresponding to the requirements of customers.

2.9.1 General Fashion Design Process

Most garments are hopefully designed to basically be comfortable for the body in daily life, fit the body for normal movements, and then be of appropriate quality, beautify style, express the personality and aesthetic taste of the wearer. Though fashions change with the design elements at different times, they are in compliance with the above need, which opens up a constantly expanding range of creative possibilities (Parsons, 2004). An effective and scientific apparel design process can lead to the success of design of an apparel product. Fashion design actually is a matter of mixing elements in new and existing ways in order to create fresh combinations and products (Jones, 2005). In the process of creation, silhouette, proportion, construction, fabric, color, graphics, texture, fabrication and embellishment should be considered and planned so as to pursue good styles and quality (Jones, 2005; McCann, 2005; McKenzie, 1997).

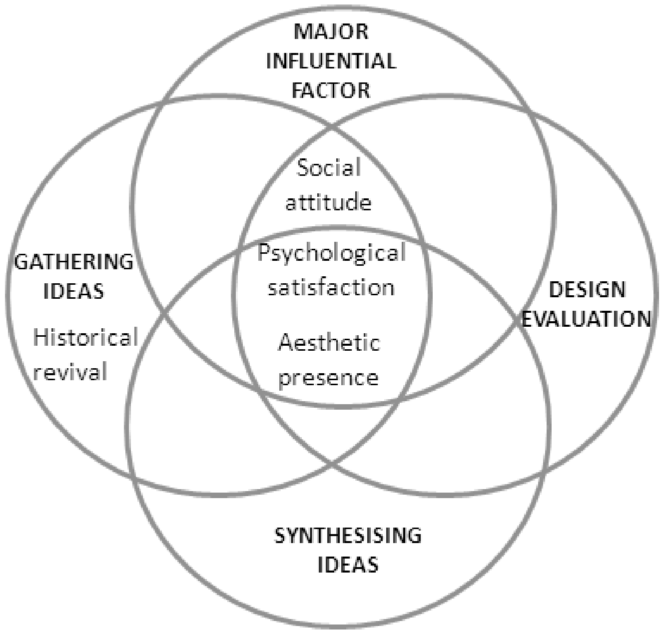


Fig. 2.13 Model of design process of European fashion designers (Au, 2003)

In the research of the fashion field, Au (2003) compared the underlying design theory of contemporary European and Japanese fashion designers and identified the design factors influencing fashion designer. The design theory and model of design process of contemporary fashion designers have been formulated when creating new fashion. The four major factors influencing fashion design included ‘social attitude’, ‘psychological satisfaction’, ‘aesthetic presence’ and ‘historical revival’. For the different fashion designers in different area or having different cultural background, the design elements involved in these four aspects may have different content. Fig. 2.13 illustrates the model of design process of European fashion designers.

In the model of European fashion design process, the fashion design is achieved in the design process of major factors, ideas and as well as synthesize of ideas and design evaluation. The two major factors of ‘aesthetic presence’ and ‘psychological satisfaction’ linked the four categories together during the design process. The factor of ‘social attitude’ linked the three categories, namely, ‘gathering ideas’, ‘major influential factor’ and ‘design evaluation’ together (Au, 2003). This model shows that the factors of ‘psychological satisfaction’ and ‘aesthetic presence’ play the most import roles in the whole fashion design process.

2.9.2 Currently Sportswear Design Process

The design process of sportswear may have differences with the process of fashion design. Since the sportswear has more requirements on provided functions, it’s very necessary and important to design garments for special needs and consider as a part of general design framework. Garments designed especially to meet with their needs is called functional fashions or functional clothing. Unfortunately, current sports participants demonstrate much interest in the fabrication and appearance of the clothing with individual preferences rather than functions (McCann, 2005).

Lamb and JoKallal (1992) established a model of 'Functional-Expressive-Aesthetic' (FEA) to distinguish the functional apparel design and fashion design, which developed the criteria for functional design of garments according to the requirements of customers. This model incorporates functional, expressive, and aesthetic (FEA) considerations for consumer needs and design requirements, as shown in Fig. 2.14. The functional aspect may include the requirements of fit, mobility, comfort, protection and donning/doffing. The expressive aspect may include the values, roles, status and self-esteem. The aesthetic aspect may include the art elements, design principles and body/garment relationship.

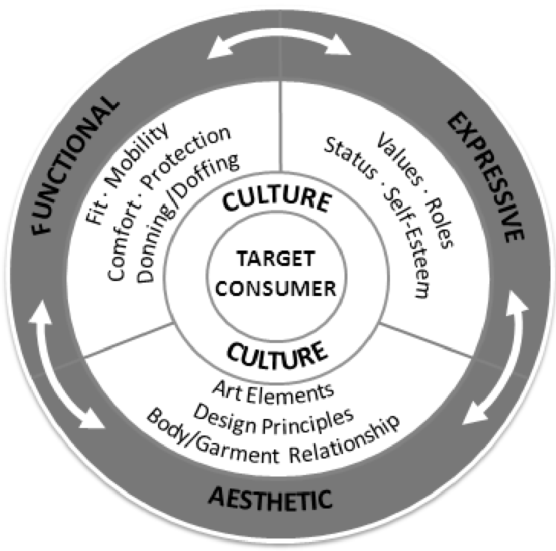


Fig. 2.14 FEA consumer needs model (Lamb and JoKallal, 1992)

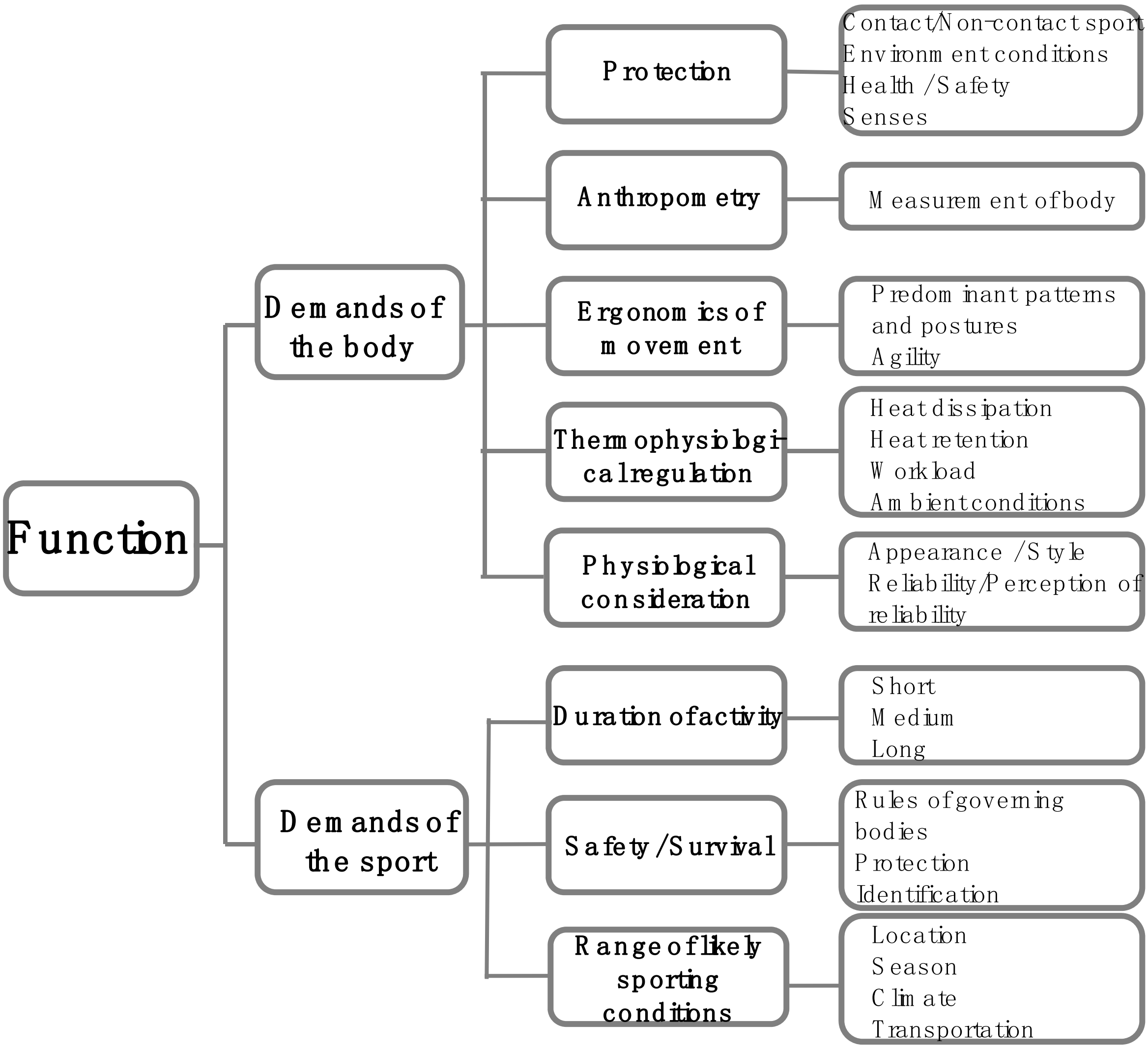


Fig. 2.15 Information tree for functional sportswear design (McCann, 2005)

McCann (2005) identified the functions in sportswear process and developed an information tree to guide the design process for performance sportswear designers, as shown in Fig. 2.15. The factors influencing the sportswear designer included two major paths, 'demands of the body' and 'demands of the sports'. The demands of the body includes protection, anthropometry, ergonomics of movement, thermo-physiological regulation, physiological consideration. Further descriptions about these demands have been given, such as protection demand related to issues of environment conditions, health senses, thermal physiological regulation related to heat dissipation, heat retention, work load and ambient conditions. The demands of the sport include duration of activity, safety/survival and range of likely sporting conditions.

Thus, the design process of sportswear just including the aesthetic presence and technical textiles is insufficient to create sportswear with desirable functional performance. The functional sportswear design need crosses the boundaries of special knowledge both within and outside the scope of art and design. These models of design for functional garments and sportswear distinguished the design issues from that in fashion design. Although they cannot be directly used as the design model for functional cycling design, they are good attempt to design the model for functional garment design and laid substantial foundations for design garment for specific requirements.

2.9.3 Analysis of the Factor Model of Cycling

Given that cycling is a popular form of exercise and sport, researchers have exerted considerable effort to benefit cyclists. Studies generally integrate the influences of several factors, including inherent and external factors. The inherent factors include the physiological characteristics of cyclists, such as the composition of muscle fiber, metabolic rate, and maximal oxygen uptake. The external factors include training, pacing, and nutritional strategies, which also influence the overall power output of the cyclists.

To illustrate the factors affecting the overall race velocity of cycling, Greg et al. (2003) proposed a factor model for cycling sport. This model summarizes the possible factors originating from diverse aspects, including inherent physiological and external factors, rider position, bike design, and retarding force (Fig. 2.16). He pointed out that inherent physiological and external factors have the potential to influence the generated power during a cycling race, whereas the rider position, pacing strategy, bike design, and retarding forces influence the power-velocity relationship.

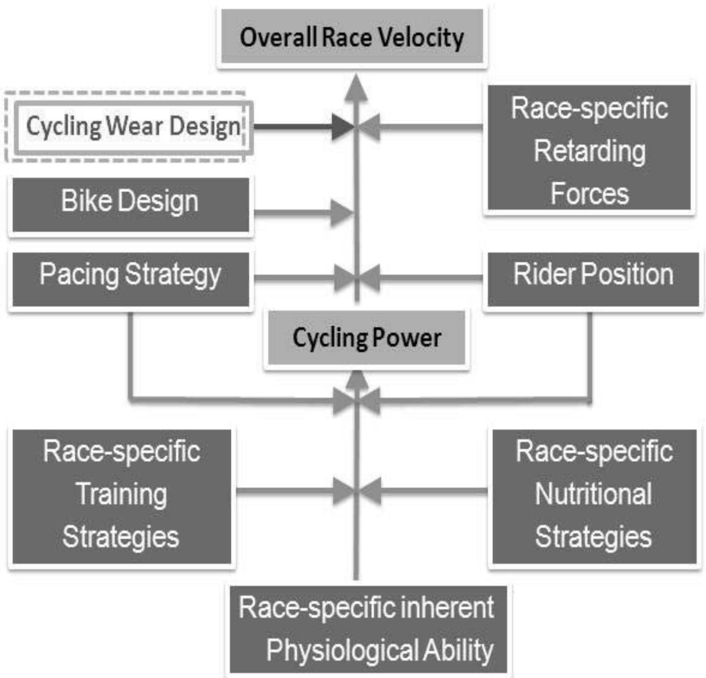


Fig. 2.16 Factors influencing the cycling overall race velocity (Greg et al., 2003)

Cycling is a form of high-velocity sport usually performed in various environments. Some physical resistance may occur in the race environment, such as hilly roads or windy climate. The pacing strategy and rider position of the cyclists can influence the magnitude of air resistance, posing an effect on the relationship between power output and race velocity. The presence of various resistances may influence the bicycle design or the choice of its components. However, cycling sportswear, which serves as important equipment for cyclists, is not considered in this model.

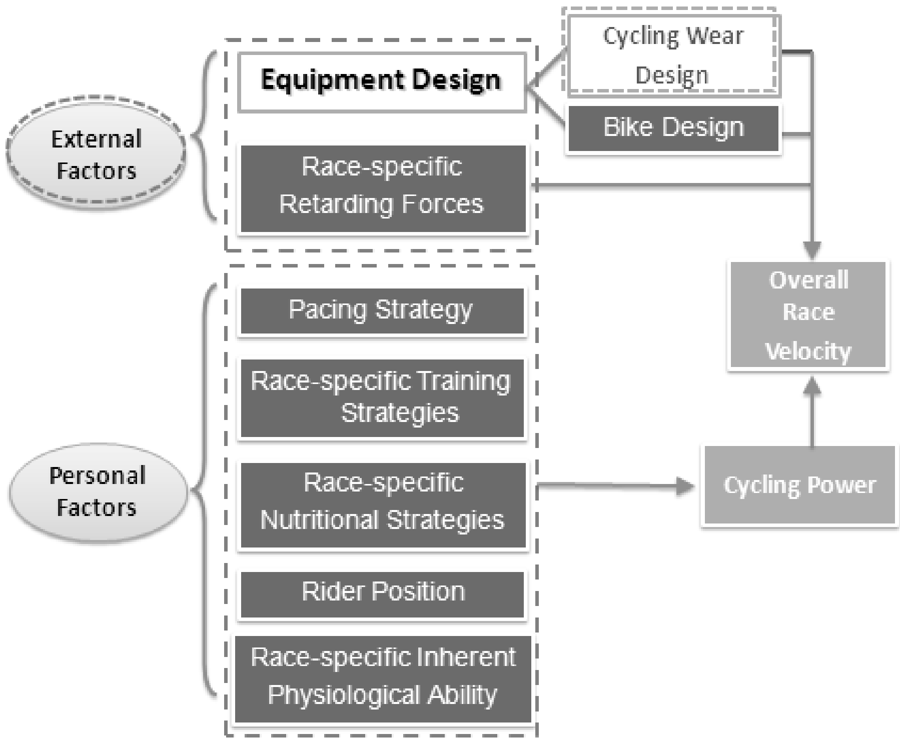


Fig. 2.17 Factors affecting the overall race velocity (Greg et al., 2003)

With the development of functional sportswear, cycling sportswear can offer considerable benefit in decreasing air resistance and improving race velocity, as well as relieving fatigue and preventing injury (Andrew, 1998; Doan et al., 2003; O'Mahony and Braddock, 2002; Wang, 2002). Thus, the cycling sportswear design should be identified as an important factor affecting the overall race velocity and considered in Greg's factor model. The cycling sportswear design and bike design can be further categorized as external factors of equipment design influencing the overall race velocity, as elaborated in Fig. 2.17. The external factors include equipment design, and race-specific retarding forces. The inherent factors include pacing strategy, training strategies, nutritional strategies, rider position, and inherent physiological ability.

2.9.4 Summary

This part has reviewed the garment design process, in which the design models of the general fashion design process and functional sportswear design process are studied and discussed. The general fashion design process includes major influential factor, gathering ideas, synthesising ideas and design evaluation. There are four factors in terms of "social attitude', 'psychological satisfaction', 'aesthetic presence' and 'historical revival' influencing the fashion designers. The design model for functional sportswear design distinguished the design issues from the fashion design. The model of 'Functional-Expressive-Aesthetic' (FEA) developed the criteria for functional design of garments according to the requirements of customers. The information tree proposed by McCann identifies the functions in sportswear design process including two major paths of 'demands of the body' and 'demands of the sports'. These design models though they cannot be directly used for functional cycling design, laid substantial fundament in design garment for specific requirements. Furthermore, based on analysis of the factor model of cycling, the cycling sportswear design has been identified as an important factor affecting the cycling velocity in the factor model.

2.10 Summary and Research Gaps

The literature review above has explored the fundamental research and status in the aspects of history of road cycling, evolution of road cycling sportswear, cycling wear markets, thermal functional design, biomechanical functional design, materials for sportswear functional design, aesthetics in sportswear design and design processes in garment industry. Though the knowledge related to the functional design of sportswear have been systematically reviewed, however, we can find that there still has no a systematic design approach to achieve functional cycling sportswear design satisfying the multi-aspect requirements in thermal physiology, biomechanics and aesthetics. In order to realize the design innovation of cycling sportswear by the fusion of aesthetic, thermal and biomechanical functional design achieving for desired functional performance, there is need to fill in the knowledge gaps.

This review has suggested that there still has a long distance to realize the design innovation of cycling sportswear with the fusion of aesthetic art and thermal functional and biomechanical functional design for desired functional performance. In order to achieve this design innovation, the following knowledge gaps need to be filled:

1) The systematic design model for cycling sportswear functional design integrating the aesthetic, thermal and biomechanical functional design is not available;

2) The aesthetic elements in cycling sportswear design, which provide the medium to fuse aesthetic design with functional design, and the aesthetic functional design of cycling sportswear are still not investigated;

3) The thermal functional design of cycling sportswear corresponding to the thermal analyses and the thermal requirements of cycling sports to provide superior thermal comfort has not been achieved;

4) The biomechanical functional design of cycling sportswear considering the biomechanical mechanisms of muscles during cycling movements to prevent the muscle injury and fatigue has not been achieved;

5) The realization of FCS design with prototypes having multi-functional performance of thermal comfort, muscle fatigue reduction and muscle injury prevention is still not available.

In order to fill in these gaps, the objectives of this study were described and the methodologies adopted to achieve these objectives were introduced in Chapter 1, respectively. Fig. 2.18 shows the linkage between the knowledge gaps, objectives and methodologies of this study.

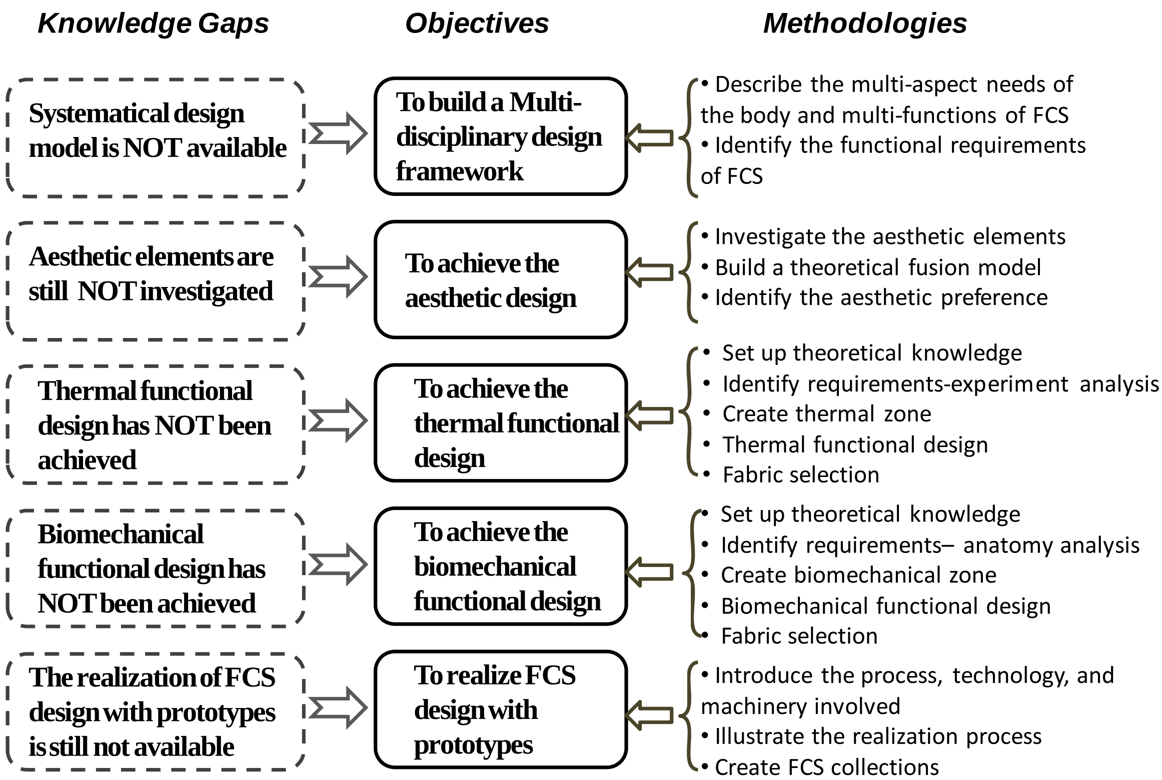


Fig. 2.18 Linkage between the knowledge gaps, objectives and methodologies

CHAPTER 3 FRAMEWORK OF FUNCTIONAL CYCLING SPORTSWEAR DESIGN

3.1 Introduction

The literature review reveals that there is still no systematic design approach that can realize functional cycling sportswear design to satisfy the multi-perspective requirements of thermal physiology, biomechanics, and aesthetics. The functional design of sportswear includes the field of art design, and also combines multi-disciplinary knowledge on sport physiology, biomechanics, and aesthetics. Hence, the functional design of sportswear needs to investigate the mechanisms concerned, integrate, and utilize multi-disciplinary knowledge. That is an approach different from traditional fashion design. Thus, the design model of sportswear should be different from the general model of fashion design. Since the functional design of sportswear covers both aesthetic and functional factors, it should fuse aesthetics with functions to provide the body with functional comfort and protection during sport activities.

This study aims to realize a design innovation model of functional cycling sportswear (FCS) by fusing aesthetic art and thermal and biomechanical functional design. The basis is the integration of multi-disciplinary knowledge on thermal physiology, biomechanics, and aesthetics. As an approach of innovative design, the aim is to establish a scientific design framework of functional cycling sportswear to accomplish the systematic work of design. This chapter first describes the functional requirements of cycling sportswear by multi-functional requirement analyses and hypothesis proposal. Then a questionnaire is created to identify the multi-functional of requirements of the cycling sportswear. Based on the survey data from professional cyclists, the correlations between the ratings on the required functions of FCS and years of cycling experience are investigated. Finally, the functional requirements on FCS are identified, and the multi-disciplinary framework for functional cycling sportswear design is proposed to integrate the involved knowledge and illustrate the process for accomplishing this design innovation of FCS.

3.2 Requirements of Functional Cycling Sportswear

As a specific type of sportswear, cycling sportswear has both the usual functional requirements of other kinds of sportswear and particular requirements arising from the characteristics of cycling sports. To provide background information on this innovative study, the functional requirements of cycling sportswear need to be identified.

3.2.1 Multi-functional Requirements Analysis

A scientific investigation of the functional requirements of cycling sportswear should begin with an understanding of the multi-functional needs of the human body during cycling. Cycling is a high-velocity and endurance sport that can be performed in various terrains and environments. A typical professional cyclist based in Europe covers 25,000 to 35,000 km in a year and participates in at least one of the major three-week tours (Horton et al., 2007). The physiology and biomechanics of the sport has become an important topic over the last two decades. With continuous research work, it is able to identify the physiological and biomechanical needs of the human body (Broker and Gregor, 1994; Faria and Cavanagh, 1978). The psychological needs of the body have also been studied to determine sportswear functions. The multi-functional needs of the human body during cycling are illustrated in Fig. 3.1 and subsequently explained:

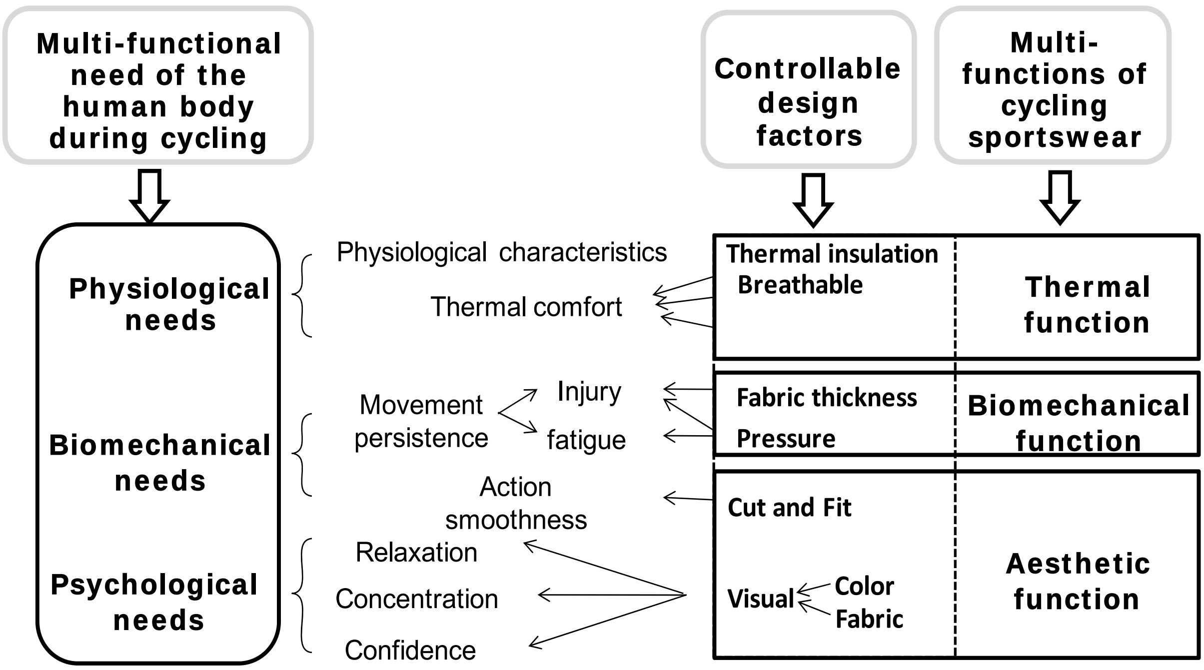


Fig. 3.1 Multi-functional needs of the human body during cycling

Physiological Needs of the Human Body

The physiological needs of the human body can be studied by reviewing the physiological characteristics of the body during engagement in sports, and probing the conditions for thermal comfort during cycling.

Physiological characteristics are the functions of organisms. They directly influence the power generated by the human body, such as maximal aerobic power, muscle fiber type, and lactate threshold (Lee et al., 2002). The cycling physiological need is concerned with the human biological functions related to cycling under the stress of muscular activities. Theoretically, the adaptation mechanism enables the oxygen transfer to the active muscles and compensate for exercise during recovery (Caputo et al., 2003).

Thermal comfort during cycling depends on the thermal equilibrium between the body and surrounding environment. When riding intensively, much heat is produced because the human body needs to consume much energy for muscular activity. The human body easily feels extremely hot if heat does not dissipate effectively. The generated sweat accumulates on the skin and causes a feeling of discomfort, which may influence the game performance of an athlete. Hence, the feeling of thermal comfort affects not only the well-being of the wearer but also their performance and efficiency in cycling.

Biomechanical Needs of the Human Body

The biomechanical needs of the human body during cycling can be studied by investigating the ways in which the body is kept healthy for movement persistence and action smoothness.

Due to the intensive and high-speed nature of cycling, the human body is easily fatigued or even injured, which influences movement persistence. The riding action can be divided into sub-actions from the upper and lower limbs. The trunk and upper limbs work statically during the cycling sport; hence, these parts are easily fatigued after experiencing a long-distance race. Consequently, the body simultaneously experiences many symptoms such as shortness of breath and nervousness. If fatigue lasts for a long time and the body is not able to rest, the muscles may be injured or even damaged. Thus, fatigue reduction and injury prevention are needed during cycling.

Another important biomechanical need of the body during cycling is maintaining action smoothness. In the present context of cycling, the mechanical factors in sports mainly include air friction, strength of material, and mechanical aspect of the muscles and joints that are responsible for turning the pedals and steering the bicycle (Faria and Cavanagh, 1978). The important biomechanical need of cycling is the bodily application of power to the bicycle and improvement in the efficiency of the bicycle by reducing the amount of resistance, such as air/wind resistance and rolling resistance, against the direction of movement.

Psychological Need of the Human Body

During sport activities, many psychological factors, such as anxiety, self-motivation, response to injury, fatigue, and external environment influence, may elicit emotions from the athlete that affect the athletic performance. Sport psychologists have developed various techniques and methods to increase sport performance by the management of emotions and minimization of the psychological effects of injury. Some important psychological skills have been discussed in sport psychology, including self-talk, goal setting, awareness and control, relaxation, concentration, and confidence (Silva, 1984). Sport psychology may change sport performance via an assortment of sports skills, and athletes with psychological skills have long been acknowledged as more likely to be successful (Silva and Weinberg, 1984). Athletes at the elite level recognize that their mind is their most important muscle; thus, they learn how to apply the concept of mind over pain.

Multi-functions of Cycling Sportswear

With regard to the above-discussed multi-functional needs of the human body during cycling, cycling sportswear is expected to have a variety of functions that can be realized by controllable design factors to satisfy the described needs of the body. These functions may include thermal, biomechanical, and aesthetic functions, as subsequently discussed.

- ***Thermal function***

The feeling of thermal comfort enables the body to have physical endurance and strength during an activity, and thus improve activity performance. The thermal functions of cycling sportswear determine the thermal comfort feeling of the wearer (Li, 2001). Cycling sportswear acts as an obstruction to the heat and moisture transfer between the skin and environment, and directly influences the thermal physiological behaviours of the human body (thermal biological regulations). Cycling sportswear with good thermal functions, which may include smart thermal insulation, good breathing ability and moisture management capability (MMF), can enable the quick drying of skin-generated sweat and decrease the skin temperature. Thus, the discomfort that may otherwise be caused by heavy wetted clothing is not felt.

- ***Biomechanical function***

The biomechanical functions of cycling sportswear should include the fatigue relief of the main body parts, and the prevention of muscular injury based on the biomechanical mechanisms of such injuries. The pressure of the garment is an important criterion in evaluating the mechanical performance of cycling sportswear. This criterion is defined as the pressure produced when the cycling sportswear vertically presses on the human body, including weight pressure, constraint pressure, and surface pressure. The injury prevention function of cycling sportswear is realized by the pressure property (Denton, 1970). Cycling sportswear with comfortable pressure not only protects the human body, but also improves the game performance.

- ***Aesthetic function***

The fabric, color, and fitting of cycling sportswear are categorized into aesthetic elements because they contribute to the garment appearance and also help to improve action smoothness and game performance during cycling. The fabric and color of cycling sportswear directly determine the visual effect, which has an important influence on the psychological process of the body.

Cutting cycling sportswear according to the cycling anatomy may realize a good fit and provide appropriate pressure gradients for the different body parts without influencing the freedom of body movement. Furthermore, the good fitting effect of cycling sportswear accompanies good tensile, bagging, and frictional abilities to allow scientific contact between the body and sportswear during cycling. Consequently, wearing comfort of the body is improved. Meanwhile, seamless knitted cycling sportswear may decrease the possible air resistance caused by the seam, especially on the shoulders, back, and legs.

The visual effects contributed by color and fabric can influence human behaviour and feelings by producing physiological signals and psychological associations to the body. Color can stimulate the central nervous system, which may have different responses to different colors. For instance, yellow, orange, and red are positive to the human body, but blue, green, and blue-red have a passive effect on the human body. Positive colors may make the human body more active, excited, and aggressive. However, passive colors may result in nervous, gentle, and aspiring emotions. The fabric directly determines the aesthetic style of cycling sportswear via the properties of weight, structure, fiber composition, and color, which partly contribute to the image establishment of the wearer.

Proposed Hypothesis

Based on the above discussion on the expected functions of cycling sportswear, the functional requirements of and market expectations on cycling sportswear are summarized by the following hypotheses:

Hypothesis I: The functional requirements of cycling sportswear involve multi-perspective descriptions in terms of thermal, biomechanical, and aesthetic needs, each of which is very important to the design of FCS.

Hypothesis II: The thermal functions of cycling sportswear can have a positive influence on the cycling performance.

Hypothesis III: The biomechanical functions of cycling sportswear can have a positive influence on the cycling performance.

Hypothesis IV: The aesthetic functions of cycling sportswear can have a positive *influence on the cycling performance.*

Hypothesis V: The multi-perspective functions of cycling sportswear are important factors in the buying decision of customers.

3.2.2 Questionnaire Design and Data Analysis

Questionnaire Design

Based on the above-proposed hypotheses, a questionnaire was designed and administered to collect the data for identifying the multi-functional requirements of FCS, which are the basic concerns in developing the framework of FCS design.

To determine the functional expectations and requirements involved in FCS design, as well as understand the satisfaction level of the participants on the design details for different levels of professional cycling race commitment, the questionnaire was designed to have three parts. Part I collected the demographic information of the participants. Part II was concerned with the functional requirements of cycling sportswear. Part III was related to preferences on cycling sportswear design. The questionnaire began with a declaration for this questionnaire (Appendix A).

- ***Part I: Demographic information***

Part I collected the demographic information of the participants, including nationality, gender, age, weight, height and years of professional cycling experience (Appendix A).

- ***Part II: Functional requirements***

In a previous research, Wong (2002) has investigated the relationship between human psychological sensory perceptions in relation to the overall clothing comfort perception. The relationships among sensory perceptions, physical and mechanical properties of the fabric, as well as comfort perception have been studied. He has built the average rating of 10 personal preferences based on their importance in clothing models, including fitness, comfort, design, fabric, color, easy care, price, durability, fashion, and brand. Cowie (2001) has identified the needs of indoor cyclists for indoor cycling sportswear via survey questionnaires. Another questionnaire has also been designed to investigate the requirements of amateurs during cycling (Sipes et al., 2011).

Part II of the present questionnaire was designed according to the proposed hypothesis of the functional requirements of FCS with reference to previous work (Cowie, 2001; Sipes et al., 2011) and a survey on injuries during cycling (Yang and Yao, 1999). The questions include the requirements of high-performance cycling sportswear (question 1), functional design of cycling sportswear that positively influence the cycling performance (question 2), factors affecting the buying decision of cycling sportswear products (question 3), and satisfaction level with the current cycling sportswear (question 4).

- ***Part III: Design preference***

Many researchers have developed or modified design process models to meet the needs of apparel design (DeJonge, 1984; LaBat and Sokolowski, 1999; Lamb and JoKallal, 1992; Watkins, 1984). Interestingly, comfort and style representing the physical and psychological requirements are almost equally important to consumers. Ho (2010) has observed that the attributes of cycling sportswear rated as most important by participants are comfort and function.

To identify the design details and preference of FCS, part III of the present questionnaire focused on the response of the professional cyclist to questions on cycling sportswear. The questions include the cycling sportswear fit satisfaction status (question 5), cycling sportswear style satisfaction (question 6), during cycling the following body parts are easily injured by solar radiation (question 7), the body parts easy to have fatigue and influence on cycling performance during cycling (question 8), the body parts need to be especially protected from injury during cycling in the cycling sportswear design (question 9), cut and seam lines on the body parts that may negatively influence the cycling performance (question 10), and preferred colors of cycling sportswear (question 11).

Participant and Data Collection

In this survey questionnaire, the participants mainly came from five countries, including Sweden, Germany, Switzerland, Hong Kong, and mainland China. All participants were excellent professional cyclists who came to China to participate in UNIVERSIADE 2011 SHENZHEN. The data were collected from August 12 to 23, 2011.

Paper questionnaires were handed out to interested volunteers. Prior to participation, the researcher explained the purpose and key points of the questionnaire, as well as the completion procedure. When finished, the participants were asked to return the questionnaire to the researcher on site. There were a total of 71 cyclists who completed the questionnaire. Three questionnaires were unusable due to missing data for many important questions.

Data Analysis

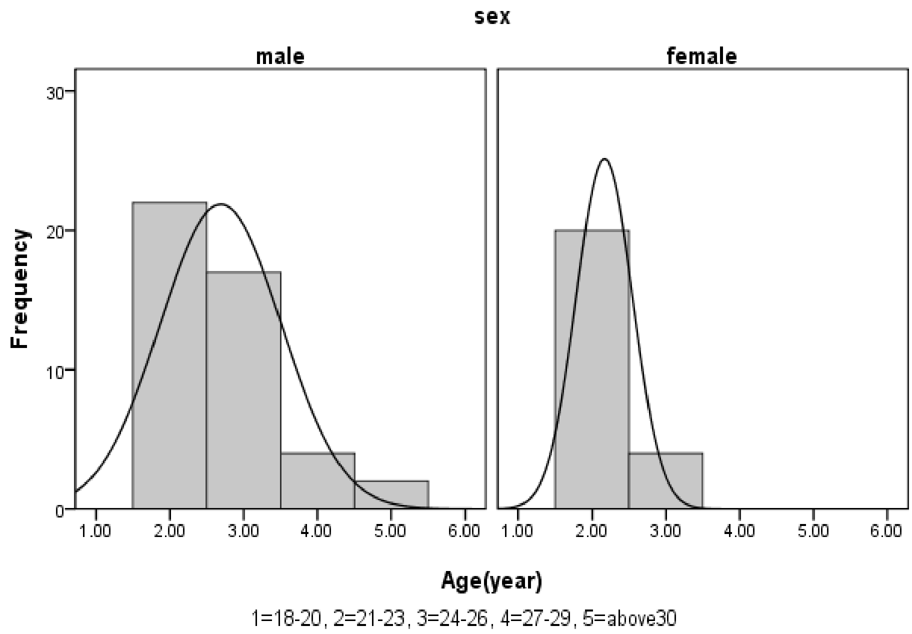
Based on the returned valid questionnaires, data analysis was performed using the professional statistical software tool SPSS to analyze the data of Parts I and II, and identify the functional requirements of FCS.

- ***Preliminary analysis***

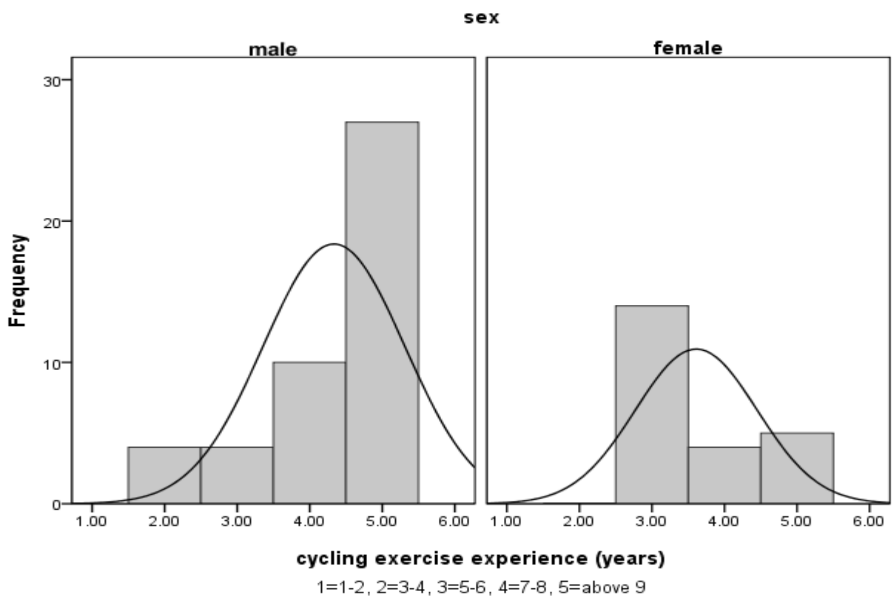
Among the survey questionnaire participants, there were 46 male and 22 female professional cyclists. The distributions of the participant gender grouped with cycling experience years are shown in Table 3.1. Fig. 3.2 reports the demographic characteristics of the participants. The age groupings and gender of the participants are shown in Fig. 3.2(a). There were 68 participants from around the world whose ages ranged from 18 years to over 30 years. For the 46 males surveyed, the largest age group was 21 years to 23 years (47.83%), followed by groups aged 24 years to 26 years (41.30%), 27 years to 29 years (8.7%), and above 30 years (2.17%). For the 22 females, the largest age group was 21 years to 23 years (81.82%) and the rest were aged 24 years to 26 years (18.18%).

Experience year	**Male**		**Female**		**Total Number**	**Total Percentage (%)**
	Number of respondents	Percentage (%)	Number of respondents	Percentage (%)		
1-2	0	0%	0	0%	0	0%
3-4	4	8.7%	0	0%	4	5.88%
5-6	18	39.13%	0	0%	18	26.47%
7-8	0	0%	14	63.64%	14	20.59%
above 9	24	52.17%	8	36.36%	32	47.06%
Total	46	100%	22	100%	68	100%

Table 3.1 Distributions of sexual participants grouped with cycling experience years



(a) Age & gender of respondents



(b) Exercise experience & gender of respondents

Fig. 3.2 Demographic characteristics of the participants

The years of cycling experience and gender of the participants are illustrated in Fig.

3.2(b). All participants had more than three to four years of cycling experience. For the 46 males surveyed, the largest group of cycling experience was above nine years (52.17%). However, for the 22 females, the largest group was seven to eight years (63.64%). For all 68 participants, the largest group was above nine years (47.06%). The other groups were five to six years (26.47%) and seven to eight years (20.59%). Only approximately 5.88% participants had cycling experience of three to four years, and all of them were male. This result was attributed to the fact that all cyclists that participated in UNIVERSIADE 2011 SHENZHEN were selected from the best and most experienced professional athletes in different countries.

- ***Factor analysis***

The principal component factor analysis is used to identify the relationship among aesthetic, thermal and biomechanical functional requirements, which were abstracted into different factors. The factor of thermal comfort was associated with the thermal requirement; the factors of power output, injury, and fatigue were associated with the biomechanical requirement; and the factor of professional image was associated with the aesthetic requirement.

Tables 3.2(a) and 3.2(b) show the unrotated results of factor analysis with three and five factors. The total percentages of variance explained by three and five factors were 77.14% and 100%, respectively. Both extracted components showed that the thermal, biomechanics, and aesthetic requirements were inseparable and had similar contributions to the requirements of high-performance cycling sportswear. However, the aesthetic requirement contributed slightly less than the thermal and biomechanical requirements in both extracted components.

Component Matrix

	Component		
	1	2	3
thermal comfort	.595	-.409	.432
power output	.768	-----	-.433
injury	.731	.405	-----
fatigue	.524	.529	.544
professional image	-----	.791	-----
% of Variance	**35.982**	**25.611**	**15.554**

(a) Three factor components extracted

Component Matrix

	Component				
	1	2	3	4	5
thermal comfort	.595	-----	.432	.526	-----
power output	.768	-----	-.433	-----	.419
injury	.731	-----	-----	-----	-.443
fatigue	.524	.529	.544	-----	-----
rofessional image	-----	.791	-----	.549	-----
% of Variance	**35.982**	**25.611**	**15.554**	**13.910**	**8.943**

(b) Five factor components extracted

Extraction Method: Principal Component Analysis. Level of significance: 0.0000
Note: All figures <0.4 or >-0.4 are marked as -----

Table 3.2 Unrotated component matrixes

- ***Correlation analyses and ANOVA***

Exploratory data analysis via scatterplots revealed a linear relationship between the independent and dependent variables, which were five groups of cycling experience.

The analysis used bivariate correlation and multivariate ANOVA to determine the direction and strength of the relationship between the variables. The results were described within the context of the following three research questions. Cyclists with longer experience may have clearer concepts about the requirements of FCS; hence, the results distinguished by the five groups of cyclists with different years of experience were analyzed to identify the requirements in FCS design.

Question 1: *Relationship between the functional requirements of cycling sportswear and years of cycling experience.*

The results of all ratings by the grouped participants for the thermal, biomechanical, and aesthetic requirements of FCS are shown in Fig. 3.3, which provides an overview of the distributions of ratings of the different groups on these items.

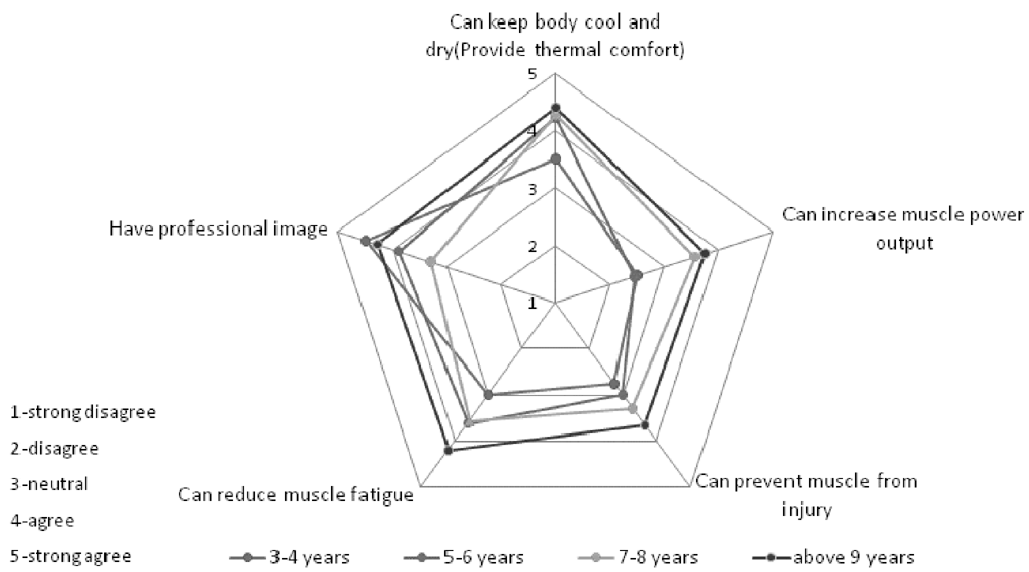


Fig. 3.3 All ratings by the grouped participants on the requirements of FCS

Bivariate correlations were performed for the thermal, biomechanical, and aesthetic requirements of FCS with the years of cycling experience, as shown in Table 3.3. The results revealed that thermal requirements (Q1.1) correlated with the years of cycling experience (r = 0.300, $p < 0.05$). The biomechanical requirements (Q1.2, Q1.3, and Q1.4) correlate with the years of cycling experience via Q1.2 (r = 0.659, $p < 0.01$), Q1.3 (r = 0.532, $p < 0.01$), and Q1.4 (r = 0.541, $p < 0.01$). However, there is no correlation between the aesthetic requirement (Q1.5) and years of cycling experience (r = 0.157, $p >$ 0.05).

		cycling exercise experience (years)
cycling exercise experience (years)	Pearson Correlation	1
	p	
	N	68
Q1.1: Can keep body cool and dry （Provide thermal comfort）	r	.300*
	p	.013
Q1.2: Can increase muscle power output	r	.659**
	p	.000
Q1.3: Can prevent muscle from injury	r	.532**
	p	.000
Q1.4: Can reduce muscle fatigue	r	.541**
	p	.000
Q1.5: Have professional image	r	.157
	p	.200

*. Correlation is at the 0.05 level.

**. Significant correlation is at the 0.01 level

Table 3.3 Bivariate correlations analysis for the functional requirements

Table 3.4 shows the results of AVOVA, which compared the ratings of the five groups for the thermal, biomechanical, and aesthetic requirements with different years of cycling experience. A significant influence was found in all variables of thermal and biomechanical requirements ($p < 0.05$ and $p < 0.01$). This result indicated that more years of cycling correlated with stricter thermal and biomechanical requirements in FCS. However, the aesthetic requirement in FCS shows no relation to the years of cycling.

		Sum of Squares	df	Mean Square	F	Sig.
Q1.1: Can keep body cool and dry (Provide thermal comfort)	Between Groups	3.004	3	1.001	3.430	.022
	Within Groups	18.687	64	.292		
	Total	21.691	67			
Q1.2: Can increase muscle power output	Between Groups	23.245	3	7.748	21.680	.000
	Within Groups	22.873	64	.357		
	Total	46.118	67			
Q1.3: Can prevent muscle from injury	Between Groups	6.704	3	2.235	8.499	.000
	Within Groups	16.826	64	.263		
	Total	23.529	67			
Q1.4: Can reduce muscle fatigue	Between Groups	8.639	3	2.880	11.115	.000
	Within Groups	16.581	64	.259		
	Total	25.221	67			
Q1.5: Have professional image	Between Groups	.482	3	.207	.247	.832
	Within Groups	43.104	64	.914		
	Total	44.985	67			

Table 3.4 ANOVA analysis for the functional requirements of cycling sportswear

Question 2: *Relationship between the factors in FCS design having positive influences on the cycling performance and the years of cycling experience.*

The results of all ratings by the grouped participants on the design factors of FCS are shown in Fig. 3.4, which provides an overview of the distributions of ratings of the different groups on these factors.

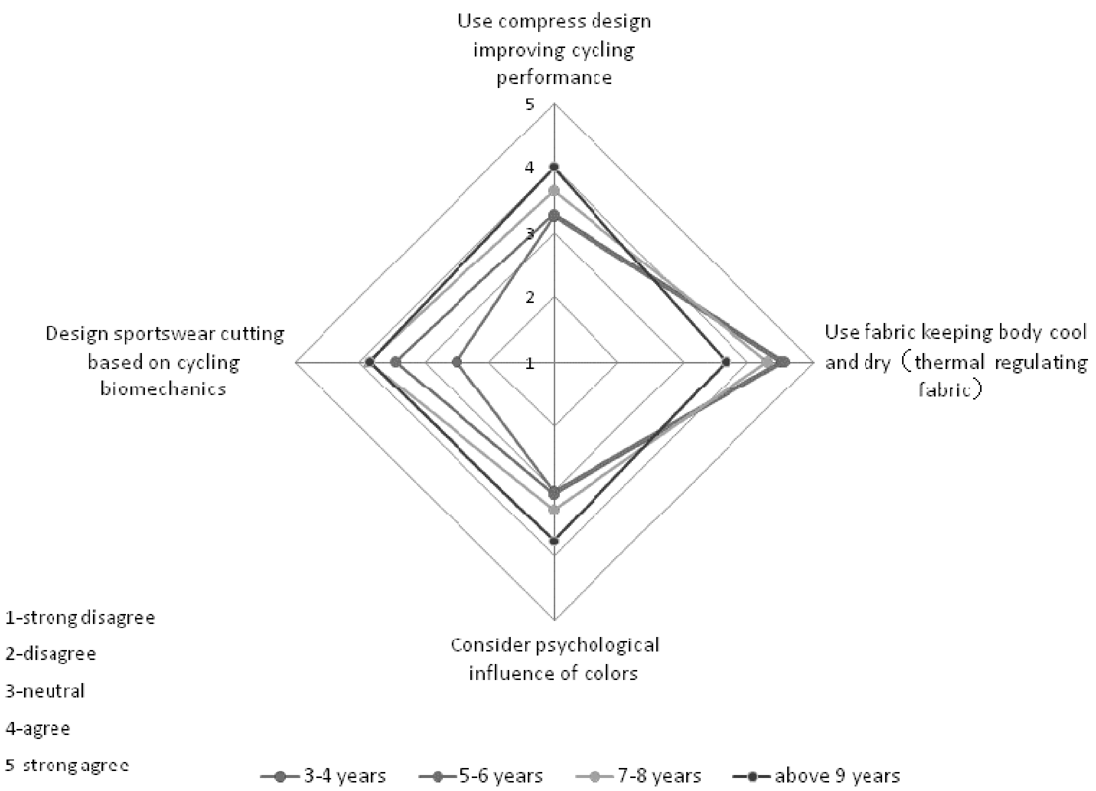


Fig. 3.4 All ratings by the grouped participants on design factors of FCS

Bivariate correlation analysis illustrates the relationship between the design factors of FCS (Q2.1–Q2.4) and years of cycling experience, as shown in Table 3.5. The results revealed that the factors of FCS design (Q2.1–Q2.4) significantly correlated with the years of cycling experience via Q2.1 ($r = 0.467$, $p < 0.01$), Q2.2 ($r = -0.411$, $p < 0.01$), Q2.3 ($r = 0.404$, $p < 0.01$), and Q2.4 ($r = 0.366$, $p < 0.01$).

		cycling exercise experience (years)
cycling exercise experience (years)	Pearson Correlation	1
	p	
	N	68
Q2.1: Use compress design improving cycling performance	*r*	.467**
	p	.000
Q2.2: Use fabric keeping body cool and dry（thermal regulating fabric）	*r*	-.411**
	p	.001
Q2.3: Consider psychological influence of colours	*r*	.404**
	p	.001
Q2.4: Design sportswear cutting based on cycling biomechanics	*r*	.366**
	p	.002

*. Correlation is at the 0.05 level.

**. Significant correlation is at the 0.01 level

Table 3.5 Correlations analysis for the factors in cycling sportswear design

The same design factors of FCS were also analyzed by AVOVA and revealed similar results, as shown in Table 3.6. The ratings of all design factors were influenced by the years of cycling experience.

		Sum of Squares	df	Mean Square	F	Sig.
Q2.1: Use compress design improving cycling performance	Between Groups	6.939	3	2.313	6.279	.001
	Within Groups	23.575	64	.368		
	Total	30.515	67			
Q2.2: Use fabric keeping body cool and dry（thermal regulating fabric）	Between Groups	11.112	3	3.704	4.989	.004
	Within Groups	47.520	64	.743		
	Total	58.632	67			
Q2.3:Consider psychological influence of colors	Between Groups	7.494	3	2.498	4.533	.006
	Within Groups	35.270	64	.551		
	Total	42.765	67			
Q2.4: Design sportswear cutting based on cycling biomechanics	Between Groups	7.843	3	2.614	5.013	.003
	Within Groups	33.377	64	.522		
	Total	41.221	67			

Table 3.6 AVOVA analysis for the factors in cycling sportswear design

Question 3: *Relationship between the factors affecting the selection of cycling sportswear and years of cycling experience.*

The results of all ratings by the grouped participants on the selection factors of FCS are shown in Fig. 3.5, which provides an overview of the distributions of ratings of different groups on these factors.

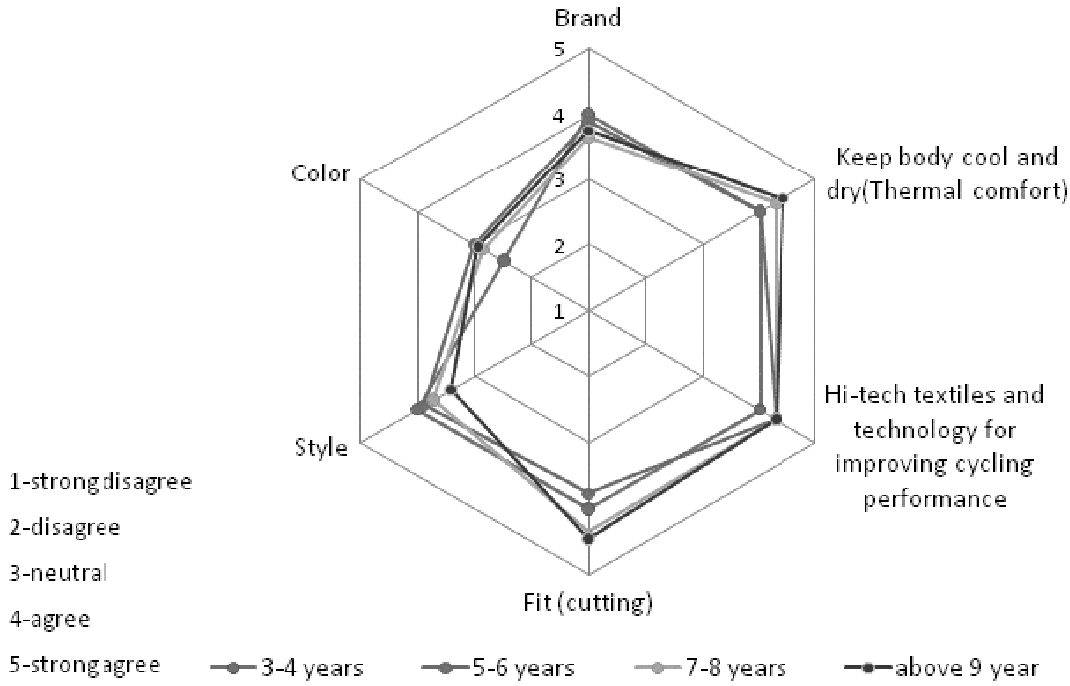


Fig. 3.5 All ratings by the grouped participants on selected factors of FCS

Bivariate correlation was performed for the factors affecting the selection of cycling sportswear and years of cycling experience, as shown in Table 3.7. The results revealed that the factors thermal comfort ($r = 0.328$, $p < 0.01$) and fitting ($r = 0.383$, $p < 0.01$) significantly correlated with the years of cycling experience. However, the factors of brand ($r = -0.137$, $p > 0.05$), style ($r = -0.213$, $p > 0.05$), and color ($r = 0.035$, $p > 0.05$) did not correlate with the years of cycling experience.

		cycling exercise experience (years)
cycling exercise experience (years)	Pearson Correlation	1
	p	
	N	68
Brand	*r*	-.137
	p	.264
Keep body cool and dry(Thermal comfort)	*r*	.328**
	p	.006
Fit (cutting)	*r*	.383**
	p	.001
Style	*r*	-.213
	p	.081
Colour	*r*	.035
	p	.779

*. Correlation is at the 0.05 level.

**. Significant correlation is at the 0.01 level

Table 3.7 Correlations analysis for the factors of selection of cycling sportswear

Table 3.8 shows the AVOVA results on the comparison of the ratings of five groups with different years of cycling experience on these factors. The results indicated that the factors of thermal comfort and fitting were significantly influenced by the years of cycling experience ($p < 0.01$). However, there was no significant difference between the five groups in terms of the brand, style, and color when selecting cycling sportswear ($p > 0.05$).

		Sum of Squares	df	Mean Square	F	Sig.
Brand	Between Groups	.699	3	.233	.878	.457
	Within Groups	16.992	64	.266		
	Total	17.691	67			
Keep body cool and dry(Thermal comfort)	Between Groups	2.174	3	.725	2.798	.047
	Within Groups	16.576	64	.259		
	Total	18.750	67			
Hi-tech textiles and technology for improving cycling performance	Between Groups	.298	3	.099	.492	.689
	Within Groups	12.937	64	.202		
	Total	13.235	67			
Fit (cutting)	Between Groups	5.941	3	1.980	4.820	.004
	Within Groups	26.294	64	.411		
	Total	32.235	67			
Style	Between Groups	3.455	3	1.152	1.048	.378
	Within Groups	70.354	64	1.099		
	Total	73.809	67			
Color	Between Groups	.881	3	.294	.233	.873
	Within Groups	80.589	64	1.259		
	Total	81.471	67			

Table 3.8 AVOVA analysis for the factors deciding the selection of cycling sportswear

- ***Satisfaction analysis of current cycling sportswear***

The questionnaire also surveyed the satisfaction of cyclists on the functional characteristics of the current cycling sportswear for NIVERSIADE 2011 SHENZHEN. The functional characteristics included color, sportswear cut based on cycling biomechanics, UV protection, professional image, muscle fatigue reduction, muscle injury prevention, muscle power output enhancement, and body cooling and drying. The results are illustrated in Fig. 3.6. All functional characteristics were below the satisfaction level. The satisfaction levels with color, UV protection, professional image, and body cooling and drying are neutral. The satisfaction levels with biomechanics-based cutting, muscle fatigue reduction, muscle from injury prevention, and muscle power output enhancement were very low. These results indicated that the cyclists were not satisfied with the functional characteristics of the current cycling sportswear, especially in terms of its biomechanical functions.

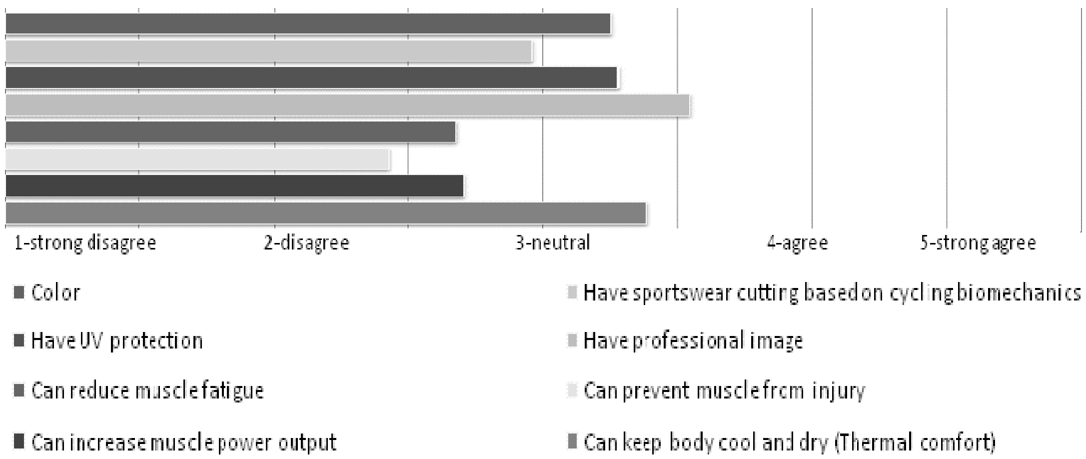


Fig. 3.6 Satisfaction levels with the current cycling sportswear for UNIVERSIADE 2011 SHENZHEN

3.2.3 Requirements Identification

At the beginning of this section, the satisfaction level with the functions of the current cycling sportswear and expected functional requirements of the FCS in the survey is illustrated in Fig. 3.7. The discrepancy pertaining to each function is shown, and the functional requirements of FCS can be identified.

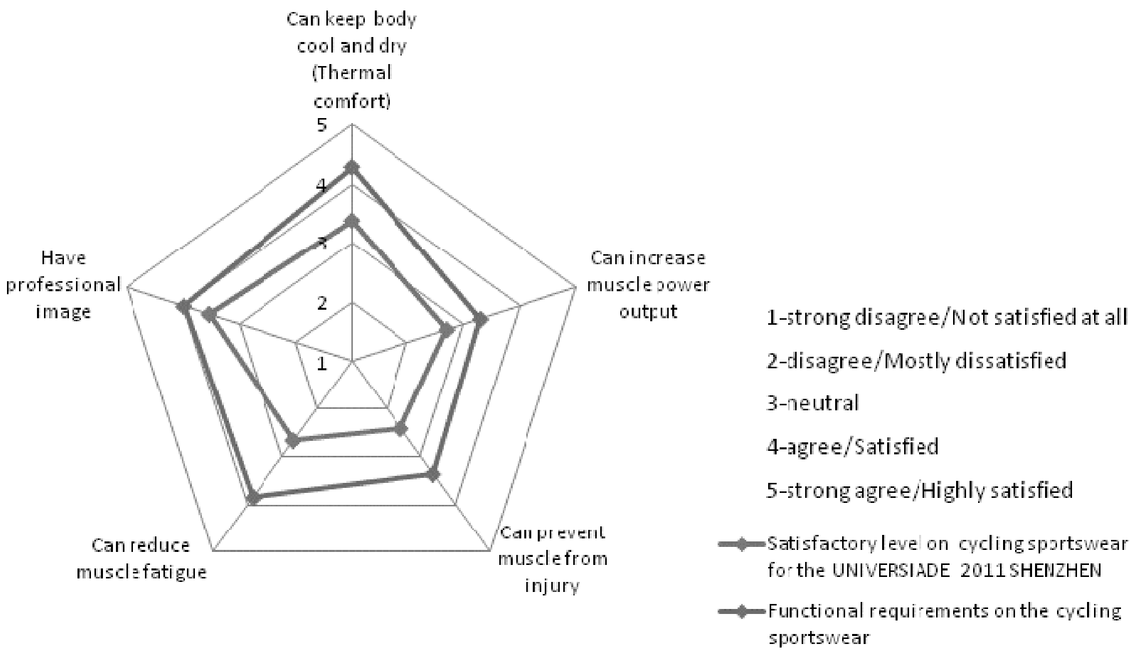


Fig. 3.7 Ratings on the functions of the current cycling sportswear and expected functional requirements of FCS

Thermal Requirements

1) Over 90% of the professional cyclists agreed or strongly agreed that a cycling sportswear should keep the body cool and dry to provide thermal comfort during

cycling. Correlation analyses and ANOVA showed that cyclists with longer cycling experience more strongly agreed with this item (correlation: $r = 0.300$, $p < 0.05$; ANOVA: $p < 0.05$). Thus, thermal comfort is a basic requirement of the FCS design.

2) Over 90% of the professional cyclists agreed that they selected cycling sportswear based on thermal comfort. Moreover, correlation analyses and ANOVA also showed that the cyclists with longer cycling experience more strongly agreed to this item (correlation: $r = 0.328$, $p < 0.01$; ANOVA: $p < 0.05$).

3) The satisfaction level with the thermal comfort of the current cycling sportswear and expected thermal comfort of FCS had a large discrepancy. Thus, the current cycling sportswear did not satisfy the functional requirements of the cyclists.

Biomechanical Requirements

1) The professional cyclists with longer cycling experience positively agreed with the biomechanical requirements of the FCS design. Correlation analyses and ANOVA on muscle power output enhancement (correlation: $r = .659$, $p < 0.01$; ANOVA: $p < 0.01$), muscle injury prevention (correlation: $r = 0.532$, $p < 0.01$; ANOVA: $p < 0.01$), and muscle fatigue reduction (correlation: $r = 0.541$, $p < 0.01$; ANOVA: $p < 0.01$).

2) The professional cyclists with longer cycling experience positively agreed with the design factors, such as the use of compression design and biomechanics-based cutting.

They regarded these factors as having positive influences on the cycling performance, as indicated by the correlation analysis and ANOVA results (correlation: $r = 0.467$, $p < 0.01$; ANOVA: $p < 0.01$) and (correlation: $r = 0.366$, $p < 0.01$; ANOVA: $p < 0.01$). They also agreed that the factor of cutting can influence their selection of cycling sportswear (correlation: $r = 0.383$, $p < 0.01$; ANOVA: $p < 0.01$).

3) The overall rating on the biomechanical functions of the current cycling sportswear was below satisfactory, whereas the rating on the expected biomechanical functions of FCS was above satisfactory. These results indicated that there was a big gap between the available and expected biomechanical functions of FCS.

Aesthetic Requirements

1) Over 80% of the professional cyclists were satisfied with the professional image. However, there was no correlation between the agreement on professional image and years of cycling experience (correlation: $r = 0.157$, $p > 0.05$; ANOVA: $p > 0.05$) because the aesthetic preference was more related to individual psychological factors than years of experience.

2) The professional cyclists with longer cycling experience positively agreed with the design factor of color. They regarded the psychological influence of colors as having a positive effect on the cycling performance, as indicated by the correlation analysis and ANOVA results (correlation: $r = 0.404$, $p < 0.01$; ANOVA: $p <0.01$).

3) Most of the cyclists did not disagree with the brand, style, and color influencing their selection of cycling sportswear. However, these responses were not influenced by the years of cycling experience (ANOVA: $p > 0.05$).

4) The rating on the aesthetic effects of the FCS was above satisfactory, as shown in Fig. 3.7. Hence, the aesthetic function is also a very important functional requirement of cycling sportswear.

3.2.4 Summary

This section described the questionnaire designed with three parts. The survey was administered to collect data for identifying the functional requirements of FCS. Based on the data from the professional cyclists from five countries and areas who participated in the UNIVERSIADE 2011 SHENZHEN, demographic analysis, bivariate correlation analysis, and ANOVA were performed to reveal the correlations between the ratings on the functions of FCS and years of cycling experience. Finally, the functional requirements on FCS were identified based on the rating of the functions of the current cycling sportswear and expected functional requirements of FCS.

3.3 Multi-disciplinary Framework of Functional Cycling Sportswear Design

With the recognition of the influence of functional sportswear on the performance of sports, there are already some studies on smart fabrics and functional sportswear developed for some specific activities, such as running, football, basketball, and swimming (O'Mahony and Braddock, 2002; Scanlan et al., 2008; Shishoo, 2005). However, the literature review in Chapter 2 reveals that there is still no systematic research on the design of functional cycling sportswear. Cyclists highly demand cycling sportswear with multi-functional requirements in terms of thermal comfort, biomechanical protection, and sport aesthetics, as surveyed and discussed in section 3.2. A theoretical framework of FCS should be developed to realize the design innovation of FCS.

Before the development of this theoretical framework, the multi-disciplinary knowledge involved in the design of FCS must be summarized. The multi-functional requirements of FCS on thermal biology, biomechanics, and aesthetics led to the design innovation of FCS to achieve desirable aesthetic effect, thermal and biomechanical functions. However, in practice, all FCS functions are realized by the textile material, fabric making, and functional treatments. Hence, the functional design of cycling sportswear encompasses the application of multi-disciplinary knowledge on thermal biology, biomechanics, aesthetics, textile materials, and art design.

Thus, the theoretical framework of FCS was developed to illustrate the design process by a systematic integration of different knowledge fields and identifying the relationship among them. In garment design, the design of cycling sportswear is a specific application for the cycling sport. The basic elements in the fashion design model, such as fabric, color, and cutting, were considered, and the functional requirements were fulfilled. The multi-disciplinary framework for the FCS design was then developed, as shown in Fig. 3.8.

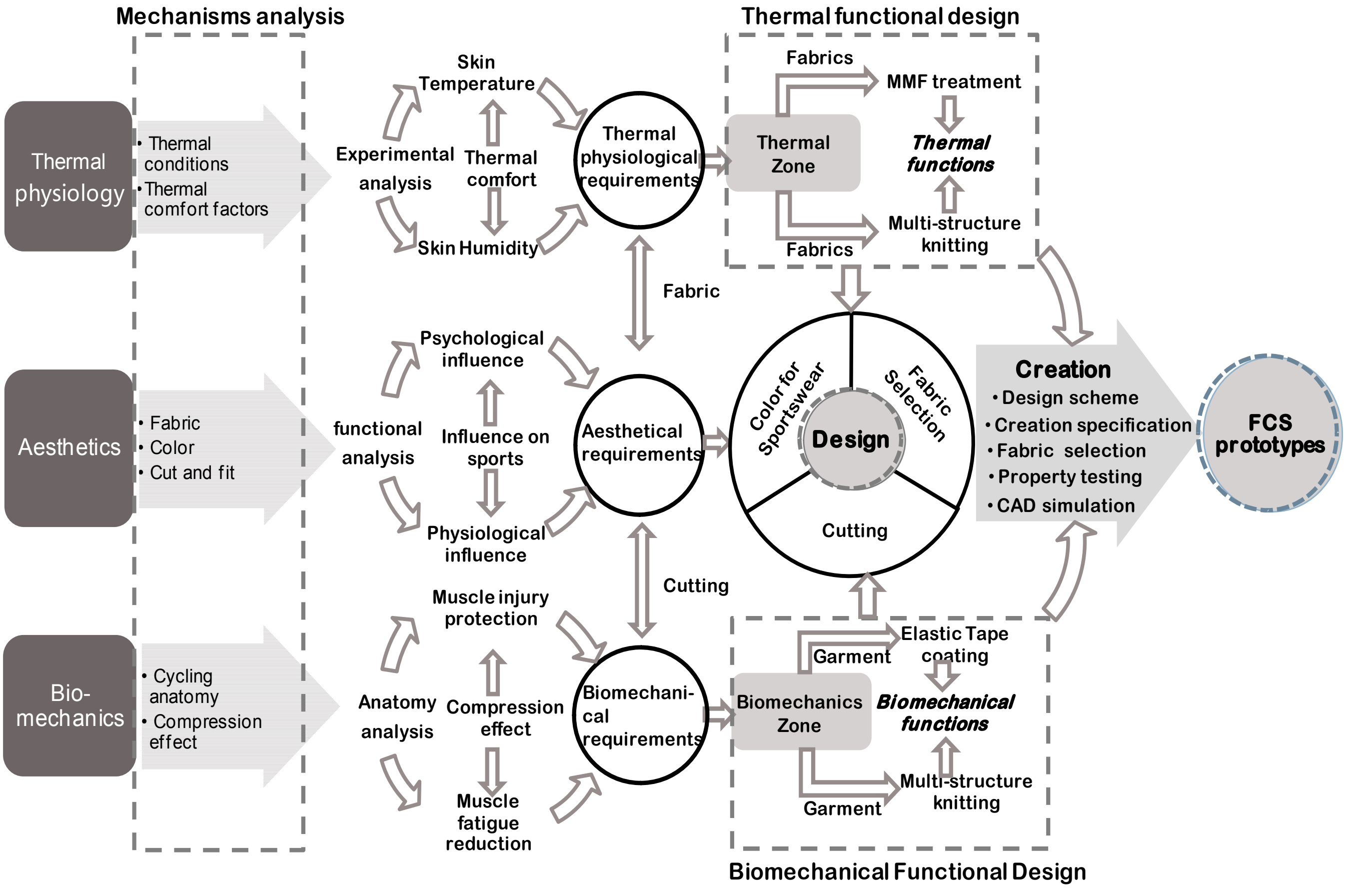


Fig. 3.8 Multi-disciplinary framework for the FCS design

As illustrated in the model, the overall design process of FCS includes mechanism analysis, key issue identification, requirement development, functional design, and FCS prototype creation. Corresponding to the multi-functional requirements, the functional design was performed simultaneously for the three aspects of thermal physiology, aesthetics, and biomechanics to realize the desired functions. Thus, the design innovation of FCS was actually the fusion of these three factors. The details are as follows.

3.3.1 Aesthetic Design

The aesthetic effect is an important requirement because it not only generates visual effect but also may significantly influence the cycling performance. In traditional fashion design, aesthetics is the main concern, which gives the focus on the shape, cut, pattern, color, and material. In contrast, in the functional design of FCS, the aesthetic design is the fusion of aesthetics and functions via the aesthetic elements of fabric, color, line and cut.

In this part, the aesthetic effects of FCS are investigated in terms of the fabric material, color and cut. The physiological and psychological influences of the fabric material, color, and cut on the sport performance are investigated by aesthetic analysis to illustrate their functions on the sport. The aesthetic preference of professional cyclists for design detail in the FCS design is identified by analyzing the data from the questionnaire survey. Consequently, the aesthetic elements in FCS design are identified and illustrated.

3.3.2 Thermal Functional Design

Thermal comfort is one of the most important functional requirements of FCS; it determines the wear feeling and further influences the cycling performance. In principle, thermal comfort is obtained via thermal insulation, air breathability, water vapor permeability, and moisture management. Thus, the thermal functional design of FCS aims to offer thermal comfort by realizing superior thermal functions.

This segment of the study intends to realize the required thermal functions based on thermal physiology knowledge. The mechanism analysis of thermal physiology was first performed by identifying the thermal conditions during cycling and the factors influencing thermal comfort during cycling. With this foundation of mechanism investigation and theoretical analysis, the thermal physiological requirements for FCS can be further developed by experimental analysis. The aim is to identify the thermal physiological characteristics of cyclists during cycling in terms of the temperature and humidity distributions on the body.

Subsequently, based on the temperature and humidity distribution, the thermal zones are created to illustrate the thermal requirements of different body parts. The thermal functional design can be realized as described in the design scheme. To confirm the functional performance of the fabrics ready for the design scheme, CAD simulation is performed to predict the thermal performance of the fabrics, which further indicates the selection of fabrics for the thermal functional design.

3.3.3 Biomechanical Functional Design

Given the high-speed nature of cycling, the muscles of the body need to perform intensive activity during this sport, which usually results in muscle fatigue and injury. The body depends on the biomechanical characteristics of muscles to performing activities. The investigation of the muscular biomechanical mechanisms during cycling was the foundation of the FCS biomechanical functional design to reduce muscle fatigue and injury, and thus improve the overall cycling performance.

This segment of the study is based on the knowledge of muscular biomechanics to realize the biomechanical functions. First, the biomechanism of cycling is analyzed by investigating the cycling anatomy and effect of compression garment on muscles. By cycling anatomy analysis, the muscle pattern recruitment of cycling is demonstrated, and the biomechanisms of muscle fatigue and injury during cycling are investigated. The detailed biomechanical needs of the body for the FCS design are also be further identified by the survey questionnaire. Accordingly, biomechanical zones are created to describe the biomechanical requirements. The biomechanical requirements of injury protection and fatigue reduction are developed specifically for each body part. The appropriate compression range for each muscle is identified for the biomechanical functional design of FCS to induce optimal compression effect on the muscles. Accordingly, the biomechanical functional design of FCS is performed by a detailed design scheme. To confirm the mechanical performance of the fabrics, CAD simulation is performed and the compression effect of the fabric is predicted, which further indicate the selection of fabric for biomechanical functional design.

3.3.4 Realization of FCS Functional Design

Given the fused aesthetic, thermal physiological, and biomechanical functional design, the FCS functional design can be realized by creating collections of prototypes for different applications. A typical creation process including the flow, technology and machines for the creation of FCS prototypes is introduced. To illustrate the realization process of the design, the design inspiration and scheme can be demonstrated and the process of fabric selection, garment pattern making and design demonstration can be presented. By applying this design innovation, different collections of FCS prototypes can be designed and created for different applications.

3.3.5 Summary

The design innovation of FCS with multi-functions of thermal comfort, biomechanical protection, and sport aesthetics can be achieved based on multi-disciplinary knowledge on thermal biology, biomechanics, and aesthetics. To illustrate the design process by systematically integrating the involved knowledge and identifying the relationships, the multi-disciplinary framework of the FCS design was developed. The framework included the flow of mechanistic analysis, key issue identification, requirement development, functional design and cycling wear prototype making. The design of FCS encompasses the fusion of aesthetics, thermal physiology, and biomechanics.

3.4 Conclusion

A framework for accomplishing systematic work for the design innovation of FCS has been developed in this chapter. The functional requirements of cycling sportswear are first identified by analyzing the multi-functional needs of the body and conducting a survey on professional cyclists participating in the UNIVERSIADE 2011 SHENZHEN. The correlations between the ratings on the required functions of FCS and years of cycling experience are investigated and the functional requirements on FCS are identified. The multi-disciplinary framework for FCS design is proposed and illustrated [illegible]ermal physiology, biomechanics, and aesthetics. The multi-disciplinary framework indicates that this design innovation of FCS is actually the fusion of aesthetic design with thermal and biomechanical functional design. The final FCS design can be realized by simultaneously carrying on the aesthetic, thermal and biomechanical functional design.

CHAPTER 4 AESTHETIC DESIGN OF CYCLING SPORTSWEAR

4.1 Introduction

The design requirements of sportswear have developed designers in fashion field with knowledge and skills. It has been realized that the performance actually turns out to be the aesthetics for the sportswear. Fabrics and related technologies comprise the sportswear trend (Shishoo, 1995). The incorporation of innovative textile materials, such as microfibers, breathable fabrics, stretch fabrics, intelligent textiles and phase-change materials, has become a part of functional design and constitute the routine procedure in the design and production of sportswear (Jacques, 1997). As reported in Chapter 3, aesthetic effect is an important functional requirement of the functional cycling sportswear (FCS) except the thermal and biomechanical functions in the multi-disciplinary framework of FCS design.

This chapter initially investigates the elements of aesthetics in sportswear in terms of fabric, cut and fit, and color. How these aesthetic elements in traditional garment design work and impose influence on the functions of sportswear, even the game performance, is described. Based on this investigation, a theoretical model is established to demonstrate how the aesthetic and functional designs are fused through these elements in sportswear. Subsequently, the aesthetic preference of professional cyclists for FCS design is identified through the questionnaire survey reported in Chapter 3. With these efforts, the aesthetic elements in FCS design are analyzed and demonstrated.

4.2 Aesthetic Elements in Sportswear

Sportswear, which mostly works as functional clothing, represents the crossing between the conventional clothing industry and evolutional technologies of biotechnology, nanotechnology, medicine, and physics. There has been close relationship between fashion and function since the 1970s when the fashion industry adopted fabric technology and sportswear and shoes on the catwalk (McKenzie, 1997). Recently, this relationship has been further popularized as fashion designers have become engaged in the development of sportswear. The intertwining influence between the fashion and sports industries is studied by exploring the mutual nature of their relationship to reach their optimal fusion. Thus, this section aims to investigate the mechanisms of the aesthetic elements of design mainly in terms of fabric, color, and cut and fit (McKelvey, 2011), illustrating how they influence the functions of sportswear and improve athlete performance in a sport.

4.2.1 Fabric Material in Sportswear

Fabric is the most basic element with which a designer can create a variety of clothing. Generally, fabrics are categorized into woven fabrics, knits and no-woven fabrics. Knitted fabrics have more elastic properties than woven ones. The role of fabric in sportswear design is demonstrated in Fig. 4.1, from which it can be observed that fabric is the basis for achieving the aesthetic style and acts as a prime factor in the functional performance of sportswear.

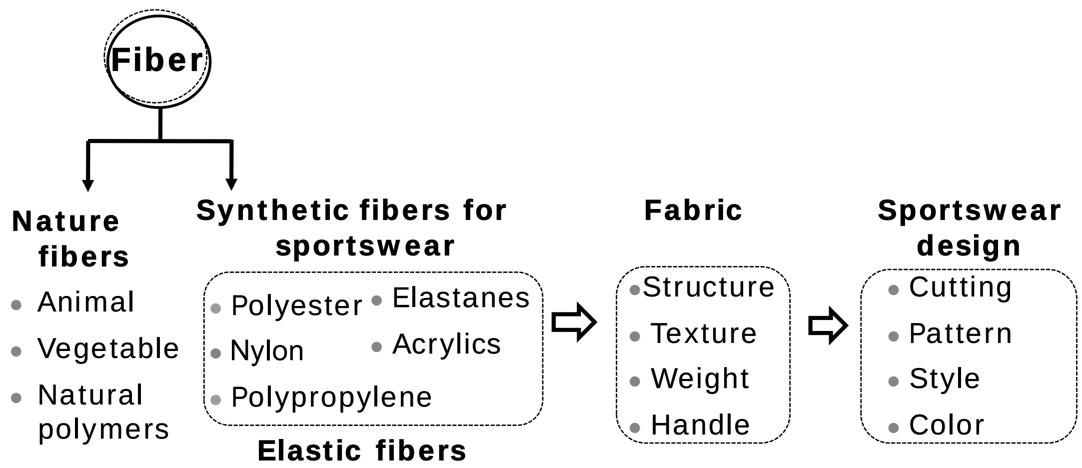


Fig. 4.1 Role of fabric in sportswear design

In traditional fashion design, the fabric determines the cut, drape, pattern, and vision of a garment, whereas fiber composition determines the performance and behaviour of the fabric and sportswear. When designing with fabric to achieve the intended garments, the fabric features and properties to be considered include weight, structure and texture (McKelvey, 2011). Even the same garment design made in different fabrics will create different effects. The fiber composition, structure (weave/knit), or bonding method determines the texture (influencing the tactile qualities); handle (rough, smooth, warm, and cool) and fabric weight and structure determine the drape.

In recent years, new fibers and fabrics have been developed for the sportswear and functional textile market, which become smarter and incorporate more performance characteristics during construction, making the development of fabric as significant as the cut and shape of the garment itself. The representative functional materials in the current market for sportswear, such as Lycra fiber, CoolMax fiber, and GORE-TEX fabric, have been reviewed and summarized in Chapter 2. The performance characteristics often required in many sportswear and sporting equipment have different properties, such as the thermo-physiological functions of thermal insulation, weather prevention, resistance to liquids, breathability and quick drying, and biomechanical functions of fit, ease of movement, and mechanical comfort and prevention (Troynikov et al., 2010).

There are animal, vegetable, natural, and synthetic polymers in the market. For sportswear design, synthetic fibers, such as polyester, nylon, polyamide, polypropylene, acrylics, elastane, are commonly used. As for the fabric, stretch fabrics with high stretch and recovery properties play an important role in the design of sportswear, as they can provide freedom of movement, reduce friction, minimize the risk of muscle fatigue and injury, and maximize comfort (Troynikov et al., 2010). Stretch fabric can be achieved by knitting technology, which is developed from handcrafts supporting the free transposition of loops, and offer good stretch ability. A large quantity of commercial sportswear products in the market is developed by knitting technology (Wilson, 2008). Meanwhile, elastane can also have great contribution to the fabric's elastic property when combined with different types of fibers. The end use of the fabric determines the required direction and degree of elasticity; thus, it also determines the required type and amount of elastane. It was reported that using 2% elastane can improve the shape retention of a fabric, whereas high-performance sportswear such as running wear and swimwear may require as much as 30% elastane (Wang, 2008).

As a result of the technological advances in the production of fibers and fabrics with unique performance properties, fusing the traditional role of fabric in aesthetics with functional design in sportswear with different requirements is now possible.

4.2.2 Cutting and fitting in sportswear

Sports enthusiasts may not have paid much attention to the element of cutting and fitting, which greatly contributes to the aesthetics of sportswear similar to traditional garments. However, cutting and fitting can be more than only an issue of aesthetics with implications on functional applications in sportswear design. As shown in Fig. 4.2, the activity of cutting and fitting is associated with functional concerns, which can be understood through the following explanation:

Fig. 4.2. Activity of cutting and fitting

Traditionally, pattern making of a garment involves the process of obtaining the measurements of the body size, and then applying these measurements into the cutting of the pattern. However, the body form comprises both concave and convex surfaces, and no two bodies are identical in figure. Anglais (1967) stated that most fitting problems are caused by figure abnormalities. The cutting and fitting of a garment thus require correct measurements and figure annotations, which means careful cutting and accurate fitting. Body contour, posture, and even anatomy in the specific sports affect the fit of sportswear. Usually, a basic pattern is cut for an average symmetrical body shape with standard body posture and anatomy; pattern alterations are then performed for individuals.

Generally, cutting of sportswear needs comfortable widths for a sense of freedom, which give generous allowance for movement. As reviewed in Chapter 2, in cycling, the position of the lower limbs is constantly changing. For example, the knee may stretch the skin by up to 50%. The characteristics of high-performance sportswear have significantly influenced the varying silhouettes and versatile details providing both function and comfort (O'Mahony and Braddock, 2002). Athletes should be able to freely move in the sportswear without restraints. Otherwise, inappropriate pressure exerted on the body may cause discomfort. On the other hand, reduced muscle fatigue and pressure can be experienced when wearing clothes that have the proper fit and cut. Performance cutting means that the sportswear follows the body contours, but is not necessarily figure-hugging. This aspect guarantees the ease of movement while considering any required pressure. Through increasing the fullness or stretch of the fabric, it can minimize the resistance caused by the garment's fit to the body's ease in movement. Increasing the stretch of the fabric is beneficial as sportswear is able to be cut and have a more streamlined appearance while conforming well to the body’s shape, and still offering comfort pressure to the wearer during activity (O'Mahony and Braddock, 2002).

Seaming is usually in alliance with cutting to finish a pattern, which is also often regarded as a feature of fashion design in sportswear. Different seaming approaches can achieve different features. For instance, stitched and glued flat seaming offers a body-conscious look; welded seaming is helpful for wind and moisture protection; covered and sealed seaming protects the stitching from abrasion and weather elements; twisted and curved seams can substitute for straight lines to follow the body’s natural form; and seams in contrasting colors, double-stitched seams, and inside-out seams can add a decorative effect.

However, seams and hems in certain ways can bunch and twist instead of lying smoothly against the wearer’s body. This characteristic may cause discomfort to the wearer due to frequent friction. With the use of knitting technology, it is now possible for sportswear to be made with a seamless construction. The distinct advantages of seamless sportswear are as follows: A) there is no stitching to puncture the fabric, reducing the risk of tearing along the stitching line; B) seamless sportswear is lighter in weight and totally weather-proof; C) the sportswear joints do not chafe or cause friction, and maintain a smooth feeling next to the skin. Seamless construction has revolutionized pattern-cutting techniques, which offers a new look and increases comfort and performance.

4.2.3 Color Effects in Sportswear

Professional athletes pay less attention to the color design of sportswear compared to other factors such as functionality. Nevertheless, a number of researchers in recent years have noted that the color of sportswear worn by athletes affects the behaviours of the competitors and influences the outcome of a game (Dascombe et al., 2008; Ioana et al., 2007; Loker et al., 2004; Song and Feng, 2006). Certain colors of sportswear, such as red and blue, may increase the likelihood of winning a game.

Hill and Barton (2005) reported an interesting finding in *Nature* that in the 2004 Olympic Games, male competitors in four combat sports (boxing, taekwondo, Greco-Roman wrestling, and freestyle wrestling) wearing red outfits had a higher likelihood of winning relative to those wearing blue outfits. The proposed hypothesis to explain this bias of color-associated winning is that red has a special psychological effect on human behaviour in competitions. Some people's intrinsic behavioural responses, such as anger and excitement, are associated with skin reddening due to an increase of blood flow; meanwhile fear, which is associated with increased pallor, can be triggered by artificial signals. Red in sportswear is believed to enforce the evolutionary and/or cultural psychological processes that increase redness during aggressive interactions, which in turn may reflect relative dominance (Loker et al., 2004).

Rowe et al. (2005) also published in *Nature* that there was a winning bias for judo athletes wearing blue outfits compared to those wearing white outfits in the 2004 Olympic Games. The authors suggested that blue is associated with a higher probability of winning due to its effect on visual abilities, which may influence game performance, such as quickly following objects in rapid movement and carry out prompt visual searches. Athletes wearing blue outfits may obtain more benefits by visually anticipating the moves of their opponents wearing white outfits.

The extent of the relationship between color and psychological functioning remains unclear and is still under investigation. Nevertheless, colors undoubtedly impose recognizable influences on the response and performance of humans. The emotion of the body is originally responsible for physiological signals. The effects of color function on sport performance can be understood in terms of the physiological reactions to color and the psychological functions of colors.

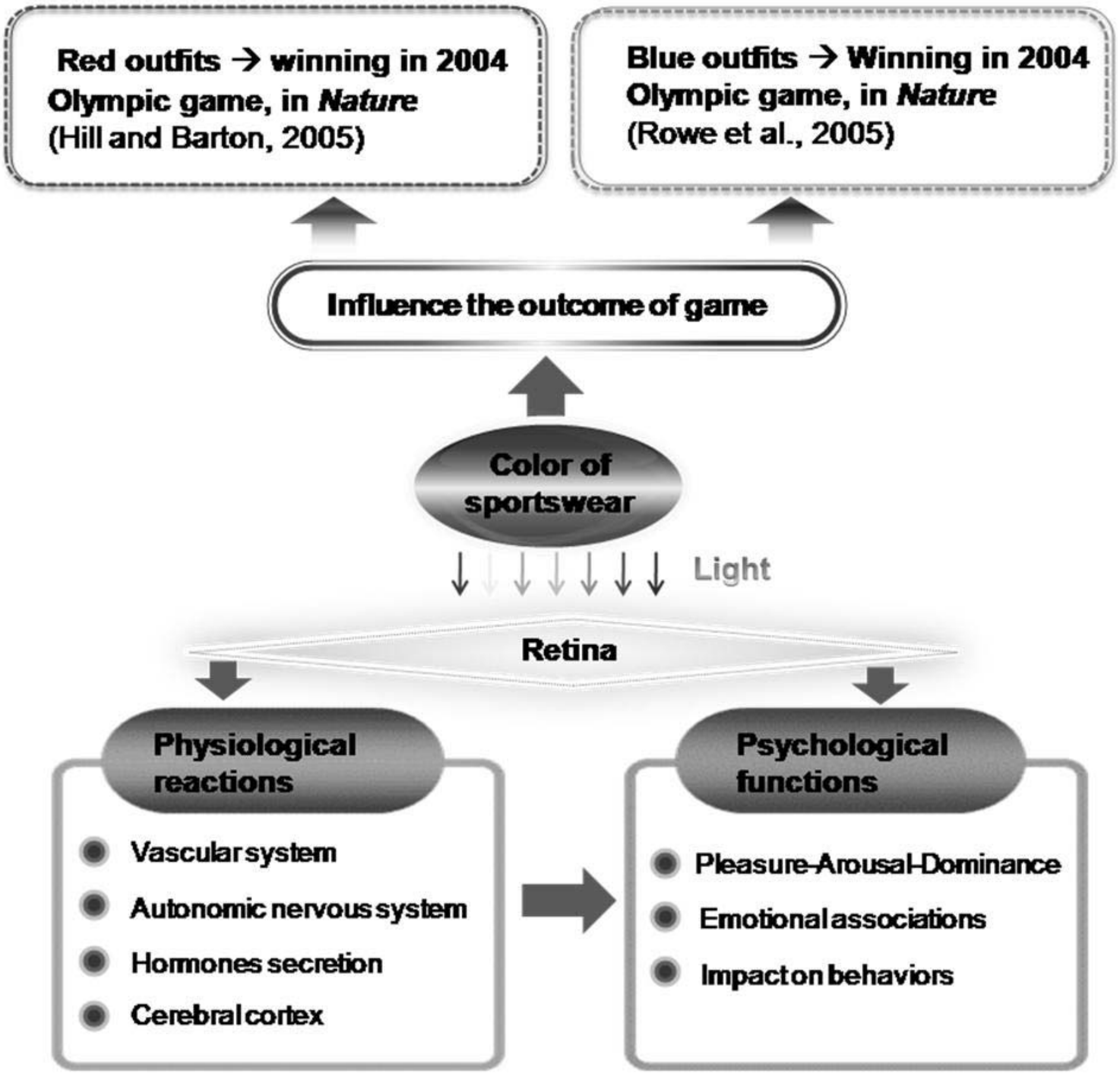


Fig. 4.3. Schematics of color functions in sportswear

The schematics of color functions in sportswear are demonstrated in Fig. 4.3. Light colors such as red, orange, and yellow are generally described as warm colors, whereas green, blue, and violet hues are described as cool colors. A detailed explanation of the physiological reactions to color and the psychological functions of colors are discussed as follows:

Physiological Reactions to Color

Color in light is characterized by wavelength distribution and identified as red, orange, yellow, green, blue, indigo, and violet when transmitted through human eyes, as reviewed in Chapter 2. Physiologically, the retina of the eyes receives the light waves, which is an optical phenomenon, and transmits them to the brain through the optic nerves for decoding (Armstrong, 1991). This process affects the secretions of hormones, the autonomic nervous system, and the cerebral cortex where emotions are located. Recently, it was found that light through the eyes can travel to the hypothalamus and hypophysis pineal body, which controls the nerve centers and bodily functions, such as respiration and heart action (Maton et al., 2006). Once the cerebral cortex is stimulated by color as a result of the active characteristics of the optic nerve system, the sensual experiences of thoughts and memories are activated, which ultimately affect human emotion and behaviour. Given that the wavelength and energy of different colors vary with intensity, colors may affect people in various ways.

Color may have influence on the vascular system by reflex action, although this condition may be caused by emotions and feelings. Some researches reported that red usually result in physiological phenomena, such as increasing perspiration, exciting brain waves, and raising respiration, pulse rate and blood pressure. Thus, intense muscular reaction and higher frequency of blinks of the eyes are evoked (Ibegbuna et al., 2003). Meanwhile, blue usually has a reverse physiological effect, manifested in lowering pulse rate and blood pressure. Thus, brain waves become declined and skin response tends to be weak. Orange and yellow induce similar reactions as red, whereas violet results in similar reactions as blue.

However, the influence of color tends to be short term. When people are exposed to an environment with any color in strong intensity, an immediate reaction can be observed that can be measured with specific instruments. Meanwhile, the body's responses may decrease or fall even below the normal level after some time. Thus, the sensation of color depends on the duration of exposure to the color.

Psychological Effects of Color

By reacting to the recognized signals of the brain, color perceptual systems further go through a psychological phenomenon associated with various emotions, which is deeply connected to sociology in terms of preferences and behaviours. The recognition process of the brain with color recognition is emotionally fulfilled as the basis of objective decisions.

The general characteristics of the color's emotional effects, which have been investigated by many experimental studies, can also be represented with a Pleasure-Arousal-Dominance (PAD) emotion model, describing emotional reactions to color saturation, hue and brightness (Naokazu et al., 2010). Saturation and brightness have shown evidence of consistent and strong effects on emotions, which directly decide the extent of pleasure, arousal, and dominance. Purple, purple-blue, blue, blue-green and green, are the most pleasant hues; yellow and green-yellow are the least pleasant hues; green-yellow, green and blue-green are the most arousing hues, whereas yellow-red and purple-blue are the least arousing ones; and green-yellow causes more dominance than red-purple. Mostly, red is associated with 'exciting' and 'stimulating', indicating pleasant and high arousal. Blue is associated with 'secure' and 'tender', suggesting pleasant and low arousal. Orange is associated with 'upset' and 'disturbing', indicating displeasure. Black is associated with 'masterful' and 'powerful', indicating high dominance (Naokazu et al., 2010). However, color associations with emotions are very complex that even the color intensity may change the associations, and the associations may vary among individuals or different cultures. Colors may excite one person while calming another; red may increase blood pressure or may have a reverse effect on different people (Andrew and Markus, 2007).

Given the emotional associations of colors, they may impact human responses or behaviours in work and life. For instance, thanks to the association of color with warmth and coolness, people in a room in blue-green may feel that 59 degrees F is cold; on the other hand, in a red-orange room, the perceived temperature, making people feel cold, falls from 52 to 42 degrees F. Currently, no widely recognized theory exists to reveal the scientific relationships between the color associations and their presumed impact on human behaviour. However, certain general reactions as identified in many experimental studies are common to many people.

In summary, color plays a primary role in aesthetics, meanwhile conveying stimuli that cause physiological reactions and contain specific meaning and information associated with sensations. The activation of color association and its further influence on perception, cognition, and behaviour occur without the individual's conscious awareness or intention. Color acts as a non-conscious stimulus, and imposes an automatic influence on psychological functions. The results of human responses to colors indicate that the color of sportswear may be taken into account in sportswear design.

4.2.4 Aesthetic Fusion with Functional Design of Sportswear

The relationship between fashion and sportswear becomes stronger, reflecting the trend that the fashion and sport industries have permeated each other. This trend is evident in the appearance of innovative high-tech/high performance fibers, fabrics, and textile materials, such as Lycra fiber, CoolMax fiber, and GORE-TEX fabric. Fashion designers can use these innovative materials in their designs to improve aesthetic effects or functions. On the other hand, people are now more concerned about their well-being and good health; they are changing their lifestyle, spending more leisure time, and preferring to wear sportswear or sports-inspired clothing in their daily activities. These developments are also an important factor in promoting the integration of functional design into fashion design.

The functional design of clothing not only achieves functional ability; it also has deeper emotional and sensual qualities, providing wearers with extra psychological satisfaction. The Tencel™ fabric manufactured by Acordis reportedly has the capacity to make the wearer feel good by decreasing negative waves emitted by the brain during periods of stress (McKelvey, 2011). Researchers observed that aesthetics addresses the activated internal processes, the multi-sensory characteristics of the object/event, and the psychological and socio-cultural factors (Fiore et al., 1996). Both physical and psychological effects are conveyed by the functional clothing to the body. Physical visual effects lead to the physiological responses of height, weight, body contour, and color or textural properties. Viewers have recognition of the differences among various bodies through these physical characteristics (Marian, 1996). The psychological effects of clothing influence the body's feelings through emotion association, which is similar to the mechanisms of color's psychological process discussed earlier, that is, different types of sportswear can make the wearer feel differently.

During the sportswear design, fabric, cutting and fitting, and color constitute the aesthetic elements of sportswear. Meanwhile, fabric and cut can also lead to the physiological responses of and psychological effects on the wearer. The functional performance of fabric and anatomical cutting can offer required thermal functions, such as air breathability and moisture management, and biomechanical functions, such as fatigue reduction and injury prevention. The aesthetic design and functional design can thus be fused through the aesthetic elements according to the theoretical model, as shown in Fig. 4.4, which demonstrates the relationships and the processes involved. It elaborates the design part of the framework model presented in Chapter 3 that how fabric selection, cutting, and color for sportswear take the role to fuse aesthetic design with functional design.

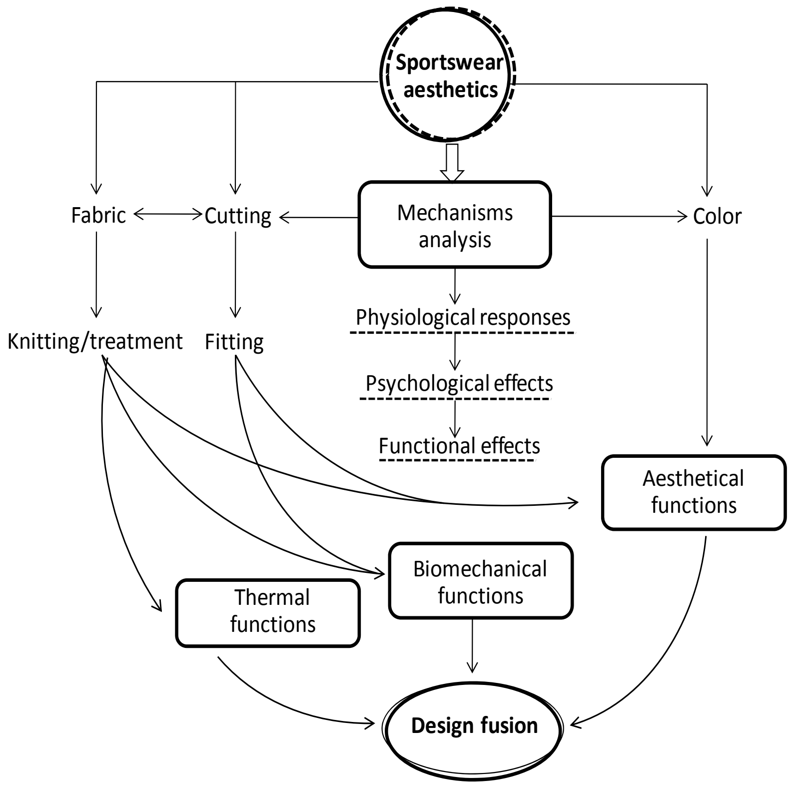


Fig. 4.4. Model for aesthetic fusion with functional design of sportswear

4.3 Identification of Aesthetic Preference

To identify the aesthetic preference of professional cyclists for FCS design, Part III of the questionnaire reported in Chapter 3 has been designed to survey the response of respondents to aesthetic design of FCS (Appendix A). The surveyed questions include 'the more satisfying cycling sportswear fit status' (question 5), 'the more satisfying cycling sportswear style' (question 6), 'the cut and seam lines on the body parts that may have a negative influence on cycling performance' (question 11), and 'the colors of cycling sportswear you prefer' (question 12). The respondents were the professional cyclists who participated in UNIVERSIADE 2011 SHENZHEN and were asked to grade their satisfactory level on the items from 1 to 5 (1=strongly disagree, 2=disagree, 3=neutral, 4=agree, 5=strongly agree).

4.3.1 Fitting Status Preference

Cutting, acting as an important factor in FCS design, can have a positive influence on cycling performance. Compression garment, which may have a positive influence on cycling performance, can be achieved by elastic fabric, while it is also influenced by cutting and fitting.

Clothing fit generally have three statuses, namely tight-fit, just-fit and loose-fit. A tight-fitting garment would constrain the body, and exert suitable pressure on the body skin while should not cause bad psychological feeling (Wang, 2011). It was reported that most of the compression garment for athletes concerns the light or mild pressure levels (Dascombe, 2008) according to standard of pressure published by the European Committee for Standardization (CEN). Thus, quantitatively, the tight-fitting garment may have the pressure range of 10-21 mmHg (AES to Class I in the CEN standard). A just-fitting garment covers smoothly over the body skin just like a outer surface in static state with much less pressure (0-9 mmHg) (Wang, 2011). A loose-fitting garment provides greater ease and much space between body skin and clothing. In order to obtain more information about the fitting preference of FCS, very-tight-fit which refers the pressure of garment is above 23 mmHg (Class II to Class IV in the CEN standard), is also set as a choice in the fitting status preference survey.

Fig. 4.5 shows the surveyed results about the evaluation of the satisfaction on the four levels of fit of cycling sportswear. The preferences of participants on fit are tight-fit, just-fit, very-tight-fit, and loose-fit.

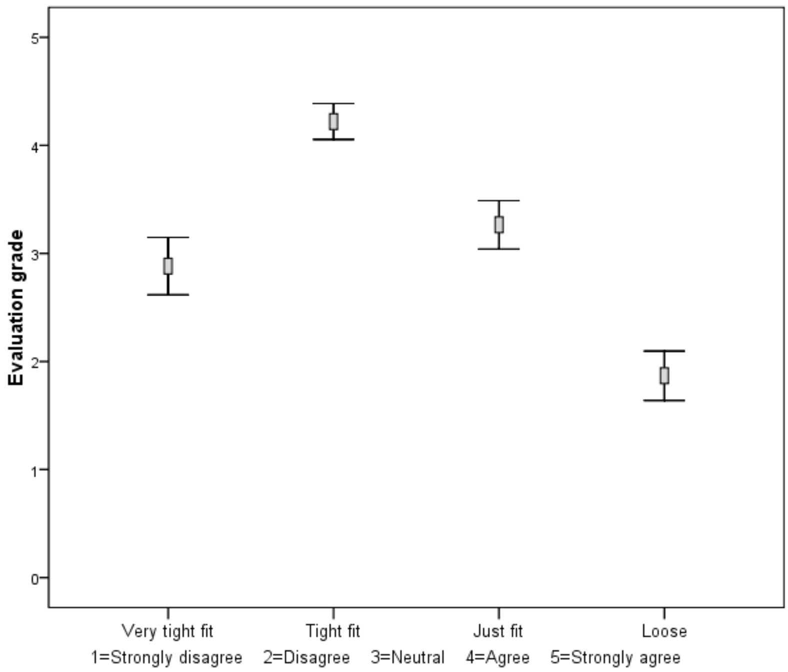
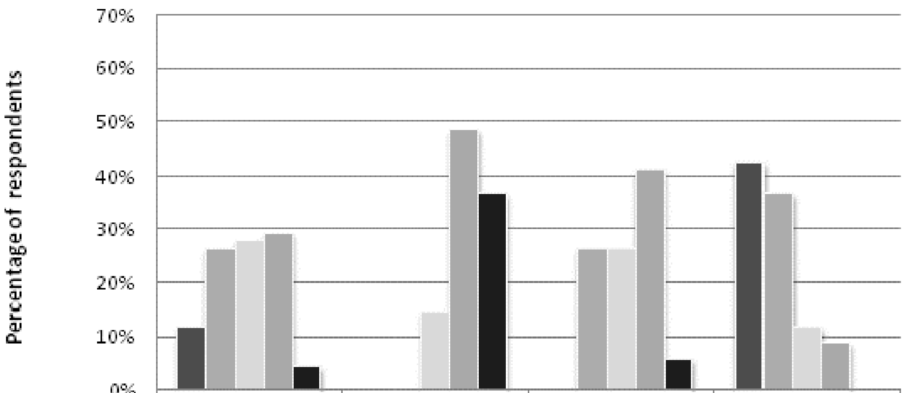


Fig. 4.5 Average grading on satisfaction of fitting status of cycling sportswear

Fig. 4.6, which shows the statistical analysis of the percentage of respondents in the grading evaluation, also proves the trends illustrated in Fig. 4.5. Fig.4.6 shows that above 85% of the participants who prefer the tight-fit have no disagreement with it. Following tight fit, 47.1% of the participants prefer the just-fit status. As to very-tight-fit, 33.8% of the participants show a preference for it, and 38.3% of the participants have no agreement. The finding is possibly due to the excessive pressure offered by the very-tight-fit cycling wear may have negative effects, reducing the ease of activity and causing obvious discomfort. In all levels of fit, most of the participants (79%) do not prefer loose-fit.



	Very tight fit	Tight fit	Just fit	Loose
1=strongly disagree	11.8%	0%	0%	42.6%
2=disagree	26.5%	0%	26.5%	36.8%
3=neutral	27.9%	14.7%	26.5%	11.8%
4=agree	29.4%	48.5%	41.2%	8.8%
5=strongly agree	4.4%	36.8%	5.9%	0%

Fig. 4.6 Statistical grading on satisfaction of fit status of cycling sportswear

4.3.2 Style Preference

The literature review in Chapter 2 summarized the evolution of cycling sportswear, indicating the three kinds of styles in its development, namely, the most common jersey and bib shorts for long time races, the traditional jersey and shorts, and the innovative all-in-one suit developed recently. These styles are demonstrated in Fig. 4.7.

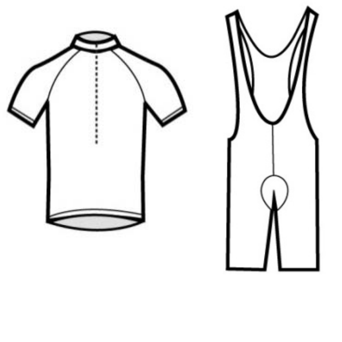
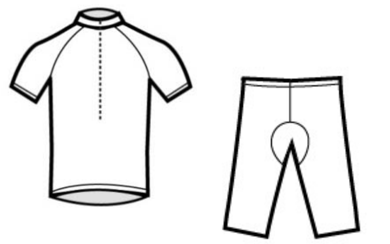
		
Jersey and bib shorts	Jersey and shorts	All-in-one suit

Fig. 4.7. Different styles of cycling sportswear

Fig. 4.8 shows the average grading of the participants on satisfaction with cycling sportswear styles. The figure indicates that the style preferences among participants are the all-in-one suit, jersey and bib shorts, and jersey and shorts.

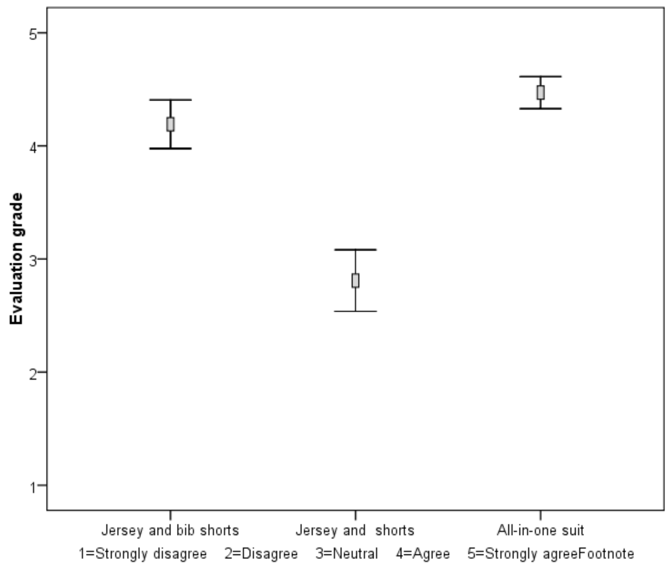
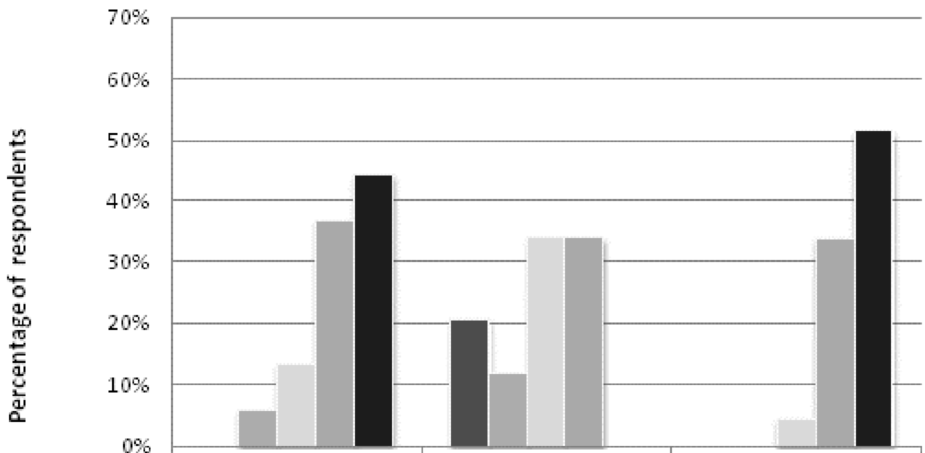


Fig. 4.8 Average grading on satisfaction with the cycling sportswear style

Similar trends can be observed in Fig. 4.9. Nearly 85% of the participants show agreement or strong agreement with the all-in-one suit. Nearly 80% of participants prefer jersey and bib shorts. The all-in-one suit style is considered as having a smoother fit, which helps in the reduction of air resistance. Hence, the all-in-one suit style has become increasingly known and popular among cyclists. There is a significant difference among participants with regard to the traditional jersey and shorts style. The percentage of disagreement, neutral, and agreement is similar. The reason may be that the jersey shorts style is not as good as the other two in relieving fatigue due to the over-bent position of the body during cycling.

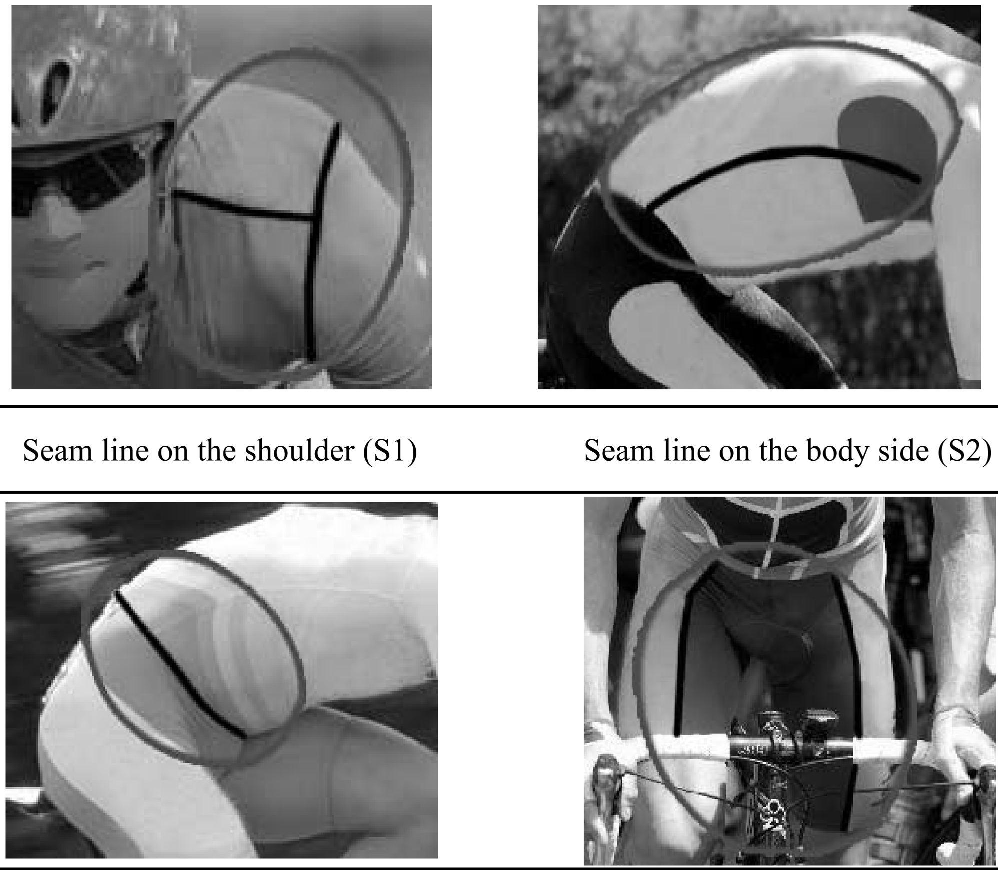


	Jersey and bib shorts	Jersey and shorts	All-in-one suit
1=strongly disagree	0%	20.6%	0%
2=disagree	5.9%	11.8%	0%
3=neutral	13.2%	33.8%	4.4%
4=agree	36.8%	33.8%	33.8%
5=strongly agree	44.1%	0%	51.5%

Fig. 4.9 Statistic grading on satisfaction with the cycling sportswear style

4.3.3 Seam Line Preference

Cutting based on cycling biomechanics has a positive influence on cycling performance, as surveyed in Chapter 3. However, some details about the cut and seam lines that may have resistance or a negative influence on cycling performance should be related to the design process as well. The common straight seam lines in cycling sportswear are shown in Fig. 4.10, including the straight seam line on the shoulder, the straight seam line on the body side, the straight seam line on the waist, and the straight seam line on the front thigh.



Seam line on the shoulder (S1) — Seam line on the body side (S2)

Seam line on the waist (S3) — Seam line on the front thigh (S4)

Fig. 4.10. Seam lines on the cycling sportswear

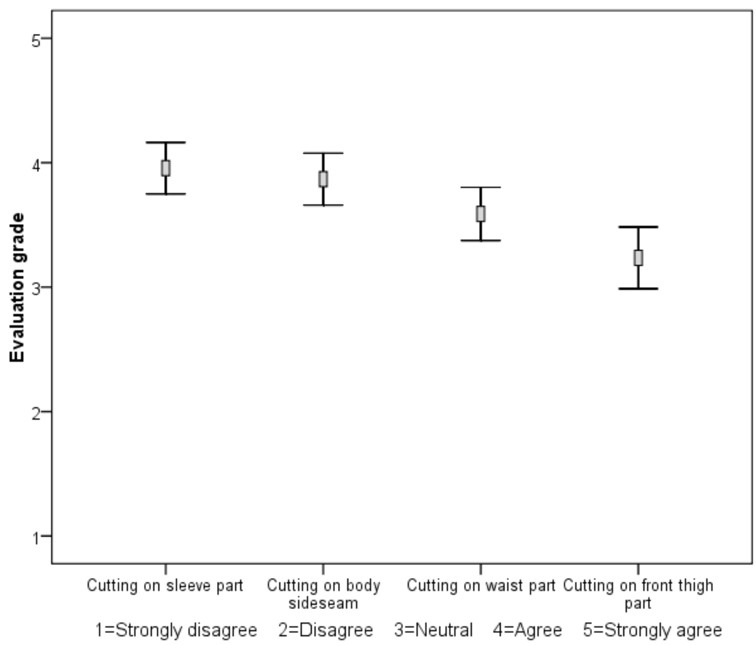
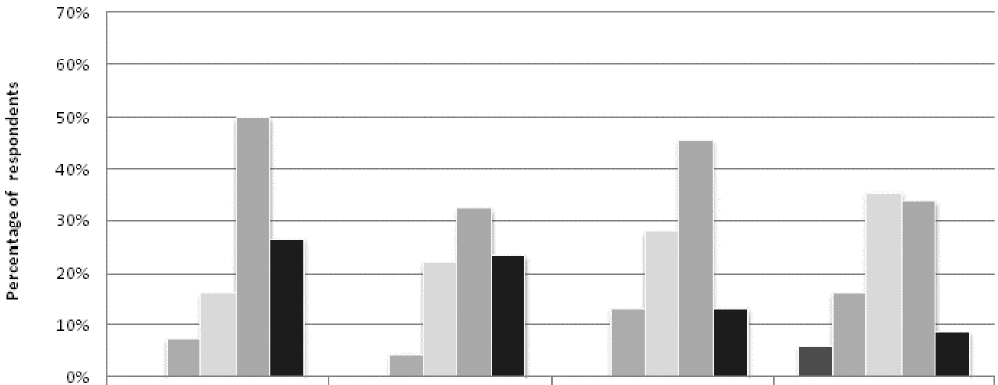


Fig. 4.11 Average grading on seam lines having negative influence on performance

The evaluation of whether these seam lines have a negative influence on cycling performance was graded, as demonstrated in Fig. 4.11. The figure shows that the straight seam line on the shoulder was regarded as mostly having a negative influence. The straight seam line on the body side followed, and the straight seam line on the waist and the straight seam line on the front thigh ranked third and fourth, respectively. However, the average of all the grading on these seam lines having a negative influence is above neutral, which means all these straight seam lines were regarded by the professional cyclists as having a negative influence on their performance.



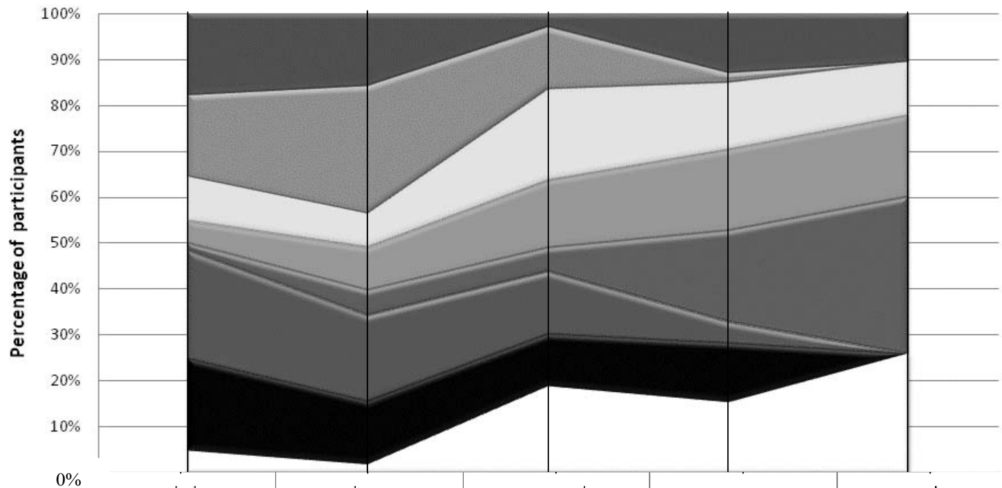
	Cutting on sleeve part (S1)	Cutting on body sideseam (S2)	Cutting on waist part (S3)	Cutting on front thigh part (S4)
1=strongly disagree	0%	0%	0%	5.9%
2=disagree	7.4%	4.4%	13.2%	16.2%
3=neutral	16.2%	22.1%	27.9%	35.3%
4=agree	50.0%	32.4%	45.6%	33.8%
5=strongly agree	26.5%	23.5%	13.2%	8.8%

Fig. 4.12 Statistic grading on seam lines having negative influence on performance

Fig. 4.12 shows the grading detail of participants on these straight seam lines. Almost 80% of the participants agreed that the straight seam line on the shoulder has a negative influence on their performance. Over 50% of the participants agreed that the straight seam lines on the body side and waist have a negative influence. Only 20% of participants disagreed that the straight seam line on the front tight has a negative influence. This result indicates that the straight seam lines on these parts should be improved according to the biomechanical needs. Due to the curved body contour shape, the curved seams following the body's natural form may increase the dynamic fit and comfort of the wearer (O'Mahony and Braddock, 2002).

4.3.4 Color Preference

The color preference of the respondents is influenced by individual experiences and social and cultural backgrounds. However, as discussed in the above section, certain colors of sportswear, such as red and blue, reportedly have a bias of winning due to the non-conscious response and sensational association of the body to these colors. The color preference of professional cyclists for the cycling sportswear has been surveyed in the range of eight common colors, including red, vermilion, yellow, green, blue, purple, black, and white.



	1=strongly disagree	2=disagree	3=neutral	4=agree	5=strongly agree
Red	32.4%	25.0%	4.4%	25.0%	13.2%
Vermilion	32.4%	44.1%	19.1%	4.4%	0%
Yellow	17.6%	11.8%	27.9%	27.9%	14.7%
Green	8.8%	14.7%	20.6%	33.8%	22.1%
Blue	2.9%	8.8%	7.4%	38.2%	42.6%
Purple	42.6%	29.4%	19.1%	8.8%	0%
Black	36.8%	22.1%	16.2%	25.0%	0%
White	8.8%	2.9%	26.5%	29.4%	32.4%

Fig.4.13 Statistic grading on color preference of the cycling sportswear

The surveyed results are shown in Fig. 4.13. Over 80% of the participants prefer the color blue, 61.8% prefer white, and 55.9% prefer green. The sequence of the rest of the preferred colors is as follows: yellow, red, black, purple, and vermilion.

4.3.5 Aesthetic Preference of Professional Athletes for FCS Design

From the above discussion of the survey data, the aesthetic preference of professional cyclists for FCS design can be identified and summarized as shown in Fig. 4.14. Tight fit, all-in-one suit style and blue color are the most preference of professional cyclist.

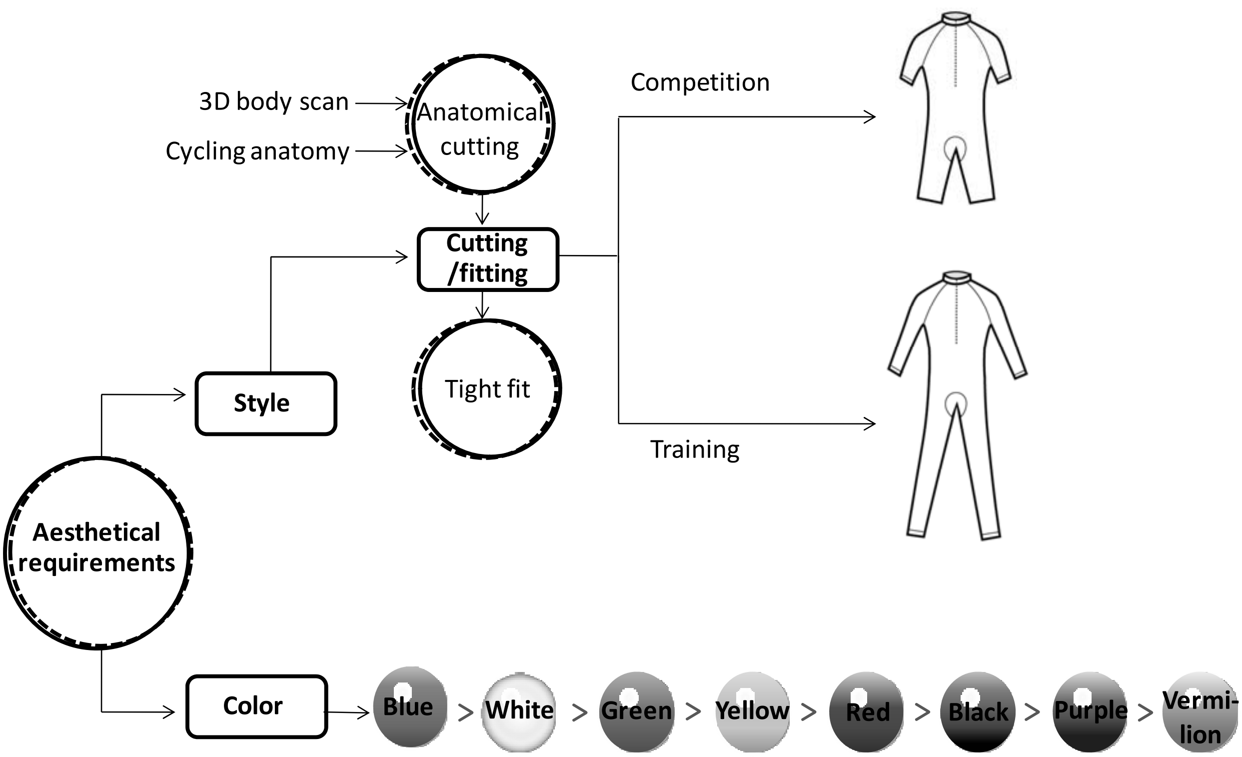


Fig. 4.14. Aesthetic preference of professional cyclists for FCS design

4.4 Aesthetic Elements in FCS Design

Based on the investigation on the effects of aesthetic elements in sportswear, a theoretical model for the aesthetic fusion with functional design of sportswear has been developed in Section 4.2. As a specific category of sportswear, the aesthetic design of FCS can be fulfilled according to this theoretical model. Therefore, the basic aesthetic elements in FCS design include cutting, color and fabric, through which the aesthetic design and functional design are fused systemically and harmoniously. Besides these basic aesthetic elements, the elements of design pattern and style, which are influenced by other components, also are discussed since they are frequently used to describe the aesthetic image of FCS (Ho, 2011).

4.4.1 Fabric

Fabric plays a primary role in influencing the aesthetic quality, meanwhile, offers required thermal and biomechanical functions. Frequently, the knitting fabric is adopted in the design of sportswear, due to its advantages of more elastic to offer required pressure for reducing muscle fatigue and ensuring injury protection, meanwhile, being able to reduce seam lines, which is expected in the anatomical cutting.

Besides the functional factor, the texture of fabric may also be considered in the design of FCS. Texture is the visible and tangible structure of fabric surface, and may appeal to the senses of human beings in terms of touch, sight and hearing. Generally, the variations of fabric texture depends on four factors including fiber content, yarn structure, fabric structure and finishes (Marian, 1996). These determinants create a vast array of fabric surface, hand qualities and light reactions. For instance, smooth and rough in surface quality, shin and thick in hand quality, as well as shiny and dull in light reaction. The examples of cycling wear with these qualities are demonstrated in Fig. 4.15. Smoother surface is possible from smooth and filament fibers, such as silk and synthetic fibers, whereas rougher surface is possible from fuzzy and crimped fibers, such as cotton and wool. Visually, the thick texture adds the size and weight, and also conceals figure contours. As to the light reactions, shiny texture may enlarge or advance the body area, making it more powerful or noticeable, whereas dull texture is likely to reduce the attention (Marian, 1996).

Fig. 4.15 Different visual effects of fabrics

4.4.2 Cutting

Aside from the fabric, cutting is another a esthetic element of FCS design, which can help achieve the desired biomechanical functions by creating wearing pressure through 3D cutting.

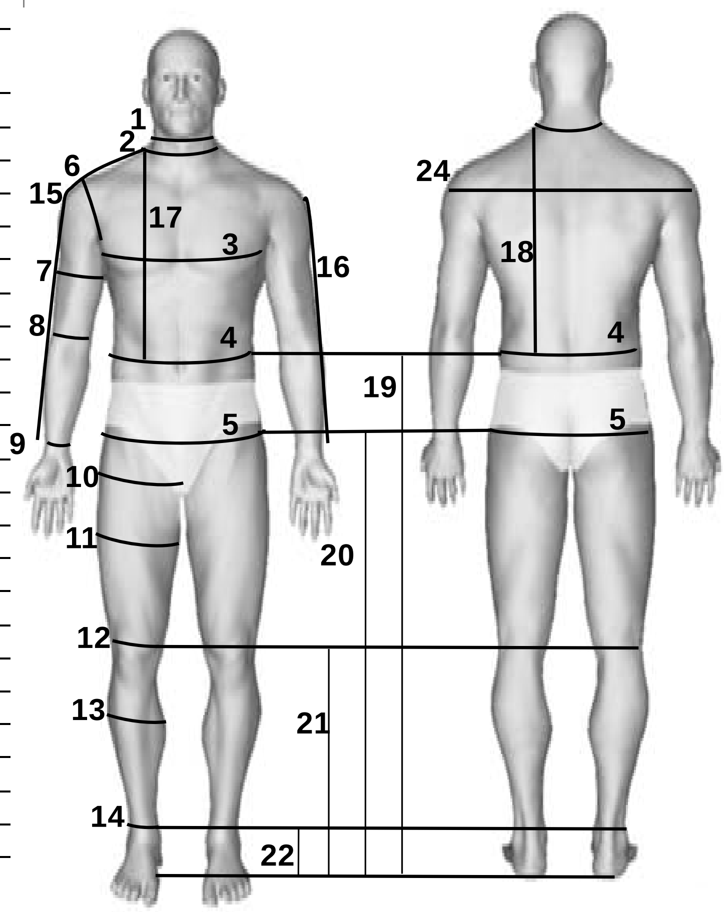
As a result of cutting, the fit status for FCS design may include very-tight-fit, tight-fit, just-fit and loose-fit, which have been defined in detail in Section 4.2 and Section 4.3. Though there are different fit styles of cycling wear on the market (see Fig.4.16), it is necessary to obtain the quantitative description about the different fit status to perform scientific design. Technically, very-tight-fit, tight-fit, just-fit can be defined through the exerted pressure on the body skin by the garment. Namely, very-tight-fit refers to a pressure of garment is above 23 mmHg; tight-fit refers to that the pressure range of garment of 10-21 mmHg; just-fit refers to that the pressure of garment is less than 9 mmHg; loose-fit refers to that the garment provides much space between body skin and clothing. The surveyed results from the professional cyclists reported in Section 4.2 show that their preference of fitting status is in the sequence of tight-fit, just-fit, very-tight-fit, and most of them do not prefer loose-fit.

Fig. 4.16 Different fit status of cycling sportswear on the market

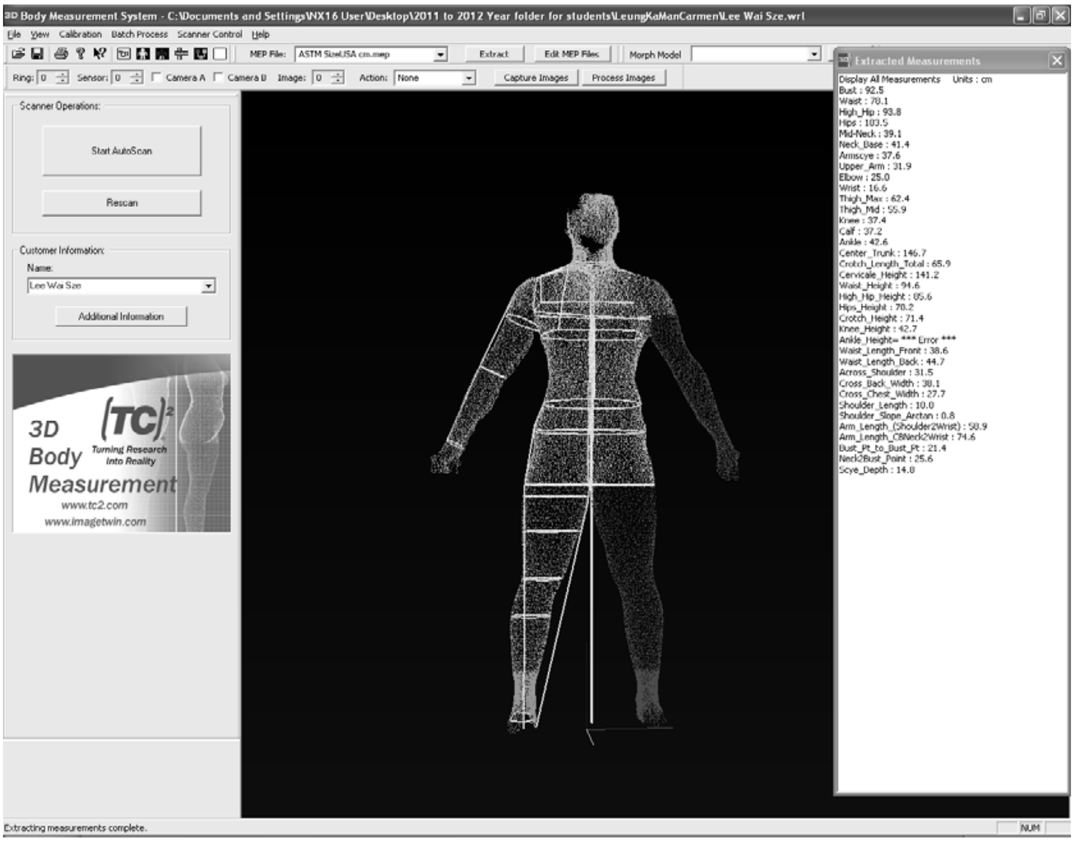
In order to achieve a tight-fit FCS, 3D cutting technology is adopted with the basis of 3D body scanning data and cycling anatomy, which can help reduce muscle fatigue and protect muscles from injury by offering adequate pressure. The cutting on the body parts of the back, waist, body side, shoulder, and thigh needs to be improved from straight seam lines, which may have a negative influence on performance.

Since the 3D size information of the body, which provides a more accurate and sophisticated measurement of the body size, plays an important role in 3D cutting of FCS, a 3D body scanner may be adopted to record the spatial coordinates from the subject's surface and measure the body size. The 3D scanning data used in this study comes from the measurement of twelve cyclists who are elite athletes from the Hong Kong Sports Institute by using a 3D scanner (VOXELAN LPW-2000FW). All cyclists have the height range of 165-175cm and BMI (Body Mass Index) range of 21-23. Through the anthropometric measuring points and lines on the body surface, there are twenty three data measuring points of the 3D body size, including the detail description about the size of height, width and girth, as illustrated in Fig. 4.17.

No.	Anthropometric measurement lines	Mean (cm)
1	Mid neck girth	35.60
2	Neck base girth	39.05
3	Bust girth	91.02
4	Waist girth	73.13
5	Hips girth	93.57
6	Armscye girth	39.82
7	Upper arm girth	28.57
8	Elbow girth	26.12
9	Wrist girth	14.30
10	Thigh max girth	56.70
11	Thigh mid girth	48.27
12	Knee girth	37.78
13	Calf girth	37.27
14	Ankle girth	24.73
15	Arm length to neck	78.23
16	Arm length	58.82
17	Waist length Front	42.33
18	Waist length back	49.90
19	Waist height	99.92
20	Hips height	79.62
21	Knee height	48.62
22	Ankle height	7.36
23	Across shoulder	38.80



a) Body measurement data b) Anthropometric measuring points and lines



c) A example of 3D scanning body shape

Fig. 4.17 3D body scanning measurements for the body size

The average value of the measurement data from these twelve cyclists provide an accurate description about the body size pertaining to twenty three data. The detail values of the data are shown in Fig.4.17 (a). This data offers the primary cutting size for creating the FCS, and can be expanded with different scales for the different groups of wearers.

4.4.3 Color

The color element imposes influence on both the aesthetic feel and functions of FCS through physiological reaction and psychological association. Certain colors, such red and blue, reportedly had a higher likelihood of winning in the 2004 Olympic Games (Rowe et al., 2005; Hill Barton, 2005). The survey results on the professional cyclist also indicate that the color blue is their most preference, followed by white, green, yellow, red, black, purple, and vermilion. These results offer a scientific indication for the designer to decide the color for FCS design.

However, in practice, the color of FCS may be influenced by the competition culture or regional culture as well. For instance, in the Tour of France, the leader of the general classification wears the yellow jersey since 1919; the green jersey rewarded the consistent finishers in individual stages since 1953 when the 50th anniversary of the race (Longmore, 1999). Meanwhile, the cycling sportswear for the individual team or club also frequently considered the colors representing their sponsors. For instance, the RABOBANK cyclist team adopted the color from the logo of rabobank, which is the sponsor of the team (see Fig. 4.18). Furthermore, the national or regional cultures may often impose an important influence on the design of sportswear (McCann, 2005). Especially, in the Olympic Games, the cycling sportswear often adopts the colors from the representative pattern or elements of the country, for instance, the national flag, for easily identifying the country or region of the athletes (see Fig. 4.19).

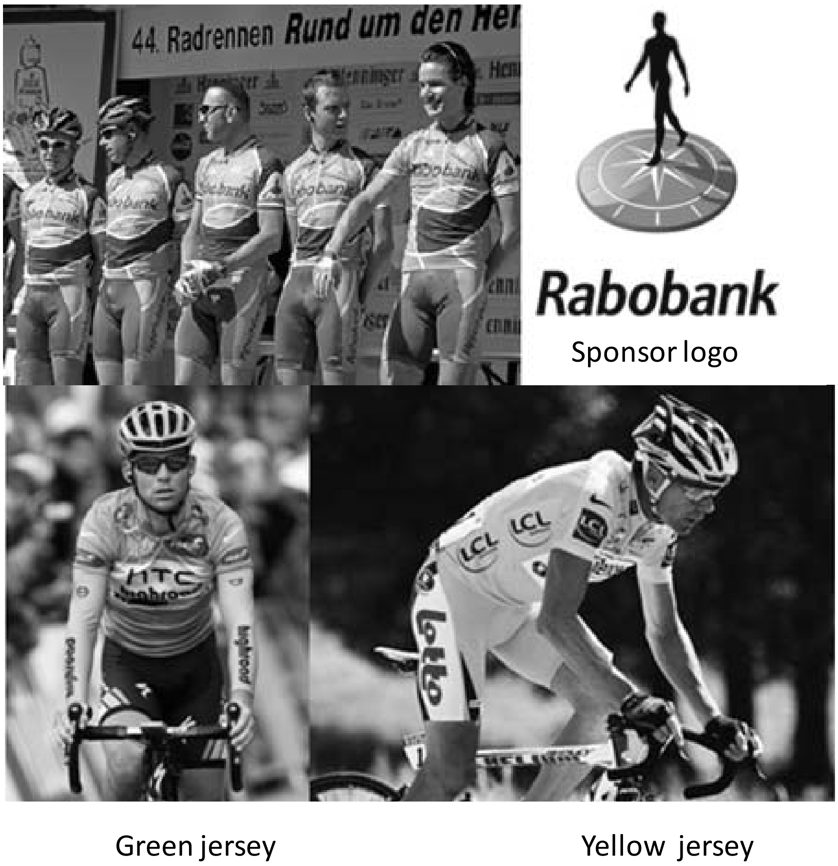


Fig. 4.18 Colors of cycling sportswear influenced by the competition culture

Fig. 4.19 Colors of cycling sportswear influenced by the regional culture

4.4.4 Design Pattern

Design pattern refers to the arrangement of lines, spaces and shapes on the fabric and garment (Marian, 1996). In the garment design, it is often treated as an element which acts as a medium to manipulate with visual effects in practice. Through strengthening or weakening the physical and psychological effects of line, space and shape, design pattern can make versatile overall effect, being greater than the sum of the influence of its components.

In the design of FCS, design pattern may be considered as an element to create desired visual effects according to the design inspiration. For instance, the crossed lines with acute angle, which are printed on the express road, may be adopted in the FCS design to create a feeling of speed. Fig. 4.20 shows some examples of the cycling sportswear with different design patterns on the market, which create special feeling from the lines and space.

Fig. 4.20 Examples of design patterns on the cycling sportswear

4.4.5 Style

As reviewed in Chapter 2, there are mainly three kinds of styles in the evolution of cycling sportswear, including jersey and bib shorts for long time races, traditional jersey and shorts, and the innovative all-in-one suit. Through questionnaire survey on the professional cyclists reported in Section 4.3, it is found that the all-in-one suit style was preferred by most professional cyclists surveyed.

Usually, a cycling race includes long-distance trials and individual time trials. For instance, the Tour de France includes both trials. As a new technology, the all-in-one suit is mostly selected for individual time trials due to its tight fit in the whole body and lower air resistance, and is also becoming popular in long-distance trials. However, in practice, all these styles may be adopted according to the practical requirements. For instance, the short-pant style FCS is used for races, whereas the long style FCS can be used for training. Fig. 4.21 shows the usual styles of short-pant for races, which include jersey and shorts, jersey and bib shorts, and all-in-one suit, and also the long pants and sleeves for training.

Fig. 4.21 Usual styles of cycling sportswear for competition and training

4.5 Conclusion

This chapter has described the achievement of the aesthetic design of the FCS. First, how the aesthetic elements of fabric, cut and fit, and color influence the functions of sportswear and game performance is discussed. By investigating the physiological and psychological effects of these aesthetic elements on the performance of sport, a theoretical model for fusing aesthetic and functional design in sportswear is consequently established. Further, the aesthetic preferences of professional cyclists for FCS design are identified and recognized through an analysis of the questionnaire survey results. Finally, the aesthetic elements in FCS design are discussed and illustrated in terms of fabric, cutting, color, design pattern and style, which provide the most important concern in the aesthetic design of FCS.

CHAPTER 5 THERMAL FUNCTIONAL DESIGN OF CYCLING SPORTSWEAR

5.1 Introduction

As reported in Chapter 3, a multi-disciplinary framework for functional cycling sportswear (FCS) design has been proposed to integrate relevant knowledge from different disciplines and illustrate the design process. Thermal comfort is identified as being one of the basic functional requirements of FCS. In order to achieve the desired thermal functions of FCS and offer thermal comfort to cyclists during cycling, the thermal functional design of FCS is implemented in this chapter.

First, the thermal mechanism of cycling sport is analyzed by summarizing the thermal factors and illustrating the thermal conditions in order to gain scientific understanding of the cycling sportswear wearing system. Next, an experimental analysis of cycling exercise is conducted to scientifically identify the thermal requirements of cyclists. The thermal distributions of cyclists in terms of skin temperature, stratum corneum water content (SCWC), and transepidermal water loss (TEWL) during cycling are measured, visualized and analyzed. Based on the analysis, the thermal zones are created to express the thermal distributions and distinguish the thermal requirements of different body parts. Subsequently, the thermal functional design scheme is developed to satisfy the required thermal functions of different body parts. Finally, the thermal properties of fabrics both for this study and from a commercial cycling sportswear are measured and compared, and the numerical simulation of the thermal performance of FCS designed with different fabrics is performed to illustrate the fabric selection for the thermal functional design.

5.2 Thermal Mechanism Analysis

The thermal mechanism analysis of cycling sport is carried out by analyzing thermal comfort during cycling and investigating the thermal conditions involved in cycling exercise.

5.2.1 Thermal Comfort during Cycling

Thermal comfort is a subjective perception that depends on the evaluation of the wearer based on the integration of a range of physiological, psychological, and physical variables and their multiple interactions with the environment (Li, 2001; Tarafder and Chatterjee, 1994). When wearing the sportswear, the thermoregulatory system in the human body may maintain a nearly constant internal body temperature ranging from 36.1 ºC to 37.8 ºC (Jiang et al., 2004). As reviewed in Chapter 2, thermal comfort is obtained when the energy exchange between the human body and the surrounding environment reaches a thermal equilibrium, which can be maintained if the heat generated by the human metabolic system is dissipated. The cycling sportswear worn in various environments, such as cold, warm, hot, dry and humid, can potentially improve the body's ability to achieve a state of thermal balance with its surroundings.

When conducting further analysis, dampness and thermal sensations have been considered as key factors for thermal comfort (Wang, 2002). Physical properties of temperature and humidity should be also taken into account when investigating these sensations and evaluating thermal comfort perception (Wong et al., 2005). Thus, thermal comfort during cycling provided by the cycling sportswear is determined theoretically through complex thermal behaviours and multiple interactions, such as the physical structure and properties of the textile material, the heat and moisture resistance properties of the sportswear, the thermal regulations of the cyclists, and the nature and levels of physical activity.

5.2.2 Thermal Conditions of the Cycling Sport

In order to analyze the thermal conditions that determine dampness and thermal sensations during cycling, thermal behaviours and interactions involved in the cycling sport are investigated and shown in Fig. 5.1. The possible thermal behaviours and interactions are listed as follows:

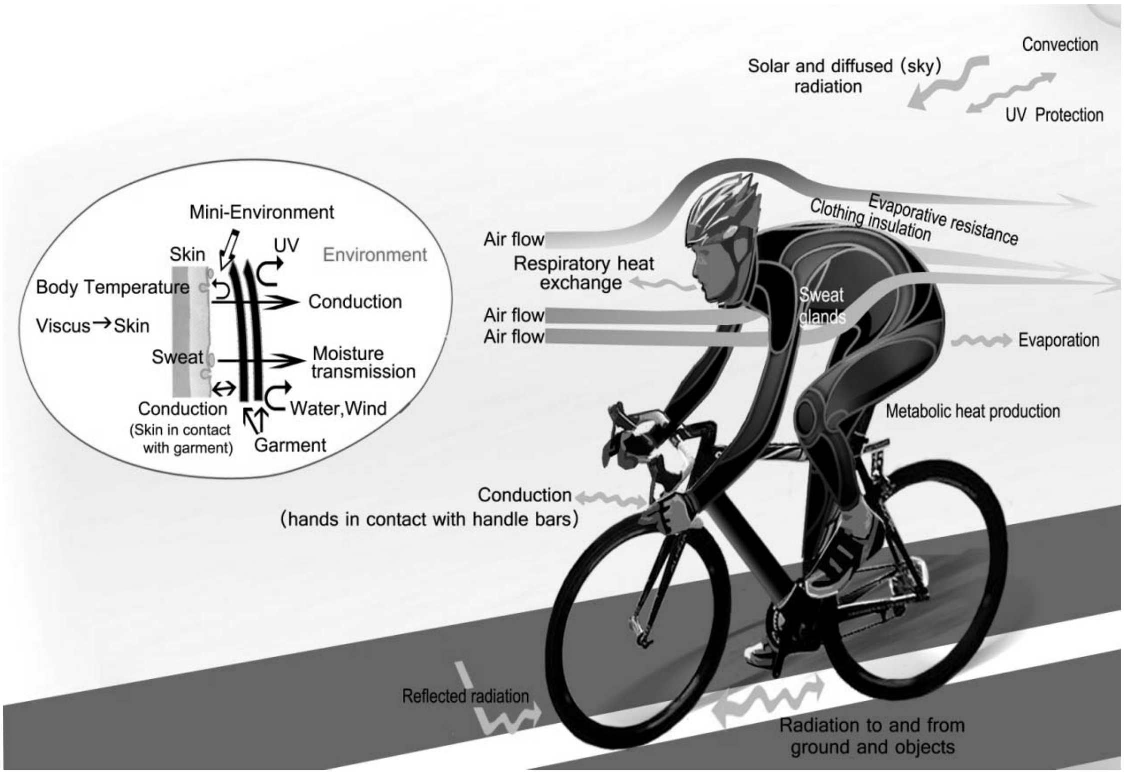


Fig. 5.1 Thermal conditions of cycling sportswear wearing system

1) The heat and moisture transfer in the cycling sportswear. This is influenced by the physical structure and properties of the textile material, such as moisture permeability, moisture regain, and thermal conductivity.

2) The heat regulation of the body through physiological behaviours. This includes metabolic heat production, respiration, and sweat generation, which may take away the heat produced by the body during the course of cycling through respiratory heat dissipation and sweat evaporation.

3) The thermal interactions between the cycling sportswear, cyclist, and environment. These include heat conduction, sweat transmission between the skin and the sportswear, the heat radiation from the sun, reflected radiation from the ground, heat radiation to/from the ground and other heating sources, heat convection caused by the air flow during the cycling, heat conduction when the body comes into contact with the bike, and the moisture evaporation in the sportswear.

As a high-speed activity, cycling may generate more complicated interactions than many other sports, and proceed in varying states. In cycling competitions, excellent cyclists can ride at speeds from 14 km/h to 40 km/h and generate an equivalent facing wind speed, which may increase the extent of heat loss through convection and evaporation (Saunders et al., 2005). Through experiments, Saunders et al. (2005) observed that skin temperature increased significantly in 0.2 km/h wind speed with time. In another experiment, Kwon et al. (1998) found that the skin temperature dropped quickly upon a cyclist's exposure to 5.4 km/h wind velocity. These findings imply that both convection and evaporation are important during a race as they could decrease the body temperature. Furthermore, the metabolic heat of athletes may increase 6 times during cycling, whereas their perspiration rate may increase 14 times more than those engaged in normal routine indoor activities (Bardhan and Sule, 2001). These dynamic physical properties of athletes result in the response of the psychological process that could influence the overall comfort perception of cyclists.

5.3 Thermal Biological Requirements Identification

In order to provide quantitative analyses for the thermal functions of cycling sportswear, a cycling experiment with a group of participants was conducted in a chamber. The quantitative analysis was carried out by executing the cycling experiments and collecting data from the participants. The data analysis involved analyzing and visualizing the thermal data and identifying the thermal physiology of the cyclists. Through the experimental analysis, thermal zones can be created to describe the thermal distributions of the skin. Following these processes, the thermal requirements of cyclists can be identified pertaining to all thermal zones.

5.3.1 Experiment of Cycling Exercise

Experimental Protocol

Prior to participation, all the participants were asked to sign a consent form approved by the Human Subjects Ethics Sub-Committee of the Hong Kong Polytechnic University. Experimental procedures were explained to each subject and a cycling experience questionnaire was administered.

Nine young athletes participated in this experimental study; their ages ranged from 19 to 24 years old, with average height and weight levels of 172.8 cm and 61.7kg, respectively. All the participants were healthy and had no known history of ITBFS or any other lower extremity disorders.

The experiment had four stages: 20-minute rest, 5-minute warm up, 30-minute cycling, and 30-minute recovery. The experiment was carried out in a chamber with air temperature of 25.6 ± 0.5°C, relative humidity of 24 ± 1% and wind condition of 14.4 km/h in average, imitating general conditions in the cycling sport. All participants were instructed to accelerate during the cycling until the body reached 70% maximal oxygen consumption. At this stage, data such as skin temperature, stratum corneum water content (SCWC) indicating sweat accumulation on the skin, and transepidermal water loss (TEWL) indicating sweat evaporation on the skin were collected. The detailed protocol of this experiment is shown in Fig. 5.2.

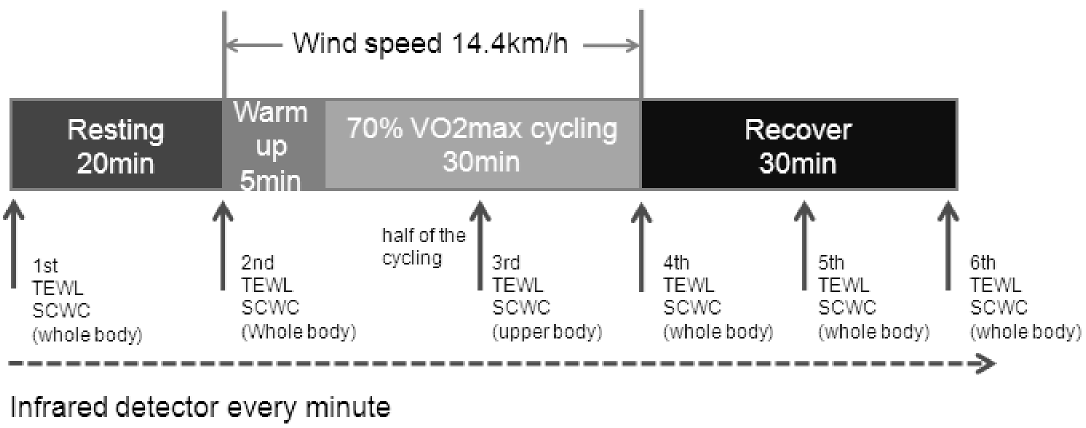


Fig. 5.2 Protocol of the cycling experimental trial

The cycling exercise experiment was designed with the following steps:

1) Surface temperature sensors were attached to the back neck, upper back, middle back, lower back, bottom, back thigh, popliteal fossa, and calf of each participant.

2) The seat height was adjusted based on safe cycling standards; the knee angle ranged from 25° to 308°, which was measured by a goniometer. The subjects were asked to pedal slowly to ensure that the seating was comfortable at the start.

3) Every subject was given a 20-minute rest to eliminate the interference of the external environment. Infrared photos (IR), SCWC and TEWL were recorded beginning from this part of the experiment.

4) By controlling cycling power, the ride frequency was maintained at 60 r/min. Each subject warmed up for 5 minutes and then rode for 30 min at 70% VO2max. The airflow was simulated by an electric fan, and the speed of airflow was measured by an anemometer placed on the front handle of the bicycle.

5) The subjects stopped to rest and recover for 30 minutes.

6) An infrared camera was used to take photos of the front of the body every minute throughout the cycling exercise. Eight surface temperature sensors attached to different parts of the back of the body were used to measure the skin temperature. The TEWL

and SCWC data were measured manually six times from 14 points of the body during the experiment.

7) The sensors and cardiotachometer were removed.

During the experiment, all the participants rode the bicycle clad only in short sport pants, as illustrated in Fig. 5.3. Fig. 5.4 shows the points of the body from which measurements were performed and data were obtained. The skin temperature was measured from 17 points of the body, including the head, chest, abdomen, armpit, upper arm, forearm, hand, front thigh, front leg, back neck, upper back, middle back, lower back, bottom, back thigh, popliteal fossa, and calf. The SCWC and TEWL were measured from 14 points of the body, including the head, chest, abdomen, armpit, upper arm, forearm, hand, upper back, lower back, front thigh, front leg, back thigh, popliteal fossa and calf.

Fig. 5.3 Scene of the cycling experiment

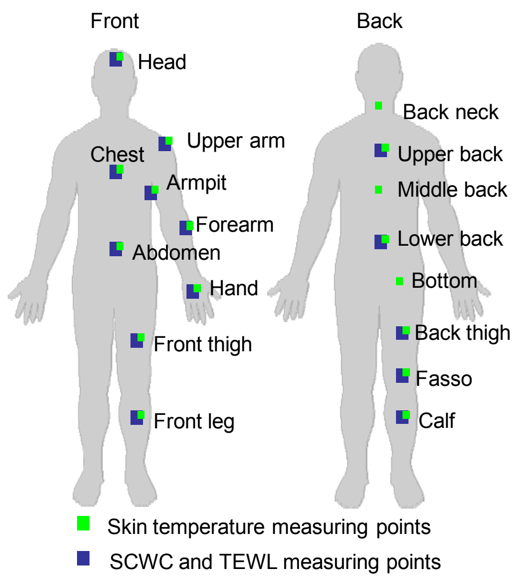


Fig. 5.4 Measurement points on the body

Data Measurements

The body weights of the participants were measured with an electronic scale (EA 150 FEG-1, Sartorius AG, Germany) at the beginning and end of each experiment. The infrared thermograms of the participants were obtained by an infrared thermographic system (Nikon Thermal Vision, LAIRD-S270, Nikon Corporation). A total of 85 thermograms of the front body were obtained at a frequency of one photograph per minute for each subject. Fig. 5.5 shows the IR photos in different stages during the cycling experiment. The infrared thermograms were digitized using a thermographic data-converting program (FAI-Controller, Nikon Corporation). The temperatures of the back part of the body were measured with thermistors (Nikkiso-YSI, Japan) taped at eight points. All temperatures were recorded continuously, stored in the data logger LT-8A (Nikkiso-YSI, Japan) every 2 minutes and then sampled by a computer through a converter.

Fig. 5.5 IR photos of the front body during the cycling experiment

The SCWC and TEWL were measured at 14 points of the body respectively using a Skicon 200EX (Tagami et al., 1980) and Cutometer MPA580 (Courage + Khazaka, electronic GmbH, Cologne Germany) (Fluhr et al., 1999). Measurements were performed six times for each subject. The gold-plated probe protection cover without screen and grid was used and held on the skin surface until stable TEWL was established. The SCWC was expressed digitally in corneometer value.

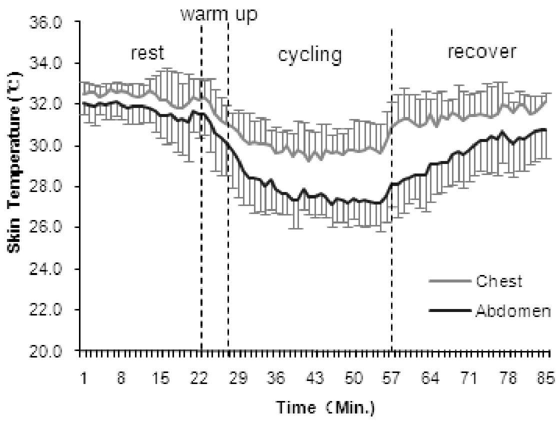
5.3.2 Data Analysis

Data analysis of the individual properties was carried out in accordance with the details presented below.

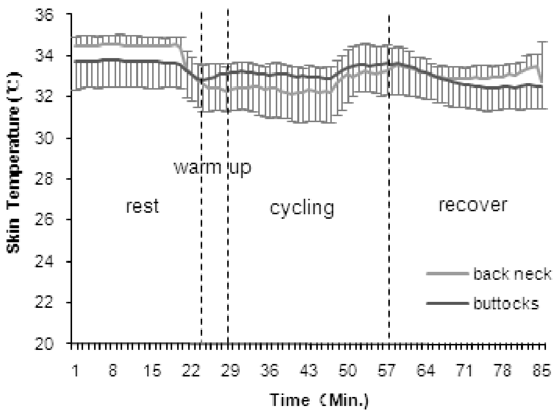
Skin Temperature Analysis

The skin temperature distribution of the different body parts can be viewed in terms of the results from infrared photos of the front and digital sensors on the back. The trend of change in skin temperature of the different body parts during the four consecutive stages of rest-warm up-cycling-recovery is shown in Fig. 5.6.

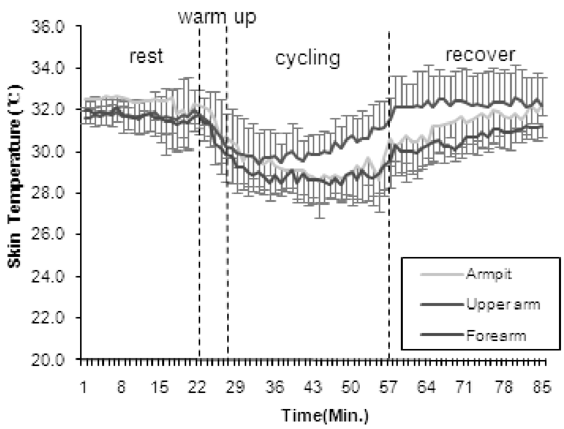
Items (a), (c), and (e) show the results of skin temperature distributions throughout the front of the body as converted by the infrared photos taken during the cycling exercise. The positions shown include the chest, abdomen, armpit, arm (upper and forearm), and lower front limbs (front thigh and front leg). Items (b), (d), and (f) show the skin temperature distribution throughout the back of the body based on the digital sensors taped on the back including the neck, bottom, upper, middle, and lower back, and lower back limbs (back thigh, popliteal fossa, and calf). A common trend could be observed that the skin temperature of all the measured body parts became stable during the resting period, started to decrease during the warm up stage and increased slightly some time after the cycling exercise due to heat loss by sweat evaporation, which is measured by TEWL.



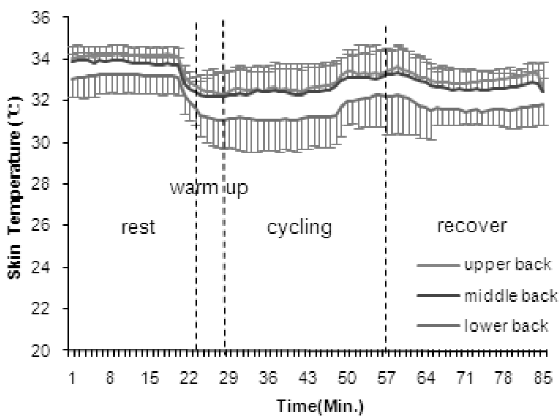
(a) Chest and abdomen



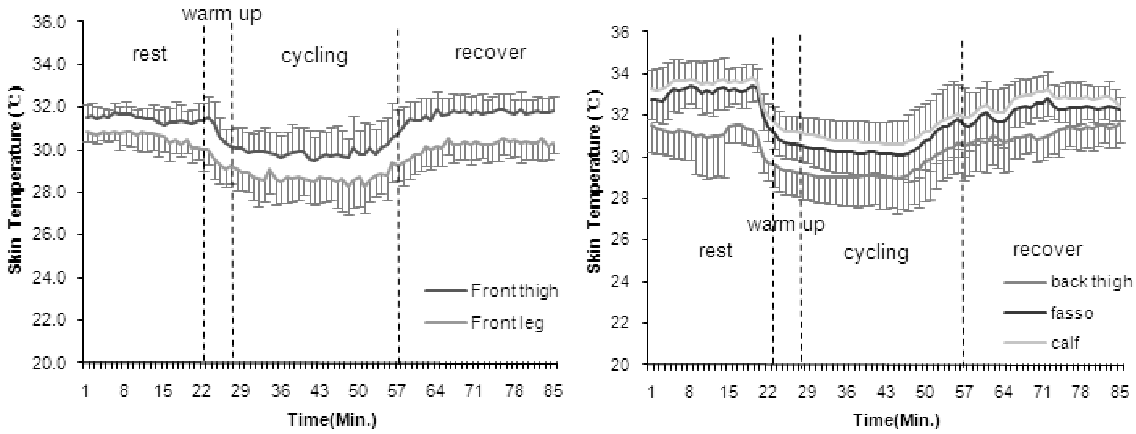
(b) Back neck and bottom



(c) Armpit, upper arm and forearm



(d) Back (upper, middle, and lower)



(e) Front thigh and front leg (f) Back thigh, popliteal fossa and calf

Fig. 5.6 Measured skin temperatures at different body parts during the cycling exercise

The decrease in the skin temperature of each body part during the cycling stage is shown in Table 5.1. On average, the skin temperatures of the upper and lower body decreased by 2.61 and 1.72 °C, respectively. The highest decrease in skin temperature of the upper and lower parts of the body was the abdomen and the popliteal fossa. These results indicate that the skin temperature of the front of the body significantly declined with a faster speed than that of the back, which is due to the air flow faced towards the front body and passed against the head and body side. However, the back of the body was influenced less by the air flow. In summary, the body parts with obvious decrease of skin temperature include abdomen, armpit, forearm, popliteal fossa, calf and chest.

Measurement points		Skin temperature decrease (°C)	Measurement points		Skin temperature decrease (°C)
Chest		2.45	Arm	Upper	1.58
Abdomen		3.81		Forearm	2.78
Back	Upper	1.45	Thigh	Front	0.61
	Middle	1.31		Back	1.94
	Lower	1.88	Popliteal Fossa		2.68
Armpit		3.08	Front Leg		1.94
Bottom		0.57	Calf		2.58

Table 5.1 Decrease of skin temperature during the cycling stage

Stratum Corneum Water Content (SCWC) Analysis

SCWC indicating sweat accumulation on the skin during the experiment was tested from 14 points of the body, including the head, chest, abdomen, armpit, arm (upper arm, forearm, hand), back (upper and lower), leg (front thigh, back thigh, popliteal fossa, front leg and calf). The points of the head and hand were ignored in the data analysis due to they are not necessary for sportswear design Fig. 5.7 shows the measured SCWC on different body parts recorded at six time positions.

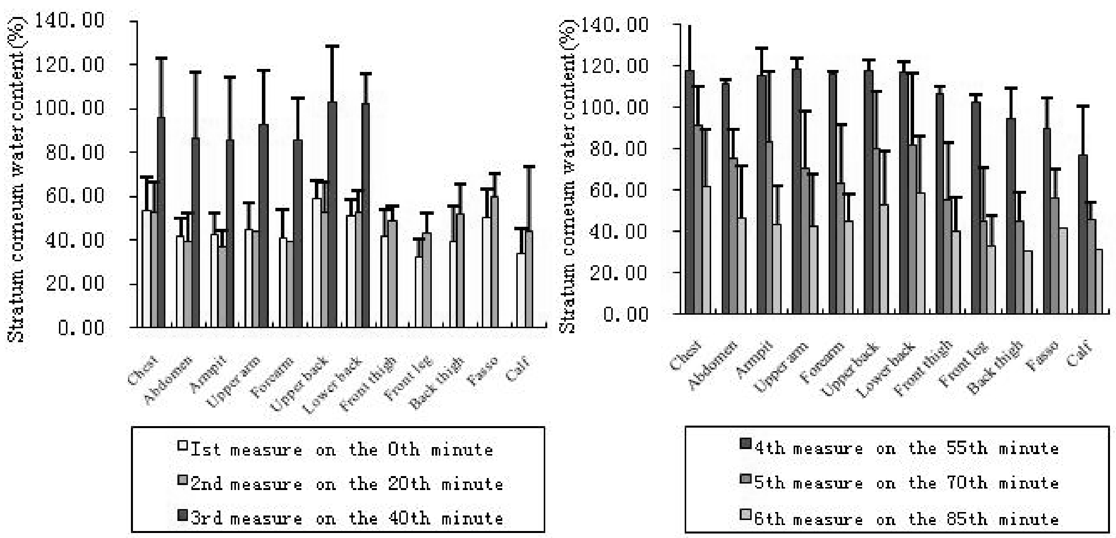


Fig. 5.7 Measured SCWC at six time positions during the cycling exercise

On the 40th and 55th minute, namely, at the middle and end of cycling stage, the SCWC increased dramatically. This increasing trend is due to the biological behaviour of sweating on the skin (Koga et al., 1997). The highest SCWC occurred at the end of the cycling stage, and quickly decreased during the recovery stage. The SCWC levels of the measurement points were significantly different on the 20th, 40th, 55th, and 70th minutes. SCWC of the lower limb in the third measurement was left out because the sensor cannot come into contact with the lower limb when the limb was moving.

The increase of SCWC during the cycling stage is shown in Table 5.2. On average, the SCWC values of the upper and lower limbs increased by 58.27% and 49.36%, respectively. The body parts with much sweat accumulation include front leg, arm, front thigh, armpit, abdomen, back and chest.

<table>
<tr><th colspan="2">Measurement points</th><th>SCWC increase (u Siemens)</th><th colspan="2">Measurement points</th><th>SCWC increase (u Siemens)</th></tr>
<tr><td colspan="2">Chest</td><td>53.67</td><td rowspan="2">Arm</td><td>Upper</td><td>61.43</td></tr>
<tr><td colspan="2">Abdomen</td><td>58.57</td><td>Forearm</td><td>60.50</td></tr>
<tr><td rowspan="2">Back</td><td>Upper</td><td>54.70</td><td rowspan="2">Thigh</td><td>Front</td><td>61.26</td></tr>
<tr><td>Lower</td><td>58.12</td><td>Back</td><td>48.62</td></tr>
<tr><td colspan="2">Armpit</td><td>60.91</td><td colspan="2">Front Leg</td><td>64.82</td></tr>
<tr><td colspan="2">Popliteal Fossa</td><td>34.22</td><td colspan="2">Calf</td><td>37.88</td></tr>
</table>

Table 5.2 Increase of SCWC during the cycling stage

Transepidermal Water Loss (TEWL) Analysis

TEWL indicating sweat evaporation on the skin during the cycling experiment was tested at the same 14 points as that of SCWC. Fig. 5.8 shows the TEWL data of different body parts measured at six time positions during the cycling exercise. TEWL of the lower limb on the third measurement could not be obtained because the sensor could not come into contact with the moving lower limb.

As shown in Fig. 5.8, there are obvious differences in the TEWL of measurement points on the 20th, 40th, 55th, and 70th minute. However, the trend of TEWL distribution is similar to that of the SCWC. TEWL reached the highest point at the end of the cycling stage and started to drop during the recovery stage.

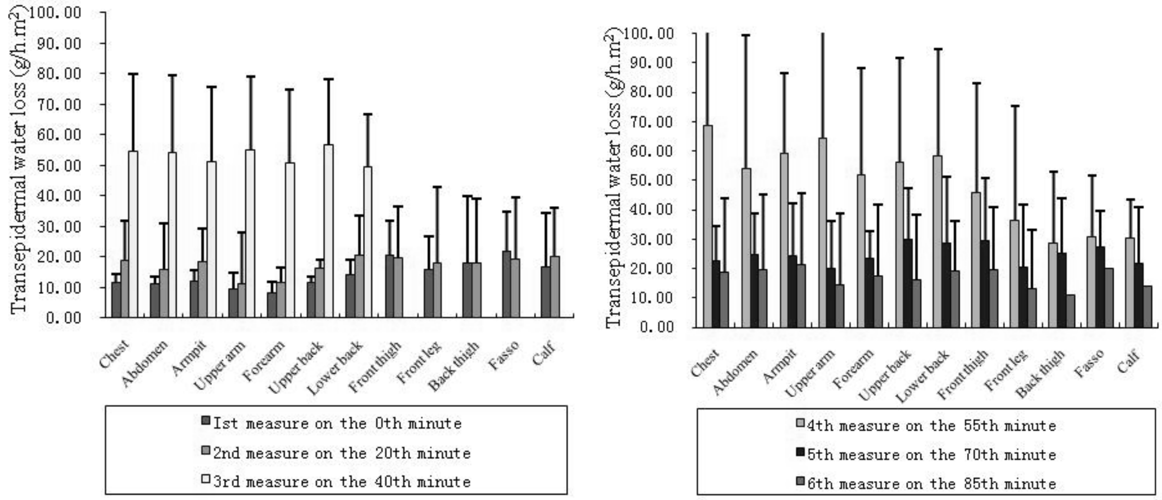


Fig. 5.8 Measured TEWL at six time positions during the cycling exercise

Since the cycling exercise was exposed to a wind velocity of 14.4 km/h, which caused an increase in TEWL, it shows an opposite trend of TEWL compared with the increase in skin temperature. Table 5.3 summarizes the increase of TEWL during the cycling stage.

Measurement points		**TEWL increase (g/h.m2)**	**Measurement points**		**TEWL increase (g/h.m2)**
Chest		46.36	Arm	Upper	49.27
Abdomen		40.63		Forearm	41.28
Back	Upper	42.42	Thigh	Front	25.58
	Lower	36.46		Back	10.69
Armpit		39.85	Front Leg		19.40
Popliteal Fossa		10.25	Calf		11.87

Table 5.3 TEWL data during the cycling period

On average, the TEWL increased in the upper and lower limbs by 42.33 and 15.56 g/h.m^2, respectively. The highest TEWL data recorded on the upper limbs came from the upper arm, and the highest TEWL data recorded on the lower limbs came from the front thigh. In summary, the body parts with much sweat evaporation include the upper arm, chest, upper back, forearm, abdomen, armpit, lower back and front thigh.

5.3.3 Data Mapping Visualization

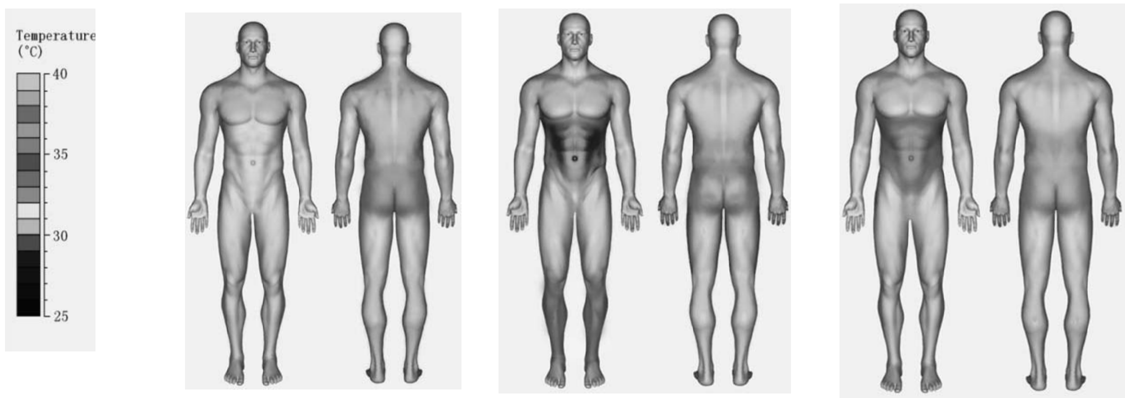
In consideration of the difficulties involved in direct reading and understanding of the measured data for the designer, the data values of skin temperature, SCWC, and TEWL were mapped with color on the body. The different values are mapped to different colors according to the color bar. Thus, the thermal distributions of the skin are easy to observe and associate with specific data values given a color bar key (wherein low values with blue, medium-low with cyan, and medium with green, etc.). By recognizing the color differences in different areas, it would be easier for the designer to distinguish the thermal requirements of cycling sportswear and integrate such information into their designs. For instance, if the color difference in skin temperature is significant (red and blue), it means the design requirement should be different (cooling down and keeping warm).

Skin Temperature

Using measured skin temperature on the different body parts, including back neck, bottom, back (upper, middle and lower), and leg (back thigh, fossa and calf), the color mapping was constructed. Details are presented in Table 5.4. The visualization of skin temperature distributions on the different body parts are shown in Fig. 5.9.

Measurement points		**Skin temperature (°C)**		
		Rest	**Cycling**	**Recovery**
Chest		32.39	29.94	31.43
Abdomen		31.77	27.96	29.57
Back	Upper	34.16	32.71	33.11
	Middle	33.85	32.54	32.79
	Lower	33.21	31.33	31.74
Armpit		32.4	29.32	31.30
Arm	Upper	0.834	30.11	32.23
	Forearm	0.980	28.92	30.53
Bottom		33.73	33.16	32.89
Thigh	Front	31.47	30.86	31.62
	Back	31.22	29.28	31.06
Popliteal Fossa		33.15	30.47	32.19
Front Leg		30.65	28.71	30.15
Calf		33.56	30.98	32.63

Table 5.4 Skin temperature data on the different body parts for color mapping



Color Bar Rest Cycling Recover

Fig. 5.9 Color mapping visualization of measured skin temperature

As illustrated in the visualized picture, the color of the front chest changed from red during the rest stage to blue during cycling and light red during recovery. That indicates that the skin temperature of the chest is higher than that of the abdomen and limbs during the rest and recovery period. However, the skin temperature of chest decreased greatly during cycling since the color became blue. Meanwhile, the color of the front thigh changed from yellow to green, while the color of back thigh changed from yellow to blue, indicating that the front thigh generated more heat than the back thigh since it is more active. From the color comparison, we can also find that the skin temperature of the upper arm is higher than that of the forearm and armpit, especially during the cycling stage, indicating that the upper arm is the most active part of the upper limbs. The skin temperature of the calf is higher than that of the back thigh, and decreased during the cycling stage.

Stratum Corneum Water Content (SCWC)

Color mapping was executed based on the measured SCWC data of different body parts, as summarized in Table 5.5. The color mapping visualization of the SCWC distributions of the different body parts is shown in Fig. 5.10 with a spectrum of colors representing a range of SCWC values. The common trend can be observed based on the color change: SCWC is at the highest level during the cycling stage and is stable during the rest and recovery stages.

Measurement point		**SCWC (u Siemens)**		
		Rest	**Cycling**	**Recovery**
Chest		52.95	106.62	76.34
Abdomen		40.44	99.02	60.87
Back	Upper	55.78	110.48	66.35
	Lower	51.76	109.88	70.19
Armpit		39.59	100.49	63.42
Arm	Upper	44.04	105.47	56.57
	Forearm	40.19	100.69	54.19
Thigh	Front	45.36	106.62	47.84
	Back	45.71	94.33	37.82
Popliteal Fossa		55.19	89.41	49.03
Front Leg		37.55	102.38	38.71
Calf		38.91	76.79	38.55

Table 5.5 SCWC data on the different body parts for color mapping

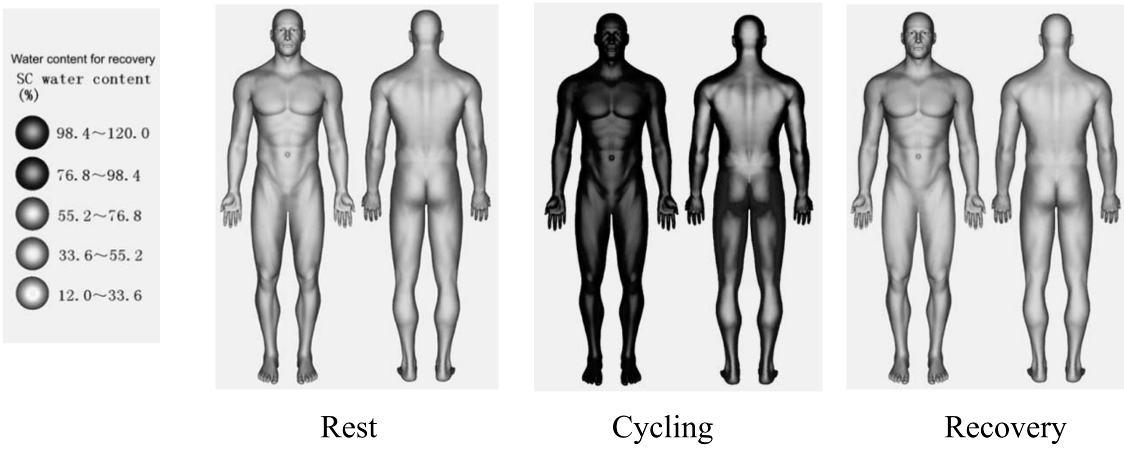


Fig. 5.10 Color mapping visualization of measured SCWC data

Similar to the principle for skin temperature color mapping, the color bar adopted the colors brown (low values), blue (medium-low values), and cyan (high values) to represent SCWC data. As illustrated in the visualized picture, the color of the front trunk, thigh and leg changed from blue to cyan and returned to blue during the rest and recovery period, indicating the SCWC of the front body increases considerably during cycling. At the back area, the color of the head, trunk, and limbs changed from blue during the rest stage to light cyan during the cycling and then returned to blue during the recovery indicating that the SCWC of these areas increase during the cycling and decrease during recovery. The trunk and upper limbs show a higher increase in SCWC than that of the thigh and lower limb because fewer sweat glands are distributed throughout the back thigh and legs.

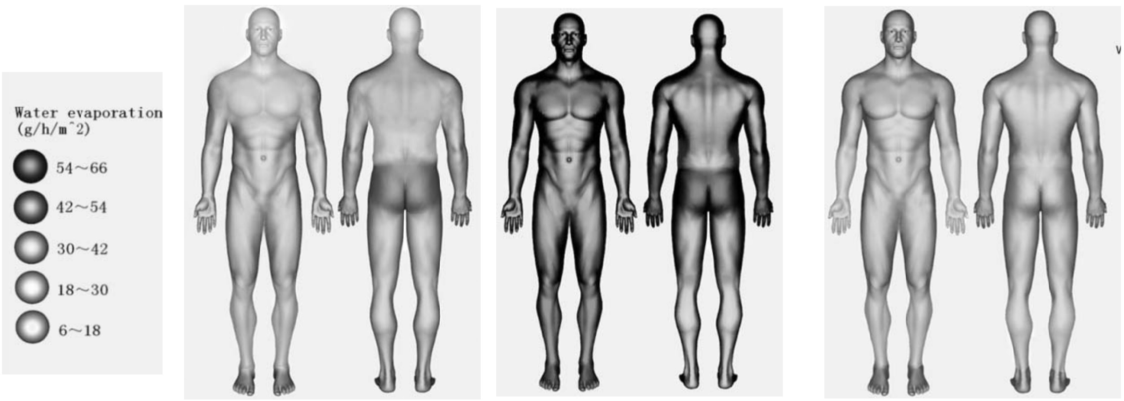
Transepidermal Water Loss (TEWL)

With the measured TEWL data of different body parts (Table 5.6), color mapping according to this data can be executed. The color mapping visualization of the TEWL distributions is shown in Fig. 5.11.

Measurement point		TEWL (g/h.m^2)		
		Rest	Cycling	Recovery
Chest		15.13	61.48	20.70
Abdomen		13.49	54.12	22.31
Back	Upper	13.93	56.35	23.10
	Lower	17.46	53.92	23.76
Armpit		15.25	55.10	22.77
Arm	Upper	10.29	59.56	17.31
	Forearm	9.92	51.21	20.41
Thigh	Front	20.31	45.89	24.62
	Back	18.07	28.77	18.05
Popliteal Fossa		20.55	30.80	23.60
Front Leg		16.86	36.26	16.88
Calf		18.37	30.23	17.95

Table 5.6 TEWL data on the different body parts for color mapping

Similar to the color mapping for SCWC, the color bar adopted brown (low values), green (medium-low values), and dark green (high values) to represent TEWL values. Fig. 5.11 reveals a dynamic change of TEWL from brown and light green to dark green, and then returned to light green for the consecutive rest-cycling-recovery cycles. The TEWL of the body increased obviously during cycling, especially for the chest and arm, which show the most increase in TEWL due to convection evaporation. A comparative higher increase in TEWL can be observed in the trunk and upper limbs as compared with those of the thigh and lower limbs. There are no obvious differences observed in the TEWL of different body parts during the recovery period.



Rest Cycling Recovery

Fig. 5.11 Color mapping visualization of measured TEWL

For cycling sportswear design, concerned areas include the chest, abdomen, armpit, arm (upper arm and forearm), leg (front thigh and front leg) in the front view, and the back neck, bottom, back (upper, middle, and lower), and lower limb (back thigh, fossa, and calf) in the back view. The mapping visualization of skin temperature, SCWC, and TEWL offers a direct understanding of the different thermal physiological characteristics of these areas on the body during the cycling exercise.

5.3.4 Thermal Zone Creation

According to the experimental study on the thermal physiology of cyclists, it is apparent that the distributions of the thermal properties on different body parts vary during the cycling stage. In order to distinguish between the different features of different body parts, Huizenga et al., (2001) established a typical segmentation for the human model. The zones in his segmentation include the head, chest, back, pelvis, right and left upper arms, right and left lower arms, right and left hands, right and left thighs, right and left lower legs, and right and left feet. However, these segmental zones were created without consideration of thermal physiology or biomechanics of the body, which are important factors for the functional design of cycling sportswear.

Thermal comfort can help the body to have more physical patience and strength during the activity, thereby improving performance (Li, 2001). As discussed in the above sections, the thermal conditions of cycling determine the thermal comfort of the cyclists. Considering the thermal conditions and thermal distributions of the body in cycling through experimental analysis, the thermal zones of the human body can be created with reference to Huizenga et al.'s segmentations (1999). Through the thermal zones, the designer can distinguish the different thermal physiological characteristics of the body easily and have a clear division of the body for functional design.

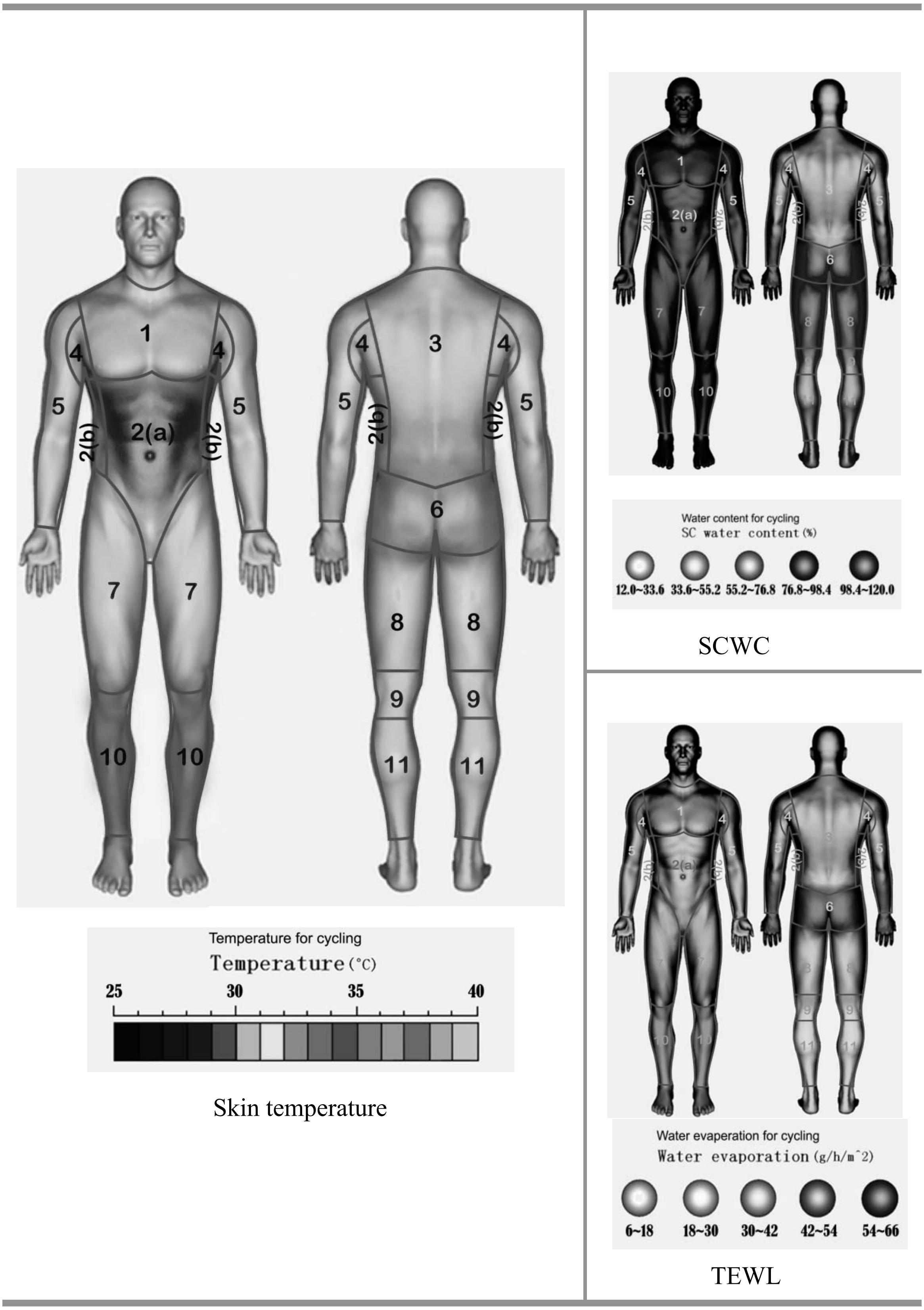


Fig. 5.12 Thermal zones of the body for thermal functional design of FCS

Fig. 5.12 shows the thermal zones created for thermal functional design of cycling sportswear. They are illustrated individually on the body with color mapping visualizations from the skin temperature, SCWC and TEWL data during cycling exercise to perform further analysis. There are 11 zones on the human body, including the chest (No. 1), rectus abdominis (No. 2(a)) and abdominal obliques (No. 2(b)), back (No. 3), armpits (No. 4), arms (No. 5), bottom (No. 6), front thighs (No. 7), back thighs (No. 8), popliteal fossa (No. 9), front legs (No. 10), and calves (No. 11).

Based on analysis of the experimental data, the thermal biological characteristics of thermal zones of the body can be discussed as follows:

On the upper part of the body, the chest (No.1) generates much sweat during cycling, resulting in much sweat accumulation indicated by SCWC. Meanwhile, it also has a great amount of sweat evaporation indicated by TEWL due to the facing air flow. The skin temperature of the chest has an obvious decrease (2.45 °C) during the cycling stage. Compared with the chest, the abdomen (No. 2(a) and No. 2(b)) show more sweat accumulation but less evaporation, meanwhile, the most amount of skin temperature decrease (3.81 °C) in all the zones. In summary, both the chest and abdomen areas are characterized as areas of the body prone to sweat accumulation and evaporation; moreover, they are prone to remarkable skin temperature decrease due to the air flow facing the chest and abdomen during cycling, thus accelerating sweat evaporation and decreasing skin temperature.

The back (No. 3) also generates much sweat, resulting in much sweat accumulation. However, sweat evaporation on the back is not obvious, and the back also has the least decrease in skin temperature (1.55 °C) because of the weaker air flow on the back. The armpit (No. 4) has more sweat accumulation than the back, although these two parts have similar sweat evaporation. However, the armpit shows a higher decrease in skin temperature (3.08 °C) as compared with the back.

The arm (No. 5) including the upper arm and forearm has more sweat accumulation and evaporation as compared with other zones in the upper body. The arm also has obvious skin temperature decrease (2.18 °C).

Given that the main active muscles during cycling are located in the lower body, features of these thermal zones are different from those on the upper body.

The bottom (No. 6) has the highest skin temperature but the least decrease in skin temperature (0.57 °C) during cycling, since the bottom sits on the bicycle most of the time, making it difficult to dissipate the heat and accumulated sweat.

The front thigh (No. 7) has a great volume of sweat in the lower body part, but has the least skin temperature decrease (0.61 °C). The back thigh (No. 8) has less sweat accumulation and sweat evaporation than that of the front thigh; however, it has more skin temperature decrease (1.94 °C). These results are due to the fact that the front thigh is more active, thus generating more heat than the back thigh during cycling.

The front leg (No. 10) has the most sweat accumulation in all the zones, and the decrease of skin temperature by 1.94 °C during cycling. The popliteal fossa (No. 9) has lesser sweat accumulation and evaporation than that of the front leg; and the skin temperature decreased by 2.68 °C during cycling in this area. The calf (No. 11) has similar sweat accumulation and evaporation, and decrease of skin temperature to that of the popliteal fossa.

In summary, the thermal distributions of thermal zones on the body indicate that the zones on the upper body (Nos. 1 to 5) generated more sweat than those of the lower body (Nos.7 to 11). The variations in skin temperature distributions of thermal zones on the different body parts are due to the fact that the active muscle groups during cycling are located mainly on the lower body, thus generating more heat in these parts.

5.3.5 Thermal Functional Requirements

Based on the experimental analysis above, the thermal physiological characteristics of cyclists during the cycling exercise have been discussed and illustrated pertaining to individual thermal zones. Thus, the key point in thermal functional cycling sportswear design is to help the body dissipate the generated heat and release the accumulated sweat on the skin quickly in order to offer cyclists thermal comfort. However, some researchers also found that a slight increase in body temperature (2.0 to 2.5 °C) is helpful for the high intensive sport as it may cause a corresponding increase in the excitation of the nervous system (Koga et al., 1997). Another study also reported that an environment with higher temperature has a slight influence on sports performance, using a comparison of the performances of athletes in 3 conditions: 22.0 °C, 30% RH; 30.0 °C, 85% RH; and 40.0 °C, 40% RH (Backx et al., 2000). These results indicate that a comparatively warmer environment is helpful in improving the performance of cyclists during cycling race.

With these considerations, the thermal requirements of cycling sportswear can be identified as follows:

1) The chest (No.1) and abdomen (No. 2(a) and No. 2(b)) generate much sweat and have remarkable skin temperature decrease. Thus it is crucial to release the accumulated sweat, while it has no need of special design to dissipate heat.

2) The back (No. 3) also generates much sweat but less evaporation, and has the least decrease in skin temperature. Thus it is necessary to release the accumulated sweat or even to accelerate the releasing speed. Meanwhile, it should be able to quickly dissipate the generated heat on the back. This capacity of sweat releasing should also be offered to the armpit (No. 4), which even has more sweat accumulation than the back but similar sweat evaporation. However, the armpit has no need to dissipate heat since it has a remarkable decrease in skin temperature.

3) The arm (No. 5) has more sweat accumulation and evaporation as compared with

other zones in the upper body, and also has obvious skin temperature decrease. Thus it is necessary to release the accumulated sweat and no need to dissipate heat.

4) The bottom (No. 6) has the highest skin temperature and is easy to accumulate sweat due to it contacting the seat most of the time, thus it is quite necessary to dissipate heat and release the accumulated sweat.

5) The front thigh (No. 7) has a great volume of sweat but has the least skin temperature decrease. The back thigh (No. 8) has less sweat accumulation and evaporation but more skin temperature decrease. That indicates it needs to release the sweat on these parts. However, there is no need of special design to accelerate heat dissipation since the thigh with slight higher skin temperature is helpful to the performance.

6) The front leg (No. 10) has a great volume of sweat in the lower body, and the popliteal fossa (No. 9) and calf (No. 11) has lesser sweat accumulation and evaporation than that of the front leg. Functionally, it should release the accumulated sweat on these parts. Also, these parts have no need to dissipate heat since they are active during cycling and it is beneficial to have a slight higher skin temperature.

In summary, all the body parts have needs to release accumulated sweat, especially for the upper body. Much heat is generated by the thigh, front leg and calf which are more active during cycling; however, there is no need to cool these parts since slightly higher skin temperature is good for cycling performance. Considering the sweat evaporation of the back is not obvious and the temperature of the back is higher than other parts, thus, it is crucial to dissipate heat for this part.

5.3.6 Summary

This section provides quantitative analyses of the thermal physiology of the body to develop the thermal requirements for thermal function design of the cycling sportswear. A cycling experiment was performed in a chamber following a cycling exercise protocol. Based on the measured thermal data including the skin temperature, SCWC, and TEWL, the thermal physiological characteristics of the body were investigated pertaining to each created thermal zone. The thermal zones make the designer easy to have a clear division of the body and distinguish the different thermal requirements of different body parts. Based on the experimental analyses of the thermal physiology of cyclists, the thermal requirements on all thermal zones of the cyclists were identified in order to dissipate the heat and release accumulated sweat for achieving thermal comfort of the body.

5.4 Thermal Functional Design Scheme

In creating a functional design, it is essential to understand the features of the design object, identify the functional requirements, and consider these in the design scheme in order to come up with desirable functions. As discussed in Chapter 3, thermal functional requirement is regarded as being one of the basic functional requirements of FCS design and should be first considered in the functional design of FCS. In the above sections, the thermal functional requirements have been identified through experimental analysis. The thermal physiology of the body during cycling was investigated by analyzing the thermal distributions in terms of skin temperature, sweat accumulation, and evaporation. In this section, the detailed scheme of the thermal functional design of FCS is reported.

The thermal distributions of skin temperature and sweat volume vary on different thermal zones due to the different active muscles and sweat gland distributions on the body parts. However, these thermal zones can be categorized further into four areas according to the value range of skin temperature, SCWC, and TEWL. These include Area 1: high skin temperature, low SCWC and TEWL; Area 2: high skin temperature, high SCWC and TEWL; Area 3: low skin temperature, low SCWC and TEWL; and Area 4: low skin temperature, high SCWC and TEWL. According to the report by Abbiss et al. (2008), skin temperature during cycling is regarded as warm or even hot if it exceeds 32.2 $\pm$ 0.7 °C. Moreover, by comparing the measured relative humidity on the skin, it has been found that high volume of sweat accumulated on the skin if the value of SCWC exceeds 95%, and there is high sweat evaporation if the value of TEWL exceeds 35 g/h.m2.

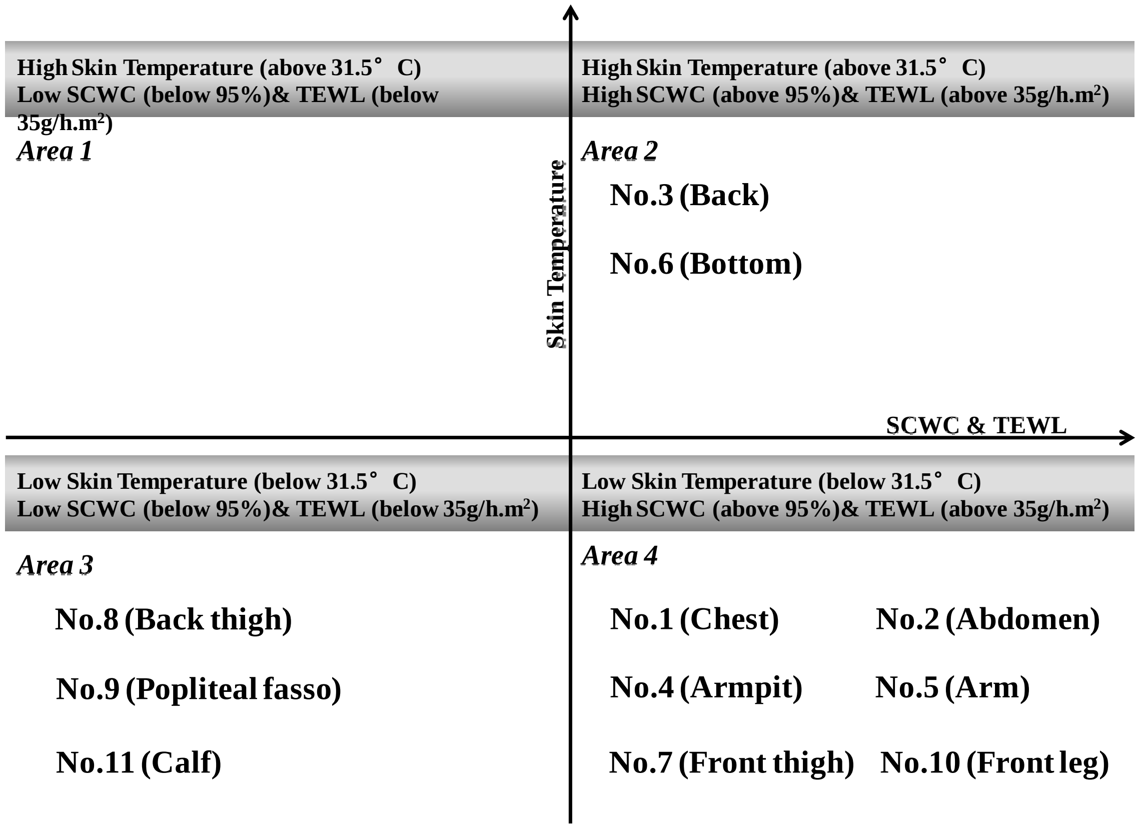


Fig. 5.13 Thermal zones categorized into four areas

Fig. 5.13 shows all the thermal zones in the four areas according to the range of thermal physiology of the body during cycling. There are no thermal zones located in Area 1. Area 2 includes the back (No. 3) and bottom (No. 6). The back thigh (No. 8), popliteal fossa (No. 9), and calf (No. 11) are in Area 3. Area 4 has the most zones, which include the chest (No. 1), abdomen (No. 2), armpit (No. 4), arm (No. 5), front thigh (No. 7), and front leg (No. 10). The illustrations of these four thermal design areas on the body can be seen in Fig. 5.14. The four areas with different thermal characteristics are visualized using four different colors and padding.

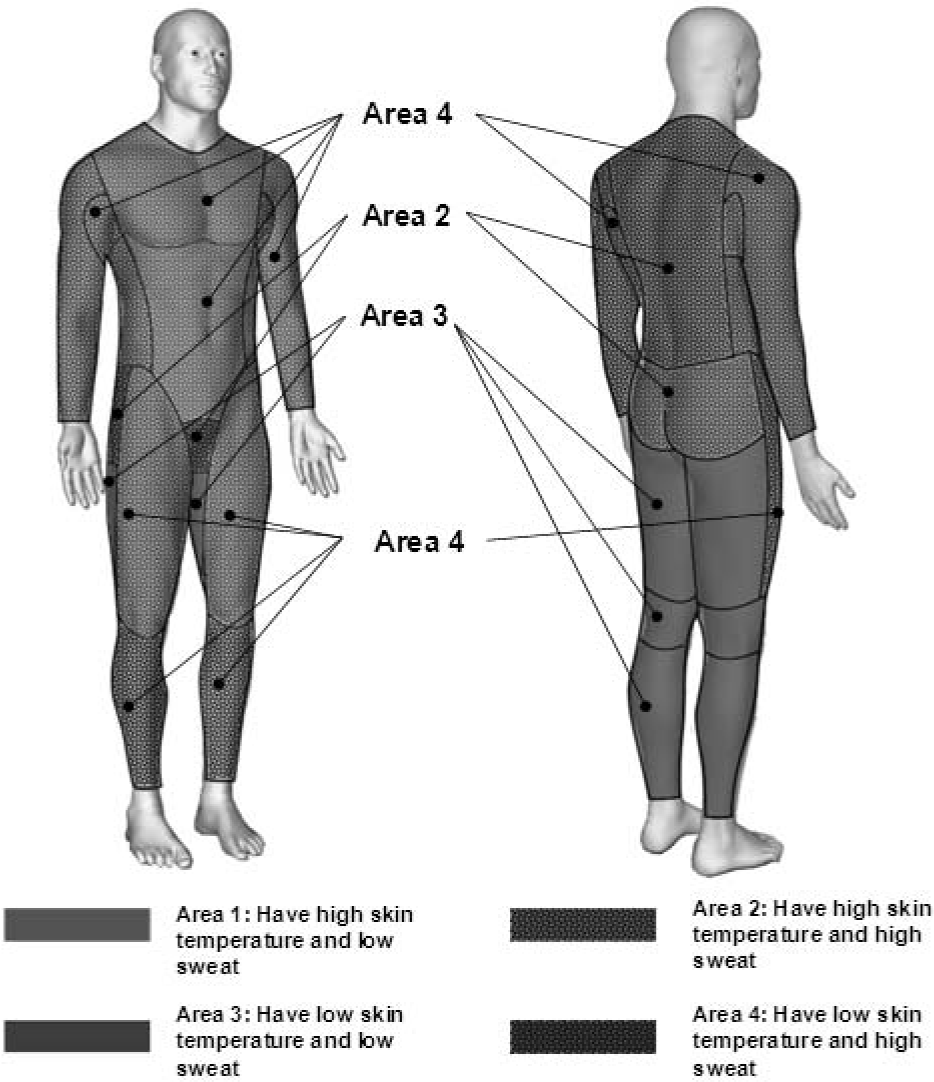


Fig. 5.14 Illustration of the four thermal design areas on the body

As discussed in Section 5.2, the functional properties of temperature and humidity are the most important factors in achieving thermal comfort. According to the thermal functional requirements identified, there is a critical need for quick sweat release and fast drying, indicating that the thermal functional design of FCS must utilize moisture management and breathability function of garments to improve the conditions for thermal comfort during cycling. Given this idea, the thermal functional design can be realized, and the scheme is shown in Fig. 5.15.

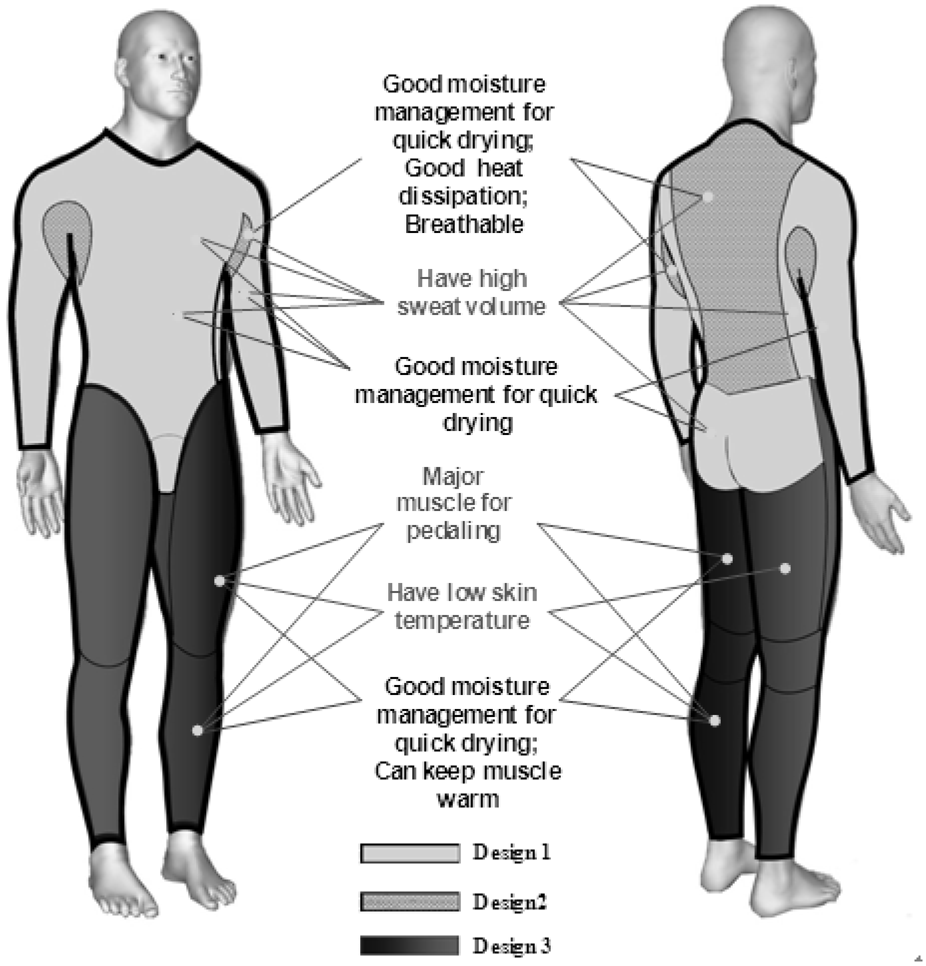


Fig. 5.15 Thermal functional design scheme of FCS

In Area 2, which includes the back (No. 3) and bottom (No. 6), the common thermal characteristics are high skin temperature and high sweat generation. Thus, the design with capability of good heat dissipation, breathablity and moisture management (design 1) must be considered to efficiently dissipate heat and release sweat for quick drying. However, the breathable fabric, for instance, the fabric with mesh structure, is not suitable for the bottom, which undergoes constant contact and friction with the seat; hence, a comparatively thin fabric with no mesh can be adopted for this part. Furthermore, in order to strengthen the breathablity for the back, the armpit (No. 4), which has a great volume of sweat, also can adopt this design.

In Area 3, which includes the back thigh (No. 8), popliteal fossa (No. 9), and calf (No. 11), there are comparatively few sweat glands distributed on these parts (Weiner, 1945). The thermal characteristics of this area are low skin temperature and low sweat generation. Since the back thigh (No. 9) , calf (No. 12), the front thigh (No.7) and front leg (No.10) have major active muscles that provide effective force on the pedals (Gregor and Conconi, 2000), it is beneficial to keep the working muscles warm. The thermal characteristics of the front thigh (No.7) and front leg (No.10) are low skin temperature but high sweat generation. Thus, these parts can be grouped and adopt the design with the capability to release the moisture and keep the muscle warm.

The remaining parts Area 4 include the chest (No. 1), abdomen (No. 2) and arm (No. 5) in the upper body. During cycling, which usually occurs with fast speed, a strong air flow facing the front of the body may speed up sweat evaporation, thereby decreasing skin temperature. These body parts have thermal characteristics of low skin temperature and high sweat accumulation evaporation. The design with capability of good moisture management can be considered to release sweat and keep the body dry.

In order to achieve these designs, the fabrics adopted may be produced through knitting technology, which lays a good basis for good breathability. Furthermore, in order to achieve the moisture management capability, all the fabrics may be performed with MMF treatment, which can change or improve the rate of drying of the fabric as well as provide the fabrics with excellent breathability through the efficient movement of moisture away from the skin (Hu et al., 2005). Thus, the sweat accumulated on the skin during cycling can be released quickly to the outer surface of FCS, and the skin can then have a dry and comfortable feeling.

5.5 Thermal Performance Simulation

With the aid of professional CAD tools, this section aims to predict the thermal performance of FCS numerically designed by the fabrics and further indicate the fabric selection for the thermal functional design. By measuring and inputting the thermal characteristic properties of fabric, the numerical design and simulation of FCS wearing scenarios can be performed on professional CAD tools to predict the thermal performance of FCS. Based on these efforts, the designers can scientifically predict and determine the proper design to satisfy the functional requirements.

5.5.1 Thermal Properties Measurement

The thermal properties of fabrics, including the thickness, density, water vapor permeability, air resistance, thermal conductivity and MMF properties, were measured to illustrate the fabric's capability of heat insulation and moisture management. MMF treatment, which is a developed technology reported in Li's patent (Li, 2001), aims to improve the capacity of moisture management of the fabric. The detail description about the testing instruments and standards for thermal properties are listed in Table 5.7.

<table>
<tr><th colspan="2">Physical property</th><th>Testing instruments</th><th>Standards</th></tr>
<tr><td colspan="2">Thickness</td><td>SDL fabric thickness tester</td><td>ASTM D 1777</td></tr>
<tr><td colspan="2">Weight per unit area</td><td>Balance</td><td>ASTM D 3376</td></tr>
<tr><td colspan="2">Water vapor permeability</td><td>Balance, wide-mouse vessels</td><td>ISO 15496</td></tr>
<tr><td colspan="2">Air resistance</td><td>KES Air-permeability tester</td><td>KES FB-AP18</td></tr>
<tr><td colspan="2">Thermal Conductivity</td><td>KES thermal LABO II Tester</td><td>KES F7</td></tr>
<tr><td rowspan="6">MMF</td><td>Wetting Time Top</td><td rowspan="6">Moisture management tester (MMT)</td><td rowspan="6">AATCC Test Method 195</td></tr>
<tr><td>Wetting Time Bottom</td></tr>
<tr><td>Top Max Wetted Radius</td></tr>
<tr><td>Top Spreading Speed</td></tr>
<tr><td>AOWTI</td></tr>
<tr><td>OMMC</td></tr>
</table>

Table 5.7 Measurement instruments and standards for thermal properties

With these measurement instruments and standards, the thermal properties of fabrics can be obtained. Table 5.8 lists out the thermal properties of some knitted fabrics which are ready-for-use in this study.

Thermal properties	Fabric types				
	PP—plain	PP--plating	PP--tuck	PP--1x1 rib	PP--2x2 rib
	Original	Original	Original	Original	Original
Weight per unit area [g/m2]	153.7	144.2	168.3	210.9	243.4
Thickness [cm]	0.75	0.98	0.97	1.14	1.51
Water vapour permeabili [g/m2.day]	507.9	441.9	469.9	423.1	406.5
Air resistance [KPa.s/m]	0.230	0.189	0.287	0.276	0.326
Thermal Conductivity [W/mk]	0.051	0.049	0.048	0.052	0.055
Wetting Time Top [sec]	13.8	7.8	11.4	15.3	16.1
Wetting Time Bottom[sec]	4.5	7.8	3.8	4.8	5.3
Top Max Wetted Radius [mm]	5.0	5.0	5.0	5.0	4.9
Bottom Max Wetted Radius [mm]	12.5	15.0	8.3	9.3	9.5

Table 5.8 Thermal properties of some ready-for-use fabrics

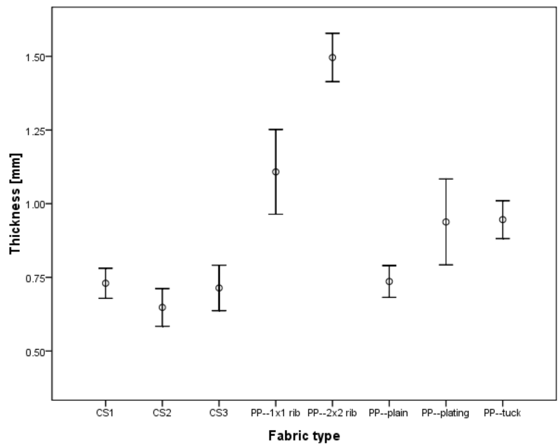
From this table, it can be observed that the density and thickness of rib structure is higher than those of other structures. The plain structure has the best in moisture water vapour permeability whereas the plating structure has the lowest air resistance, which indicate the plain structure can quickly release moisture but the plating structure are the best in terms of breathability.

In order to evaluate the thermal functions of these fabrics, a commercial FCS suit was purchased from a popular cycling sportswear shop and its fabrics were also measured with the thermal properties in Table 5.8. The commercial cycling suit was composed of three types of fabrics found in the chest, back, and thigh parts, namely CS1, CS2, and CS3. Five samples of each fabric were tested for the thermal functional properties using the measurement instruments and standards described in Table 5.7. The mean thermal properties of these commercial fabrics are shown in Tables 5.9.

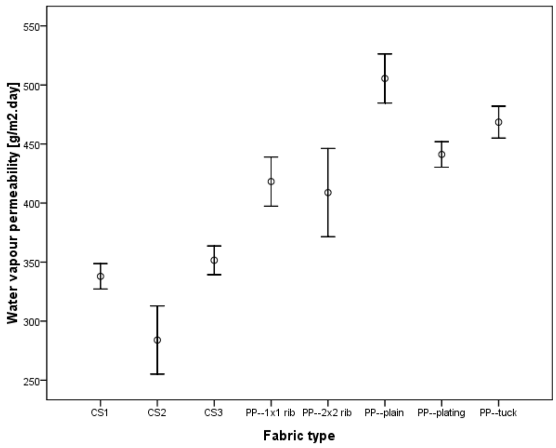
Thermal properties	**Fabric type**		
	CS 1 Original	CS 2 Original	CS 3 Original
Weight per unit area [g/m2]	136.9	152.4	163.2
Thickness [mm]	0.71	0.69	0.67
Water vapour permeability [g/m2.day]	335.3	295.6	343.4
Air resistance [KPa.s/m]	0.09	1.16	0.07
Thermal Conductivity [W/mk]	0.059	0.058	0.076
Wetting Time Top [sec]	3.6	4.5	5.4
Wetting Time Bottom [sec]	52.3	63.2	63.7
Top Max Wetted Radius [mm]	5.0	5.0	5.0
Bottom Max Wetted Radius [mm]	5.0	5.0	5.0

Table 5.9 Thermal properties of fabrics from commercial FCS

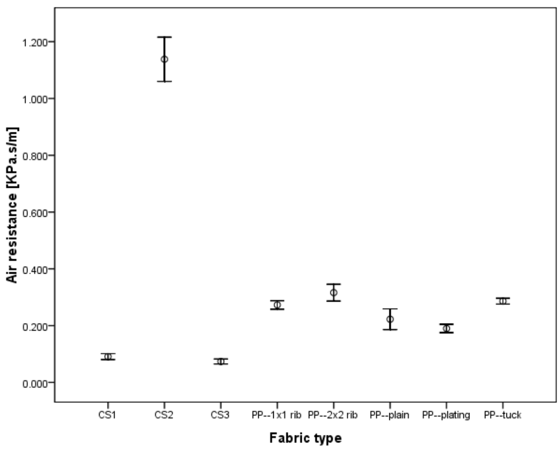
A comparison was carried out between the measured thermal properties of the ready-for-use fabrics, namely, PP-plain, PP-plating, PP-tuck, PP--1x1 rib and PP--2x2 rib, and the fabrics from the commercial FCS. Fig. 5.16 shows the data plots of the compared functional properties in terms of thickness, weight in unit area, water vapour permeability, air resistance, thermal conductivity.



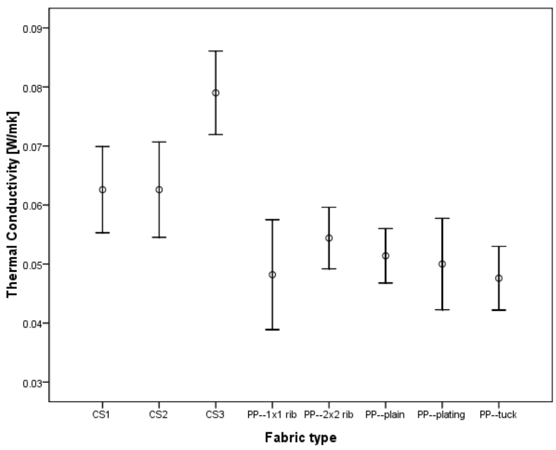
Thickness



Water vapour permeability



Air resistance



Thermal conductivity

Fig. 5.16 Compared functional properties of the fabrics

From the shown data plots, it can be seen that all the ready-for-use fabrics have better capacity of moisture management than the commercial fabrics due to the higher water vapour permeability. Meanwhile, the fabric from the back of the commercial FCS (CS2) has inferior air breathability and moisture management caused by its highest air resistance and lowest water vapour permeability. That can not satisfy the functional requirements of the back, which has much sweat generation during cycling.

5.5.2 Numerical Simulation

As a pioneer research, Mao and Li (2006) developed a CAD software system (P-smart), especially for clothing thermal functional design, which offers the designers the capacity to achieve the functional clothing design. It adopted an engineering method based on the simulation of thermal behaviours involved in the clothing wearing scenarios. Through parametric input of the properties of the fibre/fabric material, construction/treatment method, human body and environment, the designers can numerically design and simulation of the clothing and wearing scenarios, and quickly preview the thermal performance of designed garment using different textile materials. This CAD platform enables designers to iteratively attempt to improve their design until they achieve an ideal design, which reduces the duration of the design cycle and lowers the design cost. This software system has been well validated by comparing it with practical designs and experiments. It also has great potential in the design of functional textile products, such as sportswear and personal protection clothing (Mao et al., 2008).

Simulation Protocol

The FCS was designed with short style and single fabric layer. Respectively, five fabrics with different knitting structure, namely, PP-plain, PP-plating, PP-tuck, PP-1x1 rib and PP-2x2 rib, were used to numerically design the FCS in five simulation cases. An athlete with 180 cm height, 70 kg weight was specified to wear the FCS and perform consecutive activities (20-minute resting, 5-minute warm up, 30-minute cycling and 30-minute recover) in an environment with air temperature 25 °C and relative humidity 67%. In this protocol, the wind velocity is set as 13.23 m/s, which imitate the average ride velocity of the winner, Fabian Cancellara in the individual time-trials in 2009 Tour de France (France, 2009).

Design and Simulation

The interface for the design of fabric is shown in Fig. 5.17, through which the thermal properties of fabric was input. The detail design process and interfaces with P-smart system is illustrated in Appendix B. After numerical design and computational simulation, the simulation results were obtained in terms of the thermal performance of the fabric and the human body, such as the temperature and relative humidity of the fabric, and the skin and core temperature of the body. From the predicted values of the thermal performance, it can preview their distributions during the wearing scenarios and evaluate the thermal performance of the FCS prototypes.

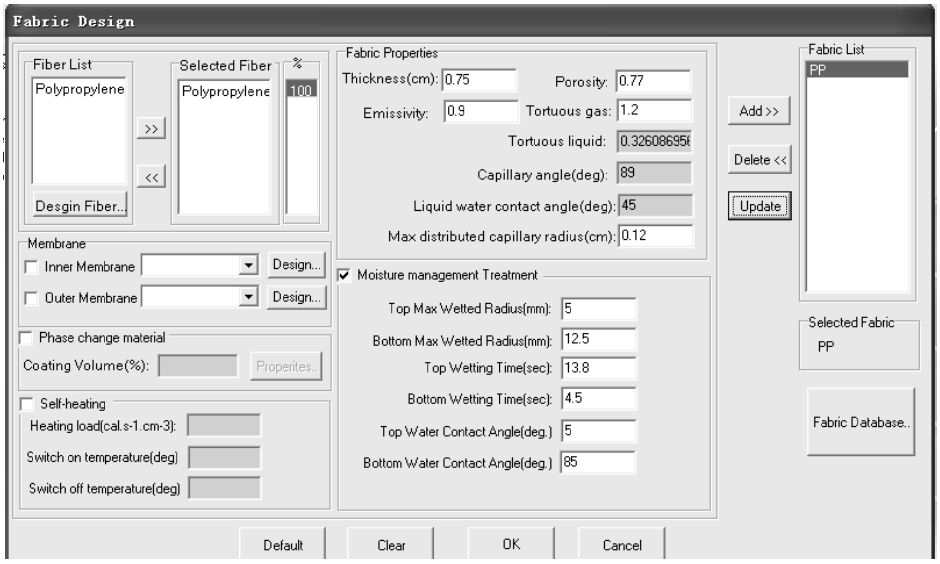
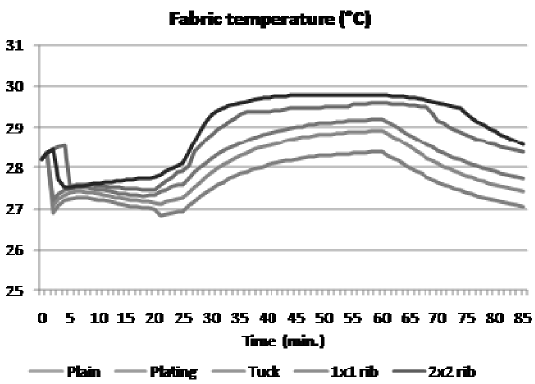


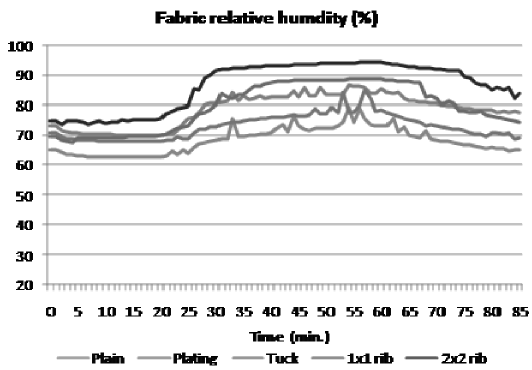
Fig. 5.17 Interface for fabric design

Simulation Results

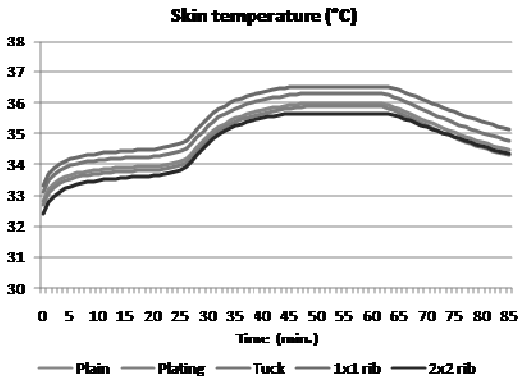
The predicted thermal performance of the fabric and the wearer in these five cases was compared and illustrated in Fig. 5.18, including temperature and relative humidity of the fabric, skin temperature, core temperature, thermal comfort and moisture comfort of the wearer.



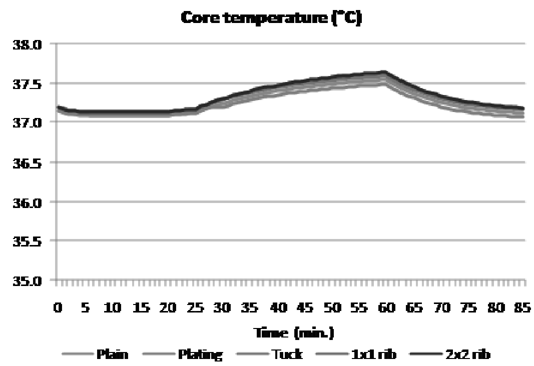
Fabric temperature



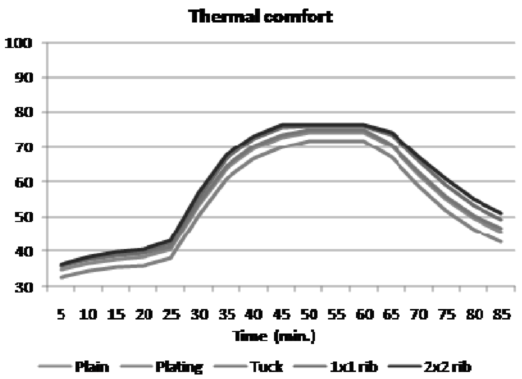
Fabric relative humidity



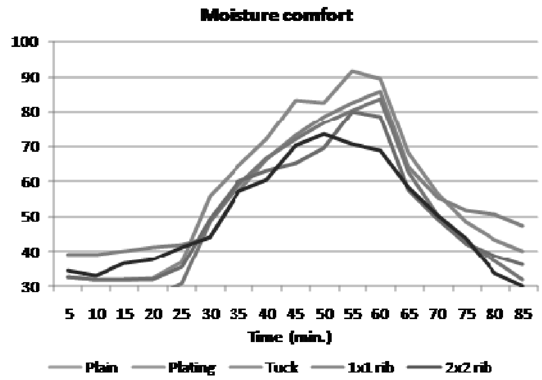
Skin temperature



Core temperature



Thermal comfort



Moisture comfort

Fig. 5.18 Predicted thermal performance of five fabrics

From the data charts 5.18 (a) and 5.18 (b), it can be seen that the rib and tuck structure fabrics reach higher temperatures than their counterparts during the cycling and resting stage. However, the plating fabric has the lowest temperature since it is thin and meanwhile the most breathable fabric. The plain fabric's temperature is also lower than that of the rib and tucks fabrics. Due to the better MMF capacity, the plain fabric has the lowest relative humidity in these fabrics. Whereas, the 2x2 rib fabric has the highest relative humidity. That indicates that the PP-rib and PP-tuck fabrics have better thermal insulation, whereas the PP-plating and PP-plain fabrics have good capacity of heat dissipation. Meanwhile the PP-plating fabric has the best capacity of quick-drying.

From the data charts 5.18 (c) and 5.18 (d), it can be observed that the skin temperature in the cases of plating and plain fabrics is lower than others since they are thin and have more heat dissipation by sweating evaporation. Whereas, the skin temperature in the cases of rib and tuck fabrics are higher than others. The core temperature is slightly different in these cases. The highest core temperature occurs in the case of 2x2 rib fabric.

From the data charts 5.18 (d) and 5.18 (e), it can be seen that both the thermal and moisture comfort during the cycling stage in these cases exceeded 70. The 2x2 rib fabric has the highest thermal comfort, and the plain fabric has the highest moisture comfort. That indicates all these five fabrics can achieve thermal and moisture comfort during cycling. The 2x2 rib fabric has the best thermal insulation, and the plain fabric has the best moisture management capability in these fabrics.

5.5.3 Fabric Selection for Thermal Functional Design

The simulation results discussed above may offer helpful implication for the thermal functional design of FCS. The different fabric with different thermal properties may influence the final thermal performance of the cycling sportswear and thermal comfort of the wearer.

Based on the simulation results, the fabrics with different thermal characteristics, such as MMF, water vapor permeability, air resistance, density, thickness and thermal conductivity, can be selected for the different thermal functional design to meet with the required thermal performance. Fig. 5.19 shows the fabric selection scheme for the thermal functional design of FCS. The detail is discussed as follows:

1) The design 1 is characterized as being good moisture management for quick drying. The fabrics with good MMF, such as the PP-plain fabric and other fabrics treated with MMF, can be selected to meet with the desired thermal functions.

2) The design 2 is characterized as being good moisture management for quick drying, good heat dissipation and breathable. The fabrics with good MMF, low air resistance and density, thin thickness and even inferior thermal conductivity, such as the PP-plain, PP-plating, PP-tuck and even PP-1x1 rib, can be adopted for this design.

3) The design 3 is characterized as being good moisture management for quick drying and having thermal insulation to keep muscle warm. The fabrics with good MMF, thicker thickness and superior thermal conductivity, such as the PP-tuck, PP-1x1 rib and PP-2x2 rib, can be concerned for this design.

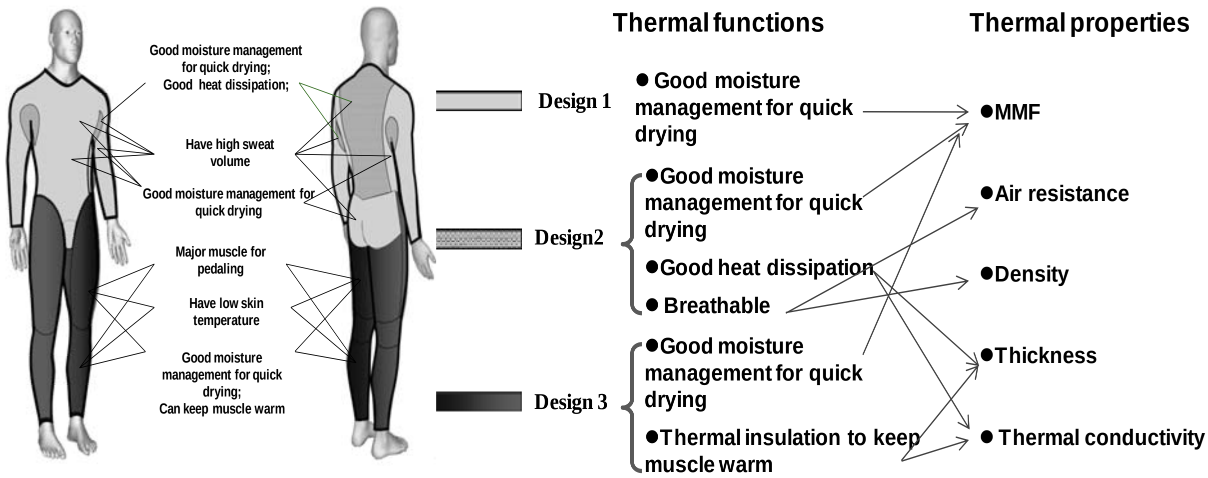


Fig. 5.19 Fabric selection scheme for thermal functional design

5.6 Conclusion

In this chapter, the thermal functional design of FCS has been performed and described. The thermal conditions during cycling are first investigated and analyzed in order to develop a scientific understanding of the thermal behaviours of the cycling sportswear wearing system. A cycling experiment is conducted to demonstrate the thermal biological characteristics of the body during cycling. A group of professional athletes employed in this experiment rode the bicycle according to a specified protocol in an indoor chamber. The thermal data, including the skin temperature, SCWC and TEWL, is collected and visualized. By analyzing this data, the thermal zones of the body are created and the thermal biological characteristics of the cyclists are described in detail. Subsequently, the thermal requirements for the thermal functional design of FCS are identified pertaining to each thermal zone. The thermal zones are then categorized into four areas according to their thermal characteristics. Based on these efforts, a thermal functional design scheme of FCS is developed to satisfy the thermal requirements. Furthermore, by measuring the thermal properties of fabrics and numerical design and simulation of the FCS designed with different fabrics, the indication of fabric selection for thermal functional design is described.

CHAPTER 6 BIOMECHANICAL FUNCTIONAL DESIGN OF CYCLING SPORTSWEAR

6.1 Introduction

Chapter 3 describes the multi-disciplinary framework for functional cycling sportswear (FCS) design. In addition to aesthetic and thermal functions, biomechanical functions have also been identified as a basic functional requirement of FCS. Ideally, FCS must be able to improve endurance and smooth action by offering biomechanical protection and enhancing muscle performance during cycling. After discussing the thermal functional design of FCS in Chapter 5, this chapter describes the biomechanical functional design.

With regard to the flow of the framework, the basic biomechanical mechanisms involved are first investigated and summarized. The biomechanical requirements for FCS are then identified by establishing the required knowledge, analyzing questionnaire data and creating biomechanical zones. The injuries in cycling are identified and the body parts covered by clothing that require injury prevention are determined. Accordingly, the biomechanical zones are further grouped according to the biomechanical features of muscles for functional design. Based on these efforts, the biomechanical functional design scheme is developed by adopting the compression concept. Finally, the mechanical properties of fabrics both for this study and from a commercial cycling sportswear are measured and compared, and the indication of the fabric selection for the biomechanical functional design is discussed based on the numerical simulation of compression effects of the fabrics.

6.2 Biomechanical Mechanism Analysis

6.2.1 Skeletal Muscles of the Human Body

The muscle is a contractile tissue able to produce force, which causes motion. When stimulated by nerve impulses, the muscle under a strong contraction can be reduced to about 60% of its relaxed length (Hamill, 1995). In the contracted state, the muscle becomes much thicker. The muscles in the body can be categorized in to three types, namely, skeletal, cardiac, and smooth (Edwards, 1981). Cardiac and smooth muscle contractions, such as the contraction of the heart and peristalsis of the digestive system, are necessary for survival and occur without conscious control. In contrast, skeletal muscles are under conscious control and also called voluntary muscles. Skeletal muscles are attached to bones and connected to joints to enable bodily movement. The human body has over 600 skeletal muscles, which accounts for approximately 40% of the body weight (Marieb, 2007).

The fundamental functional unit of skeletal muscle is the motor unit. Structurally, the skeletal muscle is composed of a motor nerve and muscle fibers, which are innervated by the motor nerve (Lawerence and Kakkar, 1980). Furthermore, each muscle fiber can be broken down into numerous myofibrils bundled together (Fig. 6.1). By activating the motor units, the muscle can generate a gradation of tension, and the frequency of activation decides muscle tension. Under tension, the muscle fibers at work are the proteinaceous structure called myofilaments, which mainly include actin, myosin, and troponin (Brooks et al., 1996). These filaments function similarly as a ratchet system analogous to a rock climber with a rope to provide the capacity to contract, as reviewed in Chapter 2. Muscle fibers generate tension by the action of actin and myosin, in which the muscle may lengthen, shorten, or remain the same under tension. Each muscle has an optimal resting length under tension. Both overstretching and under-stretching waste the full energy potential of the muscle (Allen et al., 1995).

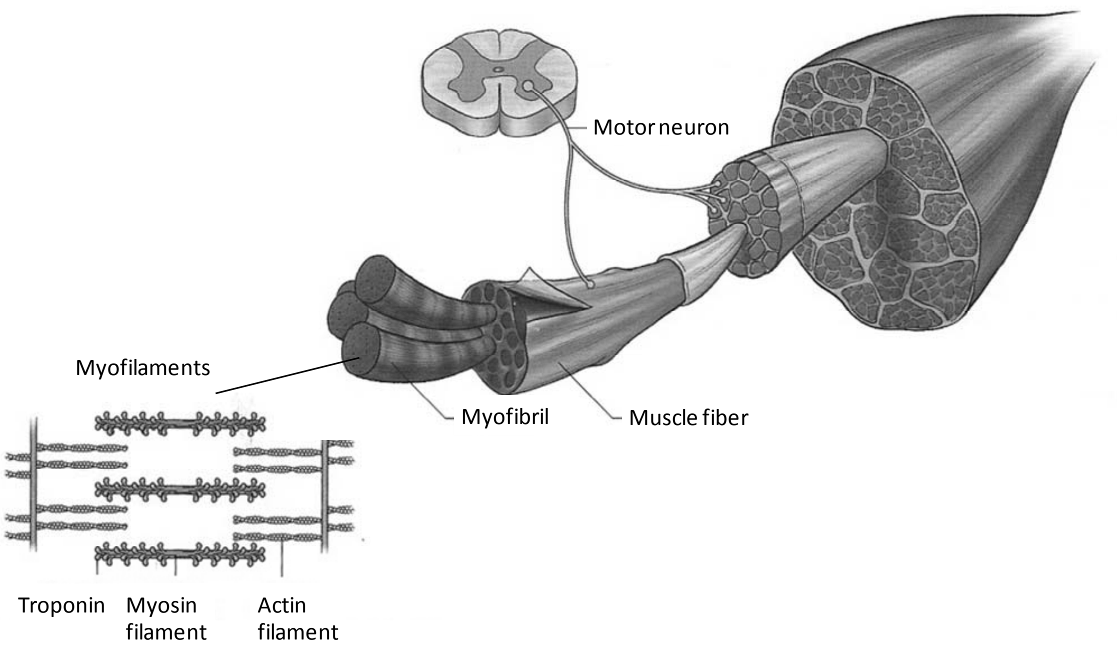


Fig. 6.1 Biological structure of a muscle fiber (Lawerence and Kakkar, 1980)

During cycling, the muscles cannot be stretched to the optimal length if the leg is not sufficiently stretched due to certain reasons. For instance, one group of muscles may be stretched to different lengths because of the angle. However, the muscles may be overstretched if the leg is overstretched for certain reasons, for example, when a seat is too high. Muscle overstretching may lead muscle fiber damage, which explains the occurrence of muscle injuries during cycling.

The muscles of the body are attached to the sides of bones in such a way that each muscle crosses over one or more joints. When receiving a nerve impulse, the muscle immediately contracts, and the attached joints also move with the muscle. Most joints alter their positions by working more than one muscle. For instance, the elbow joint is bent and straightened by the biceps brachii and tricep muscles, respectively (Ali et al., 2010).

Most skeletal muscles have Latin names that indicate some features of the muscle (Ali et al., 2010). Some examples include the size of muscles: vastus (huge), longus (long), maximus (large), and brevis (short); shape of muscles: deltoid (triangular), teres (round), latissimus (wide), and trapezius (four-sided); direction of muscle fibers: orbicularis (circular), rectus (straight), oblique (diagonally), and transverse (across); location of muscle: gluteus (bottom), pectoralis (chest), brachii (arm), and lateralis (lateral); number of origins: quadriceps (four heads), triceps (three heads), and biceps (two heads); as well as action of muscle: flexor (bend the joint), extensor (straighten the joint), levator (lifts a structure), and masseter (used in chewing).

The major muscle groups implement the main actions of the body. Fig. 6.2 shows the major skeletal muscle groups of the body from the anatomic view. The muscle groups of the body are mainly located on the head, chest, back, abdominals, leg, and arm. The functions of the major muscle groups are listed as follows (Lewis et al., 1976).

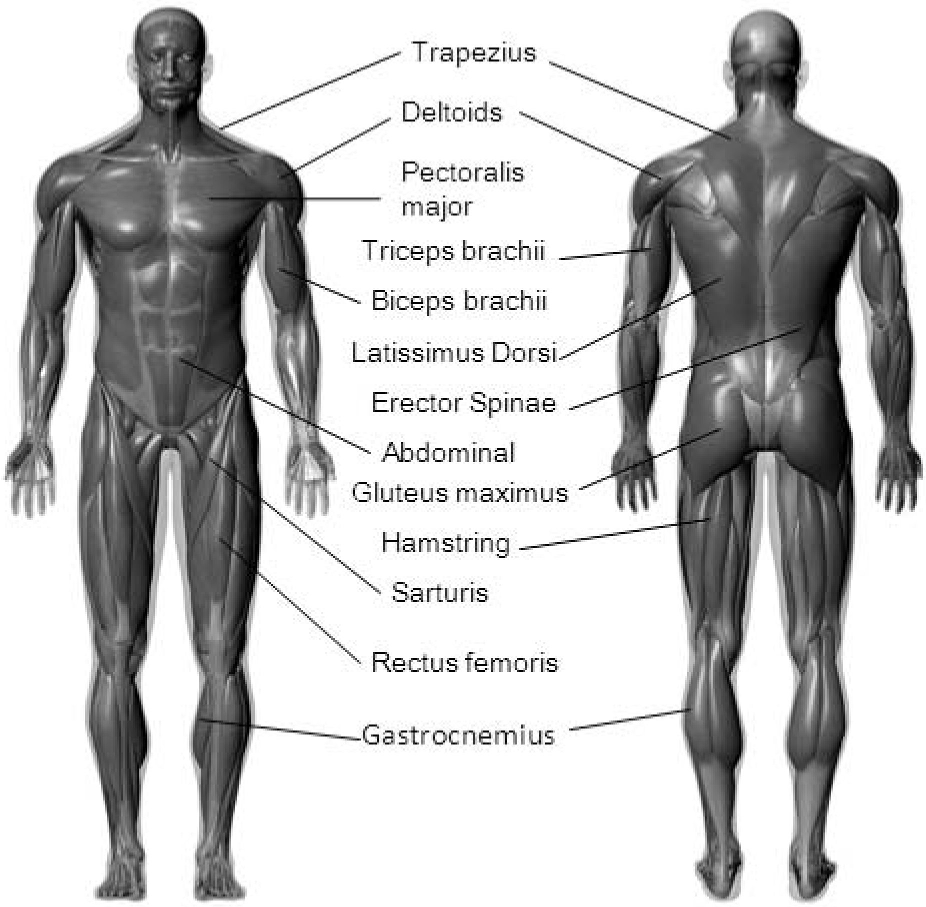


Fig. 6.2 Main muscle group of the human body

- Trapezius: located in the upper and mid-back, connects the head and shoulders, functions to move head sideways;
- Deltoids: located at the top of the shoulders, performs the functions of overhead lifting;
- Pectoralis major: located at the front of the upper chest, pulls the shoulders and arms forward;
- Triceps brachii: located at the back of the upper arm, pushes when extending the lower arm;
- Biceps brachii: located at the front of the upper arm, lifts when moving the hand toward the shoulder;
- Latissimus dorsi: located at the mid-back, functions in postural alignment, such as giving the back a "V" shape;
- Erector spinae: located at the low back, functions in postural alignment, such as back extensions;
- Abdominal: located at the stomach, functions in sitting and postural alignment;
- Gluteus maximus: located at the bottom, functions in walking and standing, also the largest muscle in the body;
- Hamstring: located at the back thigh, functions in walking;
- Sarturis: located at the front thigh, functions in climbing, walking, and standing;

- Rectus femoris: located at the middle front of the thigh
- Gastrocnemius: located at the back of the lower leg, pushes off for walking;

6.2.2 Muscle Fatigue and Injury

Muscle fatigue and injury are two common phenomena during exercise,, and influences the performance of the muscle to different degrees (Ali et al., 2010). There is a close link and even an overlap between these two phenomena; however, they should be distinguished from each other by investigating their mechanical basis.

Mechanisms of Muscle Fatigue

When a muscle is repeatedly used intensively, muscle fatigue is commonly observed as pain or weakness. Muscle fatigue is the reduction of the ability to produce a given force by muscular contractions or muscle power output, thus leading to a progressive decline in performance, which readily appears soon after the intense sport begins. This sustained muscle weakness may persist for several hours or even days following the exercise. Hence, fatigue is usually regarded as a reversible decline in performance. The mechanisms of muscle fatigue and potential consequences have been studied on different levels (Liu and Little, 2009; Marian, 1996; Reichman et al., 1967; Tetsuo et al., 2000). Regardless of the kind and nature of sport, muscle fatigue affects the strength, power, balance, speed, and endurance of athletes, and even cause muscle injury as a by-product.

In practice, most activities depend on the power output of the muscles involved. For a submaximal activity, the decline in performance is not immediately evident, and fatigue eventually manifests itself as being unable to keep the original intensity of the activity, which is often referred to as exhaustion. Sometimes, fatigue estimation is possible by interposing maximal muscle contraction (Wang, 2010). Alternatively, muscle fatigue can be graded by the ratio of the contraction time to the recovery time. This ratio is called duty cycle and is most noticeable during dynamic activities. In most cases, the duty cycle for each muscle is much less than 50% (Chatard et al., 2004).

The possible causes of muscle fatigue include muscle participation in an activity, particularly large muscle groups, for instance, in the cycling sport. Given that the contractile behaviour of muscles has multiple manifestations, the mechanism of fatigue is very complex. Until now, most studies have investigated various aspects of neuromuscular fatigue, which mainly focus on the mechanisms of intense contraction and repetitive action of muscles (Chatard et al., 2004; Liu et al., 2009; Marian, 1996).

Intense muscle contraction imposes a major strain on related physiological systems. To generate the high force levels needed to sustain the intense activity, all the muscles involved in coordination are required to retain maximal or near maximal activation. For instance, during cycling, seven different muscle groups work in a highly ordered activation pattern dependent on the riding position and action (Green and Patla, 1992). For the individual muscles, the maximal massive force that supports maximal activation requires the full use of all motor units that work at high firing frequencies (Chatard et al., 2004). From the view of the motor control system, excellent activation performance depends on precise temporal and spatial coordination, not only at the level of individual motor units within a muscle but also between groups of muscles (Lewis et al., 1976). Furthermore, in individual muscle cells, successful reaction to high firing frequencies lies in the contribution of the sarcolemma and T-tubule system, which regenerate action potentials to the interior of muscle cells at high frequencies.

Physiologists have reported that the sustenance of action potentials at high frequencies is significantly influenced by the capability to absorb potassium ions (K^+) into the cell from the interstice between cells and desorb the surplus sodium ions (Na^+) back to the interstitial space (Dossett-Mercer et al., 1994; Raz, 1993). The reestablishment of the electrochemical gradients is controlled by an electrogenic pump that restores both Na^+ and K^+ gradients across T-tubules by consuming energy in the form of ATP. Thus, the energy supply system must evidently keep regenerating ATP at a required level to prevent ATP reduction, and T-tubule membranes are then enabled to perform action potentials at high frequencies, which is required for the maximal activation of the muscle fiber.

If the intense activity is performed repeatedly, the strains on the muscular and physiological systems are greatly aggravated, especially when large muscle groups are involved. Accordingly, the exercise intensity is difficult to sustain beyond a relatively short period, and fatigue appears. Muscle cells are not able to generate action potentials on a repetitive basis at the frequency necessary for maximal or near maximal force generated by the muscle fiber. Moreover, Na^+ and K^+ gradients are difficult to restore before the next neural impulse. High-frequency fatigue may result in muscle injury invoked by repetitive and strong force generation, as well as muscle lengthening contraction.

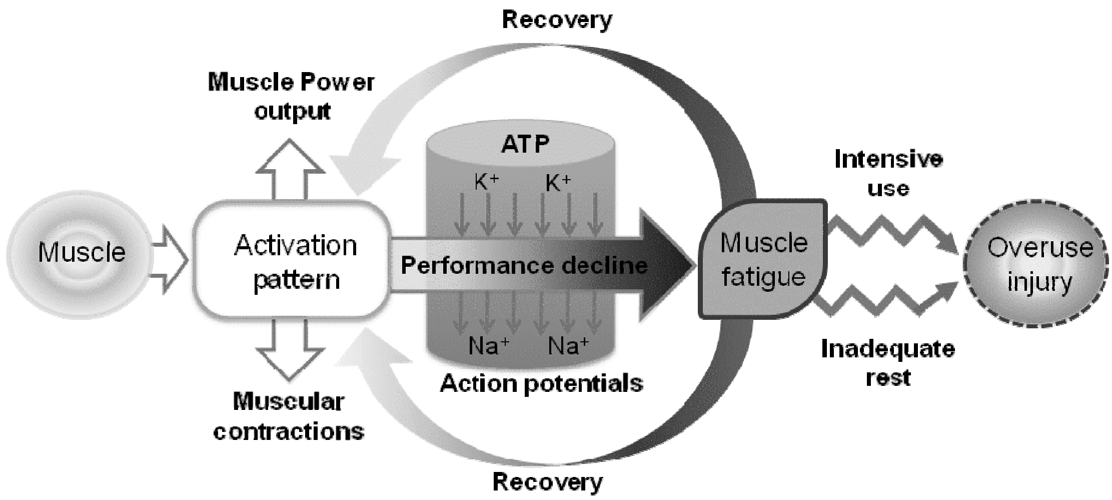


Fig. 6.3 Mechanisms of the process of muscle fatigue

The mechanism of muscle fatigue is illustrated in Fig. 6.3. The muscles, which work in a highly ordered activation pattern for force production by muscular contractions or muscle power output, may undergo a progressive decline in performance. During activity, the maximal force supporting activation requires action potential regeneration in muscle cells at high frequencies. However, this process depends on the electrochemical capability to absorb potassium ions (K^+) into the cell and desorb excess sodium ions (Na^+) out of the cell by consuming ATP energy. The ATP energy of muscles difficultly sustains such an electrochemical process for a long time by high consumption. Muscle fatigue may be recovered and the decline in performance is reversible. However, muscle fatigue may also result in overuse injury if the muscles continue to be used intensively without adequate rest.

Muscle fatigue is fairly predictable and recognizable, which benefits the identification of the limitation of the body in exercise and ensures that the muscles are safely used. Muscle fatigue is most often caused by exercise, and it indicates that the muscle requires rest. However, muscle injury is usually misidentified as simple fatigue, which can aggravate the injury.

Skeletal Muscle Injuries

Apart from muscle fatigue, muscle injury also causes a decline in performance but reverses very slowly. Skeletal muscle injuries are related to the stretching during muscle contraction, the type of contraction (eccentric rather than concentric), and the resting condition of the muscle. The characteristics of muscle injury are influenced by structural abnormalities, including sarcomeric disorder, inflammatory processes such as cytokine release and phagocytic cell penetration, as well as membrane damage resulting in the loss of soluble enzymes such as creatine kinase (Liu et al, 2009). The activation of satellite cells and regeneration of damaged fibers are mostly involved in the recovery from muscle injuries.

Injury or damage can occur on any muscle in the body, particularly the thigh and back muscles, which are the most commonly injured. Although various types of muscle injuries have been identified, they can mainly be categorized into strains, contusions, and detached injuries (Liu et al., 2009).

- ***Muscle strain***

Muscle strain is very common and usually occurs when muscle tissue is elongated with too much force or is activated during stretching. Failure to warm up sufficiently before the initialization of physical activities may result in this type of injury. Muscle strains can further be classified into mild, moderate, and severe. Mild strain occurs when the muscle is slightly pulled, but there is no muscle and tendon fiber tearing. Moderate strains involve fiber tearing and reduced strength. Severe strains involve full muscle tearing and possible need for surgical repair. Muscle strains or contraction-induced injuries account for up to 30% of all injuries.

- ***Muscle contusion***

Muscle contusions, also called bruises, refer to injuries causing damage to the muscle fiber, soft tissues, and small blood vessels, but not involving a break in the skin. Blood may leak from damaged blood vessels and flow into the adjacent soft tissue. Then black and blue phenomenon occurs and becomes visible beneath the skin surface. Blood also accumulates and blood clots form in the muscle. People can develop this muscle damage after a traumatic impact, for example, collision with an object that breaks the small blood vessels located in the muscle or group of muscles. Muscle contusion incidences are mostly high in contact sports such as football, hockey, and boxing.

- ***Muscle detachment injury (avulsion)***

Muscle detachment injuries refer to the muscle being torn or ripped away from an attached point (avulsions), and are usually caused by a strong force or overload. People with an immature skeletal system accompanied with stress fractures, overdeveloped muscles, or weakened bones are at high risk for this type of injury, which is most frequently seen in the groin and hamstring muscles.

- ***Exercise-induced injury***

Exercise-induced injuries occur when the stress imposed on a muscle and its attachments exceeds a tolerance limit. They are developed frequently after engagement in unaccustomed or excessive exercise that involves a large amount of eccentric contractions (i.e., simultaneous muscle contraction and lengthening).

6.2.3 Sport Injuries

Skeletal muscle injuries, including strains, contusions, and avulsions, which can stretch or tear the muscle tissue fibers or blood vessels, commonly occur in work or athletic settings. Skeletal muscles reportedly account for up to 55% of all sport-related injuries (Harste, 1980). Athletes are at a much higher risk for muscle injuries due to the overstretching of muscles, unexpected muscle contraction, as well as rapid and frequent change in speed or direction.

Specifically, with an increasing number of people participating in sports, the injuries that mostly occur in the muscles, tendons, ligaments, and joints need further scrutiny. Sport injuries not only present the problems that athletes have to contend with during treatment of the injured muscle tissue, but also their desire to be able play sports again as soon as possible. According to the occurrence of injuries, researchers broadly categorized sport injuries into two basic types: traumatic and overuse injuries (Harste, 1980). The category and structure of sports injuries are shown in Fig. 6.4. Muscle injuries, including muscle strain, contusion, avulsion, soft tissue injury, fracture, and sprain, are the main traumatic injuries. Muscle injury caused by fatigue, joint injury, and tendon injury are the main overuse injuries. These two types of sport injury are detailed as follows.

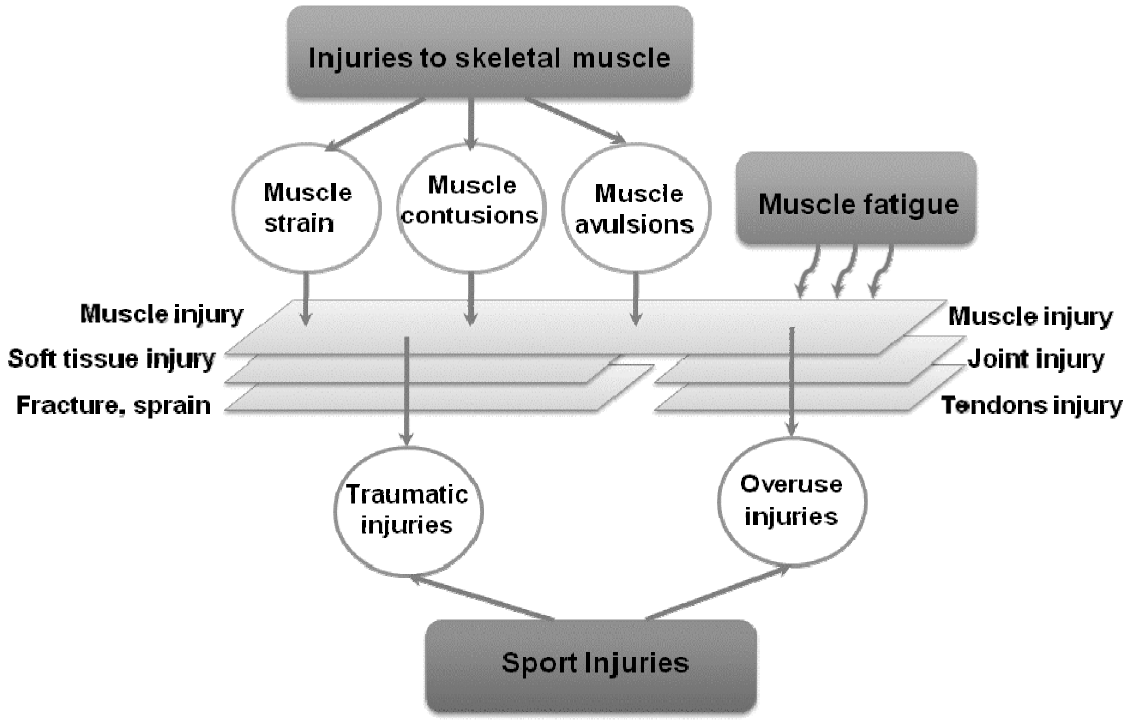


Fig. 6.4 Category and structure of sport injuries

Traumatic Injury

Traumatic injuries such as wrist fractures, shoulder dislocations, ankle sprains, and soft tissue injury strains usually occur during a traumatic event. The physiological aspects of such injuries include the following: A) a torn or strained muscle due to rapid overstretching; B) a bruised muscle due to a blow; and C) the acute compartment syndrome, which causes swelling within the muscle and pressure build-up. Complications from traumatic injuries include wound infections and blood clot formation within the muscle, which require surgical treatments.

Chronic Overuse Injury

Overuse muscle injuries may develop gradually and slowly when the same muscle or muscle group is used repeatedly or continual stress is imposed. They may also occur when the tendons, bones, and joints suffer from repeated micro-trauma. In most sports and exercises, overuse injuries are common because repetitive movements, especially those that involve a joint (e.g., tennis elbow, swimmer's shoulder, and cyclist's knee), are easy to harm muscles over time. The causes of overuse injuries may include training errors, improper technique, as well as anatomic and biomechanical factors such as an imbalance between strength and flexibility around some joints. The overuse of a muscle may cause its inflammation accompanied with swelling and pain, which further impairs tissue actions. Recovery from overuse injury requires rest and gradual resumption of training load.

Except for the aforementioned causes of overuse injury, the other general causes of sports injuries include lack of warm-up or recovery, physical weakness, prior injury, inadequate skill, lack of safety equipment, and inappropriate footwear or clothing. In many activities, there are rules governing the clothing quality to reduce the risk for injury. For instance, during gymnastic activity, protective clothing for the arms and legs are required to reduce the number of cuts, scratches, and insect bites. In general, each sport has its own set of expectations on the appropriateness and standard of sportswear for the general safety and well-being of participants.

6.2.4 Compression Garment

Compression garment, which was originally used in the medical field, is an important gear for athletes to reduce muscle fatigue and injury, as reviewed in Chapter 2. This garment enables rapid performance recovery during competition and training (Duffield et al., 2010). From a physiological perspective, compression garment mainly increases the venous blood flow in muscles, which positively affects the recovery process of venous thrombosis (Gandhi et al., 1984; O'Donnell et al., 1979). Compression garment also reduces blood lactate accumulation following exercise (Ibegbuna et al., 2003; Maton et al., 2006), reduces muscle oscillation and vibration, improves muscle contraction (Duffield et al., 2010), improves proprioception, as well as increases resistance to muscle fatigue (Anglais, 1967; Naokazu, 2010). The mechanisms of compression garment in improving muscle performance are illustrated in Fig. 6.5. These mechanisms are based on cycling anatomy knowledge, including muscle contraction and muscle action during cycling (Shannon, 2009).

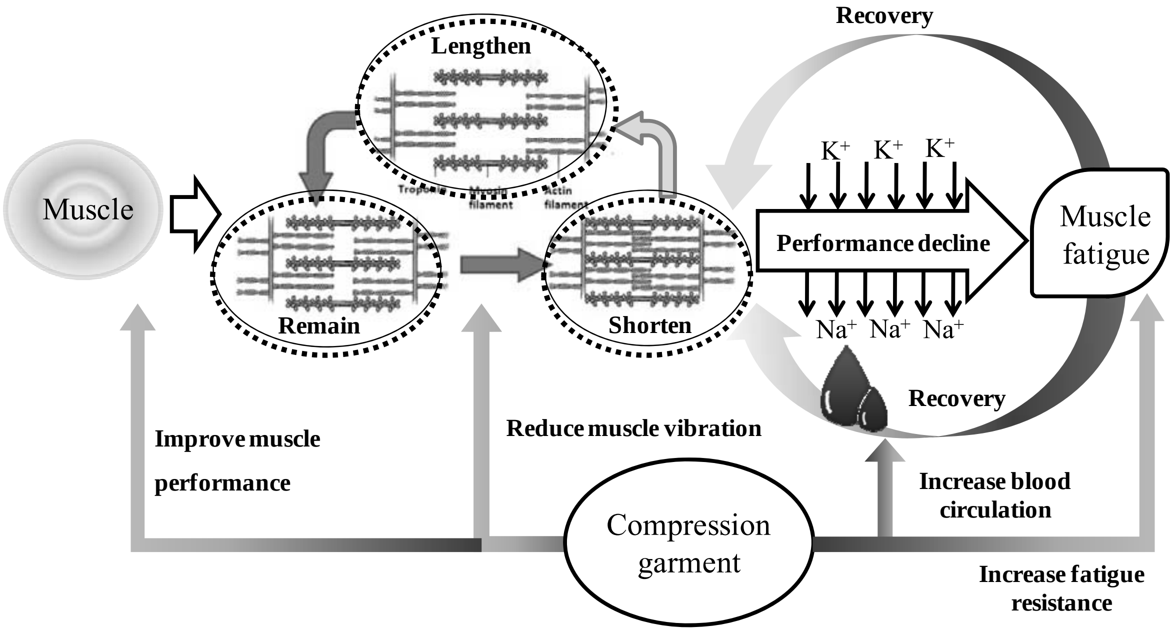


Fig. 6.5 Mechanism of compression garment

These findings of the positive functions of compression garment on muscle performance have led to its wide adoption in the design of functional sportswear (Sipes et al., 2011). However, too high pressure exerted by the compression garment can also cause negative effects. For example, very strong compression may restrict the number of venous capillaries within the muscle, and tightness at the knee especially during dynamic movement may cause an uncomfortable feeling (Naokazu, 2010). On the other hand, insufficient pressure cannot effectively support target muscles (Hackney, 2006). Therefore, different levels of compression need to be considered for different muscles according to their biomechanical characteristics. The European Committee for Standardization (CEN) has published a pressure standard defining different compression classes from anti-embolic stockings (AES) to class IV (CEN, 2001), as shown in Table 6.1. Most compression garments designed for athletes usually consider light or mild pressure levels with one fabric layer (Elliot, 2007). Ali et al. (2010) has reported that most athletes favor low-grade compression garment (4–12 mmHg) for the upper body, whereas the lower body may feel discomfort if the compression is above 32 mmHg.

Compress ion class	CEN (mm Hg)	Indications for effects
AES	10-14 (light)	Prevent blood clots during traveling and relieve discomfort from achy legs
Class I	15-21 (mild)	Relieve heaviness and fatigue, mild varicosities and Initial varicose during pregnancy
Class II	23-32 (moderate)	Relieve fatigue, post sclerotherapy, prophylaxis of thrombosis, oedema
Class III	34-46 (strong)	Lymphoedema, severe chronic venous insufficiency
Class IV	> 49 (very strong)	Primary and secondary Lymphoedema, elephantiasis and venous ulcers

Table 6.1 CEN standard of pressure with different classes (CEN, 2001)

According the discussion above, the FCS design can adopt the concept of compression garment to reduce muscle fatigue and injuries, as well as improve muscle performance during cycling. To achieve the desirable compression effect, different levels of compression should be considered for different muscles.

6.2.5 Summary

In this section, the biomechanical mechanism has been investigated in terms of skeletal muscles, muscle fatigue and injuries, sport injuries, and compression garment to lay the basic theoretical fundamentals for the FCS biomechanical design. The main skeletal muscles of the body and their individual functions have been reviewed. Muscle fatigue is manifested as a progressive decline in muscle performance, which is reversible but dependent on the electrochemical ability of the body. However, muscle fatigue may also result in overuse injury with inadequate rest. The muscle injuries mainly consist of sport injuries. According to the occurrence of injuries, sport injuries are generally categorized as traumatic and overuse injuries. Compression garment positively affects muscle fatigue and injury reduction, as well as muscle performance improvement. Thus, the FCS design can adopt the concept of compression garment to improve muscle performance during cycling. Different levels of compression should be considered for different muscles for desirable compression effects.

6.3 Biomechanical Functional Requirements Identification

Based on the review of the studies on the mechanisms of skeletal muscle structure, muscle fatigue and injuries, as well as sport injuries in the above section, the anatomy analysis of cycling for cycling sportswear functional design is discussed in this section. The questionnaire results for the detailed biomechanical needs of body parts in cycling are further analyzed. Accordingly, the biomechanical requirements for FCS design are developed by creating the biomechanical zones to illustrate the muscle groups involved and biomechanical features of all different body parts.

6.3.1 Cycling Anatomy Analysis

Classic Research on Muscle Group Recruitment in Cycling

Physiologically, the skeletal muscle system supplies the structural foundation of the entire kinetic system working in coordination to complete the cycling action. During cycling, an obligatory power needs to be imposed to the pedals to overcome the friction between the wheel and ground, as well as the friction caused by airflow facing the cyclists during high-speed cycling. To understand how the muscles contribute to generate the required power for cycling, some classic research have been conducted on muscle involvement or recruitment pattern in cycling activity (Bentley et al., 2000; Raymond et al., 2005; Shannon, 2009).

During cycling, both arms, both legs, and the bottom are the major body parts in contact with the bicycle, which act to maintain the stability and direction of the bicycle. In addition, most of the major skeletal muscle groups of the body are attended to and utilized during cycling (Raymond et al., 2005; Shannon, 2009). Raymond et al. (2005) has illustrated a crank cycle of cycling, which was divided into three phases, namely, power, pulling, and pushing.

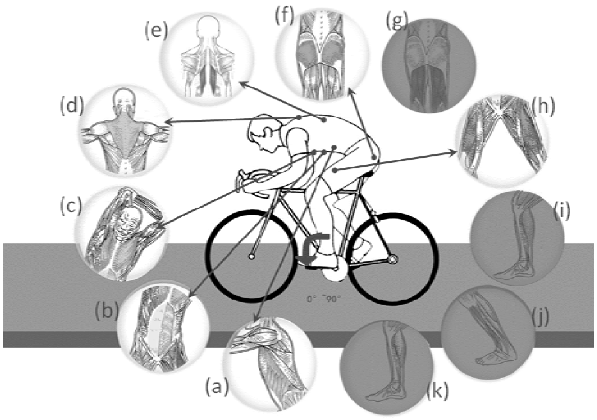
As reviewed in Chapter 2, Schmidt (1994), a sophisticated cycling coach, has described muscle recruitment during cycling. He has pointed out that the quadriceps, which propels the pedals through the hip flexors, is the most important muscle during cycling. The muscles on the lower leg push the pedaling motion forward. The calf muscles are active throughout the entire pedaling cycle, whereas the anterior tibial compartments fix the foot and pull back the pedals. All the muscles in the low limbs generate maximum force to perform pedaling by sequential concerted contraction. Also, all the involved muscles in the leg and hip transmit the power from top to bottom during the actions of pushing, pressing, and pulling. The trunk and arm muscles counterbalance each other during the pedaling motion. The muscles in the hands, arms, shoulders, back, and abdomen form a muscular sling for supporting the movement of the trunk and pelvis.

Gregor et al. (1986) have reported on the activity pattern of eight muscles in the lower limbs. They have pointed out that six muscles, namely, vastus lateralis, vastus medialis, and rectus femoris in the quadriceps femoris group, as well as biceps femoris, tibialis anterior, and gluteus maximus, are intensively utilized during the first half of the power phase. Then, the hamstrings, gluteus maximus, and gastrocnemius continue their actions until the end of the power phase. Ryan and Gregor (1992) has also reported that lateral vasti muscles exhibit a relatively constant activity in the power phase. The summary of the activity patterns of these muscles during pedaling has been presented in Table 2.1.

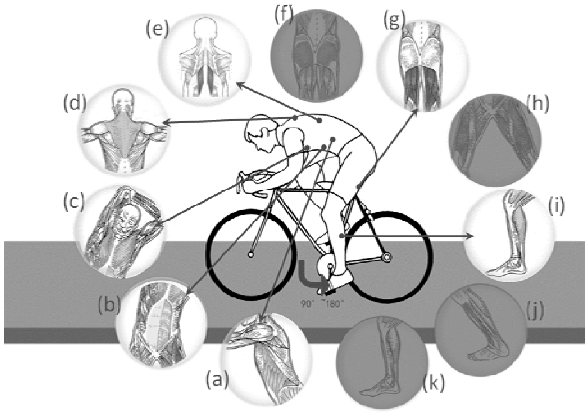
Illustration of Muscle Group Recruitment in Cycling for FCS Design

A classic description of the muscle pattern recruitment during cycling has been presented above. Accordingly, the muscle groups involved in the cycling action can be further elaborated and illustrated with regard to every quarter cycle to develop the biomechanical requirements for FCS design scientifically.

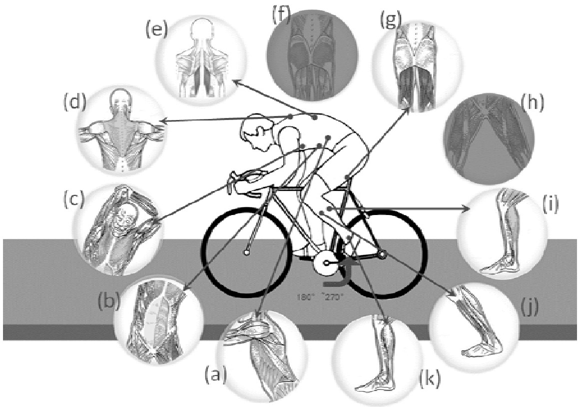
Fig. 6.6 illustrates the muscles of the body involved in a cycle of cycling action from 0°–360°. As illustrated in Fig. 6.6, the active muscles in the upper limbs (abdomen, chest, and back), including abdominal obliques, rectus abdominis, pectoralis major and minor groups, trapezius, as well as erector spinae, are involved in the entire cycle. However, the muscles in the low limbs have different performances in the individual quarter cycles. In the first 90° of the cycling action, namely, from top center to a crank position parallel to the ground, the quadriceps femoris group and gluteus maximus work heavily. From 90 to 180°, the gastrocnemius and hamstrings are more active. In the upswing of the cycle, namely form 180° to 270°, the main working muscles include the hamstrings, gastrocnemius, tibialis anterior, and flexor digitorum longus. In the last phase of the cycle, namely from 270° to 360° (top center), the main working muscles include the quadriceps femoris and tibialis anterior. The statistical summary of muscle groups involved in the four quarter cycles is shown in Table 6.2.



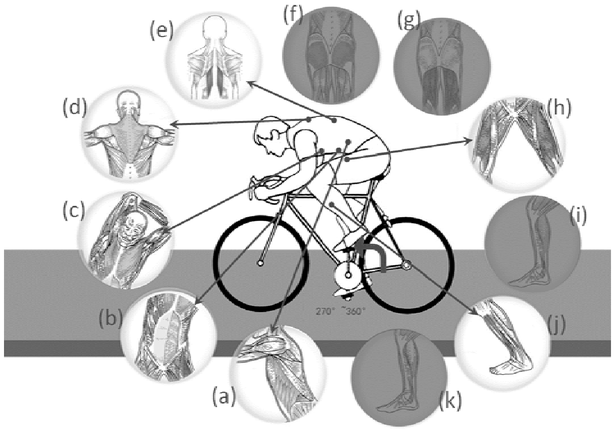
a) 0°~90°



b) 90°~180°



c) 180°~270°



d) 270°~360°

Fig. 6.6 Major muscle groups in each quarter during one cycle of cycling action

Muscle	Muscle name	0°~90°	90°~180°	180°~270°	270°~360°
(a)	abdominal obliques	Yes	Yes	Yes	Yes
(b)	rectus abdominis	Yes	Yes	Yes	Yes
(c)	pectoralis major	Yes	Yes	Yes	Yes
(d)	trapezius	Yes	Yes	Yes	Yes
(e)	erector spinae	Yes	Yes	Yes	Yes
(f)	gluteus maximus	Yes	No	No	No

(g)	hamstrings	No	Yes	Yes	No
(h)	quadriceps femoris group	Yes	No	No	Yes
(i)	gastrocnemius	No	Yes	Yes	No
(j)	tibialis anterior	No	No	Yes	Yes
(k)	flexor digitorum longus	No	No	Yes	No

Table 6.2 Muscle groups involved in the four quarter cycles

Due to the fact that the trunk and upper limbs work comparatively statically during cycling, these body parts more easily feel fatigue during long-duration exercise, especially in a race. The pedaling action by the lower limbs is the key point in driving the bicycle forward and achieving a high speed. The cooperative contractions of the muscles in the lower limbs are essential for cyclists to generate the maximum power output. Information regarding muscle group recruitment in cycling provides a fundamental basis for FCS design, which requires distinguishing the muscles in different body segments to achieve the optimal biomechanical functions of cycling sportswear.

6.3.2 Cycling Injuries

Cycling is usually performed on roads, paths, tracks, or in the countryside. Cycling event distances greatly vary, ranging from relatively short sprints to long-distance events such as the Tour de France. Cyclists can suffer from a number of cycling injuries, including the traumatic and overuse types. In general, common cycling injuries may occur on the knee, shoulder, hip, foot, ankle, neck, back, hand, eye, hand, and wrist. Fractures and abrasions can also occur.

Most traumatic cycling injuries are caused by falls; some are caused by collisions with other cyclists or motor vehicles. Another cause is torn or strained muscle caused by rapid overstretching. Obstructions or debris on the road are also cited as causes in some cases. The thigh, hip, and lower leg can experience abrasions or fractures in this type of injury. A simulation model of a cyclist created by Tetsuo has paid special attention to the horizontality of the shoulders of a bicyclist. Simulation results reveal that when the body loses balance and falls, the shoulder are the first to be injured, followed by the hip due to its easy collision with the ground (Tetsuo et al., 2000). To minimize the risk for this type of injury, the bicycle and safety equipment are usually carefully prepared. Other cycling gear can also help reduce the severity of abrasions when falling.

Overuse injuries, especially in the knee and back, are mostly due to the repetitive pedaling action (Harste, 1980). The causes of such injuries also include maintaining the same posture for a long time, inappropriate pedaling action due to poor bicycle setup (such as addle height and handlebar position), and anatomical weakness. A specific factor affecting knee pain may be cold and wet weather, which can chill the exposed knees during rapid movement. Considering the basic bent-over position during cycling, the erector spinae, latissimus dorsi, and trapezius muscle are flattened back. Consequently, the back is easily overused, and therefore, protection is a key concern.

As reviewed in Chapter 2, Yang and Yao (1999) has also pointed out that most muscle injuries during cycling occur in body parts covered by clothing. The muscles involved in the pedaling action are also prone to injuries. Considering the body parts covered by clothing, the knee, shoulder, back, and hip are the key parts that need essential special designs for injury prevention.

6.3.3 Biomechanical Needs Identification via Questionnaire Analysis

General descriptions of possible cycling injuries have been given above. However, they only refer to the representative body parts prone to develop injuries. There is no detailed explanation about the extent of fatigue and injury for each body part. This situation confers some difficulties in the FCS design for understanding the precise biomechanical needs of all body parts. The designers cannot know where to start and how to reduce injury and fatigue by adopting a functional design.

To determine the detailed design preference and need of all body parts for the FCS design, the questionnaire (Part III) reported in Chapter 3 identifies the biomechanical needs of body parts for FCS design. The questions related to the biomechanical need in this part include ‘the body parts easy to have fatigue and influence on cycling performance during cycling’ (question 8), and ‘the body parts that need special protection from injury during cycling in the cycling sportswear design’ (question 9). These questions involve nine main body parts, namely, shoulder, arm, back, abdomen, waist, bottom, thigh, knee, and calf. The respondents were asked to rate from 1 to 5 (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree) their satisfaction level on these items.

Body Parts Easily Fatigued during Cycling

The question of ‘the body parts easy to have fatigue and influence on cycling performance during cycling’ (question 8) in the questionnaire aims to determine the differences among body parts in terms of the biomechanical prevention need of fatigue, which may influence muscle performance and result in overuse injury without sufficient rest.

There were 68 valid questionnaires analyzed. Fig. 6.7 shows the mean values of the ratings of professional cyclists on the fatigue levels of the nine main body parts. The chart shows that the body parts individually prone to easy fatigability, in descending order of importance, are as follows: back, thigh, knee, bottom, calf, shoulder, arm, waist, and abdomen. The back part has the highest fatigue level in the upper limb, and the thigh part has the highest fatigue level in the lower limb. Furthermore, the average rating of the body parts in the lower limb is higher than that of the body parts in the upper limb, which means that the lower limb of the body is much more easily fatigued during cycling.

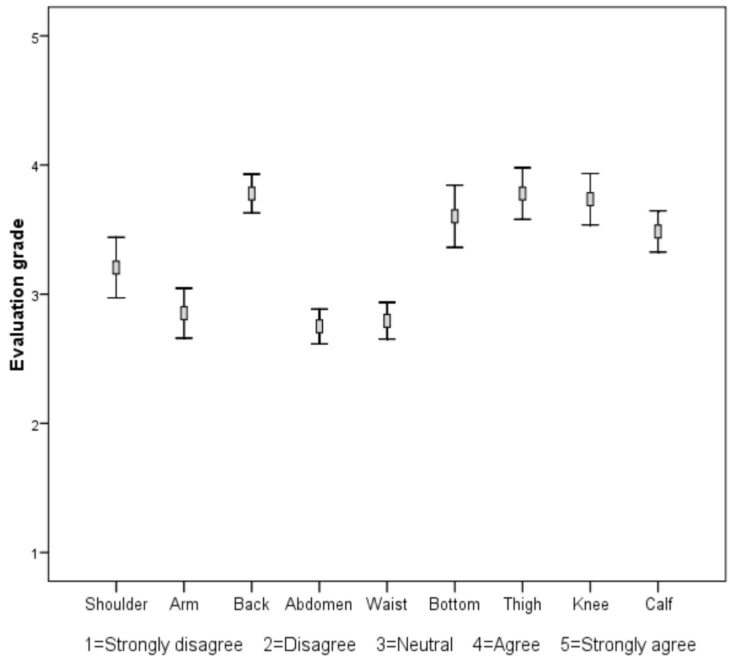
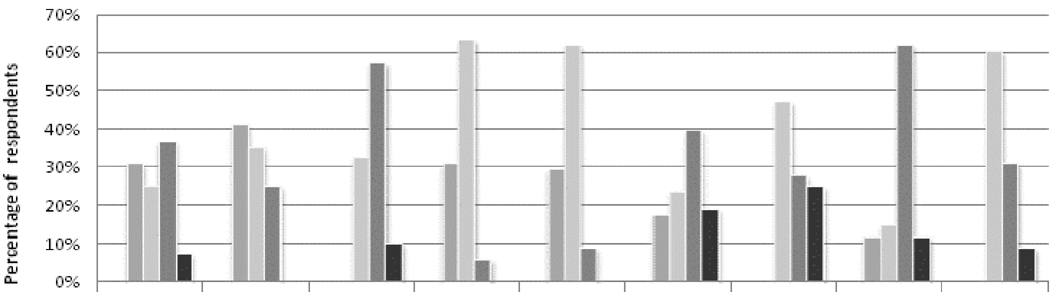


Fig. 6.7 Average rating on body parts easily fatigued and exert influence during cycling

Fig. 6.8 shows a statistical analysis of the percentage of respondents in the rating evaluation, which also supports the trends illustrated in Fig. 6.7. The percentages of respondents who gave a satisfactory rating at each level pertaining to each body part are summarized. From this chart, the number of respondents who agreed with the stratification level of fatigue for individual body parts is easily observed, thereby providing a more direct understanding of the fatigue level of each body part. In the thigh and bottom, 25% and 19% respondents graded the fatigue level with 'strongly agree', respectively. In the back and knee, 57% and 61% respondents graded the fatigue level with 'agree', respectively. The calf was also graded with 'strongly agree' and 'agree' by 39% respondents. There was no 'disagree' rating. These results also agree with the report of Wilber et al. (1995) that the most common sites of overuse injury are the knee and thigh. They also agree with the survey results of Yang and Yao (1999) that most injured muscles during cycling are those involved in the pedaling action and located in body parts covered by clothing.



	Shoulder	Arm	Back	Abdomen	Waist	Bottom	Thigh	Knee	Calf
1=strongly disagree	0%	0%	0%	0%	0%	0%	0%	0%	0%
2=disagree	30.9%	41.2%	0%	30.9%	29.4%	17.6%	0%	11.8%	0%
3=neutral	25.0%	35.3%	32.4%	63.2%	61.8%	23.5%	47.1%	14.7%	60.3%
4=agree	36.8%	25.0%	57.4%	5.9%	8.8%	39.7%	27.9%	61.8%	30.9%
5=strongly agree	7.4%	0%	10.3%	0%	0%	19.1%	25.0%	11.8%	8.8%

Fig. 6.8 Statistical rating on the body parts easily fatigued and exerts influence in cycling

In summary, the analysis of the questionnaire survey reveals that the lower limb is much more easily fatigued than the upper limb during cycling. The knee, back, thigh, calf, and bottom are recognized as the most prone to fatigability.

Body Parts Needing Special Protection from Injury during Cycling

The question of 'the body parts need special protection from injury during cycling in cycling sportswear design' (question 9) in the questionnaire aims to determine the differences among body parts in terms of the biomechanical need for preventing injuries, which may include traumatic and overuse injuries. Yang and Yao (1999) reveals 12 types of traumatic injuries and 7 types of overuse injuries, and most occur in the area covered by clothing.

Similarly, 68 valid questionnaire samples reveal the mean values of the ratings of professional cyclists on the injury prevention level of the nine main body parts, as illustrated in Fig. 6.9. The body parts needing priority individual injury prevention individually are knee, shoulder, thigh, waist, bottom, calf, back, abdomen, and arm. In these body parts, the knee, shoulder, thigh, and bottom need a higher level of injury prevention. This finding agrees with those reported by previous researchers. For instance, Tetsuo et al. (2000) has indicated that the shoulders of bicyclists are the first to be injured, followed by the bottom due to collision with the ground when the body losses balance and falls. This phenomenon explains why the shoulder and bottom injuries are the greatest traumatic injuries. Holmes et al. (1994) has explained that knee pain is the most common lower extremity overuse problem of cyclists. Yang and Yao (1999) reveals that the waist, shoulder, knee, and thigh body have higher injury frequencies than other body parts.

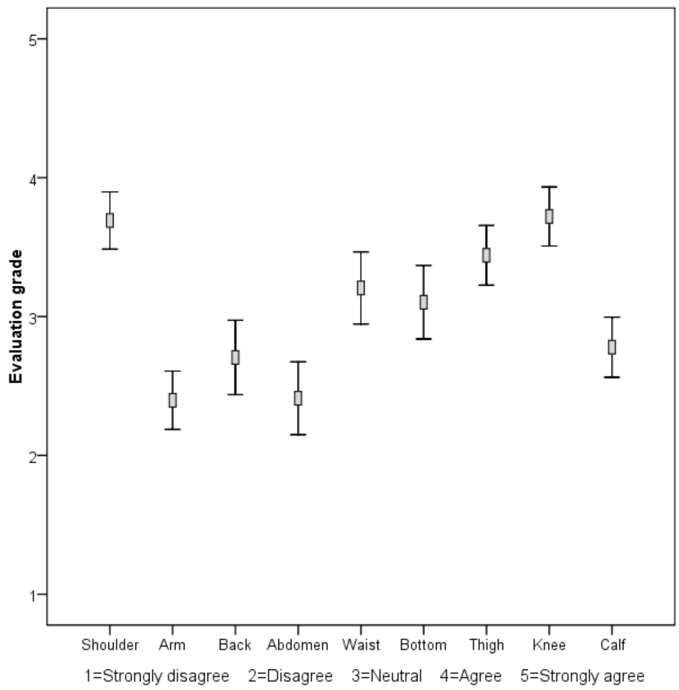
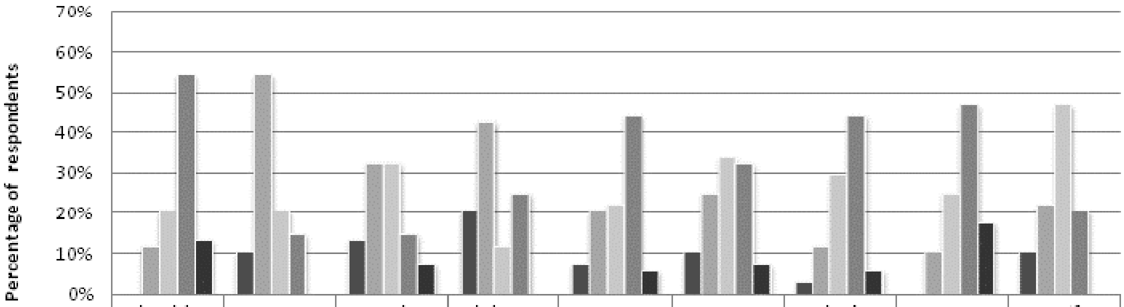


Fig. 6.9 Average rating on the body parts needing special protection from injury

Fig. 6.10 shows the percentage of respondents who graded the body parts needing special protection from injury in FCS design on each satisfaction level. Most respondents graded the knee, shoulder, thigh, and waist as needing special protection from injury in FCS design with ‘agree’ or ‘strongly agree’. The lower limb (bottom, thigh, knee, and calf) involved in the pedaling action were agreed upon by most respondents as needing the biomechanical requirement of injury prevention for FCS design.

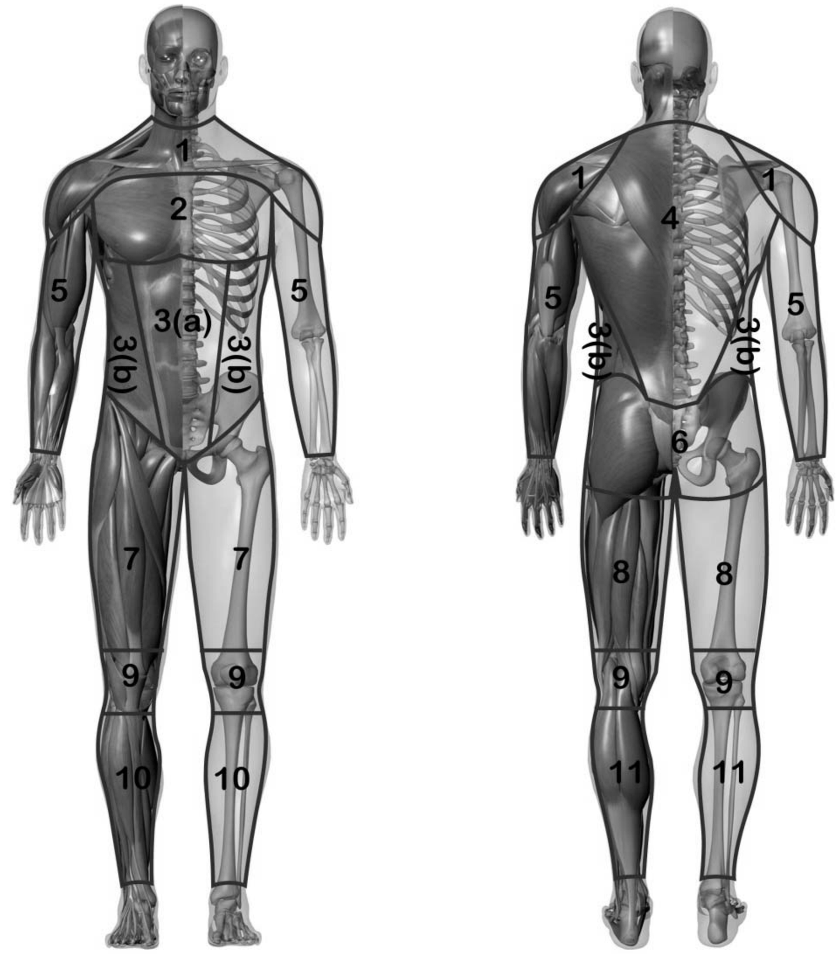


	Shoulder	Arm	Back	Abdomen	Waist	Bottom	Thigh	Knee	Calf
1=strongly disagree	0%	10.3%	13.2%	20.6%	7.4%	10.3%	2.9%	0%	10.3%
2=disagree	11.8%	54.4%	32.4%	42.6%	20.6%	25.0%	11.8%	10.3%	22.1%
3=neutral	20.6%	20.6%	32.4%	11.8%	22.1%	33.8%	29.4%	25.0%	47.1%
4=agree	54.4%	14.7%	14.7%	25.0%	44.1%	32.4%	44.1%	47.1%	20.6%
5=strongly agree	13.2%	0%	7.4%	0.0%	5.9%	7.4%	5.9%	17.6%	0%

Fig. 6.10 Statistical grade on body parts needing special protection from injury in cycling

6.3.4 Creation of Biomechanical Zones

The basic segmentation of the body for distinguishing physiological features on different body parts has been proposed by Huizenga et al. (2001). However, there is still no segmentation of the body considering its biomechanical features. To facilitate the identification of the biomechanical requirements of cyclists, biomechanical zones need to be created. In these zones, the biomechanical features of muscle fatigue and injury prevention related to each body part are considered.



Front body	Back body

Fig. 6.11 Biomechanical zones of cyclists

Fig. 6.11 shows the biomechanical zones of cyclists. There are 11 zones in the human body, namely, shoulders (No. 1), chest (No. 2), rectus abdominis (No. 3(a)) and abdominal obliques (No. 3(b), waist), back (No. 4), arms (No. 5), bottom (No. 6), front thigh (No. 7), back thigh (No. 8), knees (No. 9), front legs (No. 10), and calf (No. 11). The muscle groups involved in the cycling action can be further marked according to each biomechanical zone, as shown in Table 6.3. Numbers 3 (a) and 3 (b) belong to the same muscle group in the waist. On the other hand, No. 7 and No.8 belong to different muscle groups in the thigh. Furthermore, to achieve physiologically robust prevention and recovery, all muscles are imposed with different compression levels according to the dynamic optimal range reported by previous researches, which offers a quantitative reference for the biomechanical design of FCS. The lower body parts may be imposed with greater pressure than the upper body parts. However, the compression imposed on the knee is comparatively lower because intense tightness at the knee may cause great discomfort (Naokazu et al., 2010).

Muscle name	**Biomechanical zone**	
Deltoid	(No.1)	Shoulder
Pectoralis major	(No. 2)	Chest
Abdominal obliques	(No.3(b))	Abdomen
Rectus abdominis (waist)	(No.3(a))	
Trapezius	(No. 4)	Back
Erector spinae		
Triceps & biceps group	(No.5)	Arm
Gluteus maximus	(No.6)	Bottom
Quadriceps femoris group	(No. 7)	Front thigh
Hamstrings	(No.8)	Back thigh
Knee meniscus	(No.9)	Knee
Tibialis anterior	(No.10)	Front leg
flexor digitorum longus		
gastrocnemius	(No.11)	Calf

As to the upper limb during cycling, the shoulder (No. 1), arm (No. 5), abdomen (No. 3), and back (No. 4) rhythmically move back and forth to support the trunk and pelvis. When the cyclists hold the handlebars, the biceps, triceps, and forearm muscles work in unison to stabilize the body via the shoulder joint. The arms (No. 5) provide support to counteract the force exerted by leg extension. In the riding position, the shoulders (No. 1) of the cyclists are constantly under pressure. The muscle groups in the shoulder, including the deltoid, rhomboid, and rotator cuff, help maintain proper stability and position. The chest (No. 2) supports and balances the musculature of the back and shoulders. The pectoralis major and minor on the chest allow the cyclist to bend forward on the bike and move the handlebars from side to side while climbing. In the basic bent-over position of the cyclist on a bicycle, the muscle groups on the back (No. 4), including the erector spinae, latissimus dorsi, and trapezius, flatten back to provide better aerodynamics. The rectus abdominis (No. 3(a)) and abdominal obliques (No. 3(b)) provide lateral and anterior support to the trunk and counter the action of back muscles. Cyclists bear spinal stress and feel pain if the back, anterior, or lateral muscles are not as strong as the other muscles. Therefore, pain from back fatigue may not be caused by weak back muscles, but a lack of conditioning of the abdominal muscles (No.3). Hence, No. 3 and No. 4 zones should be considered as a group when designing cycling sportswear.

The lower limbs provide the main power for the riding action during cycling. The extensor muscle group in the knees (No. 9) is the prime muscle group that generates energy to the crank in the downstroke phase of cycling. The risk for injury to the knee is increased because the knee extensor muscles are usually emphasized in muscle training to improve race performance. Hence, the knee (No. 9) is an important zone that requires strengthened care in FCS design. From 0° to 180° in the cycling action, the muscles of the quadriceps femoris group (No. 7), gluteus maximus (No. 6), hamstrings (No. 8), and gastrocnemius (No. 11) are more active in the propulsive and power phases of cycling. Therefore, the zones of No. 6 (bottom), No. 7 (front thigh), No. 8 (back thigh), and No. 11 (calf) should be considered as a group when design functional cycling sportswear. In the upswing of the cycle (180°–360°), namely, the pulling and recovery phases, the more active muscles include the hamstrings (No. 8), flexor digitorum longus (No. 10), quadriceps femoris group (No. 7), tibialis anterior (No. 10), and gastrocnemius (no. 11) (Hamill, 1995). The difference from the muscles in the 0° to 180° cycle is the lack of no. 9 (bottom) and the presence of No. 7 (front leg), meaning that No. 6 (bottom) and No. 10 (front leg) should be regarded as individual parts for functional design. These zones with detailed muscle group information are essential to be taken into account in FCS design.

6.3.5 Biomechanical Functional Requirements

From the above discussion on the cycling anatomy, injuries in cycling, and the biomechanical need of the body for FCS design via questionnaire analysis, the biomechanical requirements of FCS design can be summarized based on the created biomechanical zones as follows:

1) The zones in the upper limbs, including the shoulder (No. 1), chest (No. 2), rectus abdominis (No. 3(a)) and waist (No. 3(b)), back (No. 4), and arm (No. 5) are the main active muscles in the upper limbs during cycling. They should be taken into account in the design of FCS. To provide the best possible biomechanical protection for cyclists, the material and structure of the garment should be able to offer more supporting force, which can help reduce the fatigue generated on the waist and back parts during a lengthy bent position, and protect the shoulders from traumatic injury.

2) The zones of the rectus abdominis and abdominal obliques (waist; No. 3) and back (No. 4) should be considered as a group in FCS design to reduce pain experienced from fatigue.

3) The zones of the bottom (No. 6), front thigh (No. 7), back thigh (No. 8), knee (No. 9), front leg (No. 10), and calf (No.11) are located in the lower limbs. They are the main active muscles involved in the riding action during cycling. They generate supportive force to perform pedaling by muscle stretching at a high frequency. Thus, these muscle groups need to be protected from fatigue or injury caused by inappropriate muscle movement for better cycling performance, especially for the zones of No. 7 to No.9.

4) The zones of the front thigh (No. 7), back thigh (No. 8), and calf (No. 11) work together during the entire cycle of cycling action. They should be considered as a group

in FCS design. However, No. 6 (bottom) and No. 10 (front leg) should be regarded as individual parts in FCS design.

6.3.6 Summary

In this section, the anatomical analysis of cycling for effective FCS design is first discussed based on a review of studies on classic research muscle group recruitment in cycling. The muscles in the upper limbs work comparatively statically during cycling and are more prone to experience fatigue. On the other hand, the muscles in the lower limbs are the key points in riding the bicycle. Their cooperative contraction is essential for cyclists to generate the maximum power output. Cycling injuries include both the traumatic and overuse types. These injuries commonly occur in the knees, shoulders, back, thighs, and hips. To obtain detailed information about the extent of fatigue and injury for each body part for FCS design, the questionnaire survey results are analyzed. The lower limbs are found to be more easily fatigued than the upper limbs during cycling. Moreover, the knees, back, thighs, calves, and bottom are recognized as the parts most prone to experience fatigue. The knee, shoulder, thigh, and waist are mostly agreed to need special prevention from injuries in FCS design. Finally, there are 11 biomechanical zones created to illustrate the muscle groups involved and the biomechanical features of all different body parts. The biomechanical requirements have been identified regarding each zone.

6.4 Biomechanical Functional Design Scheme

In the above sections, the biomechanical functional requirements have been investigated and identified for the design scheme to meet desirable functions. In this section, the detailed scheme of the biomechanical functional design of FCS is reported.

Biomechanical functional requirements have been identified as some of the basic functional requirements of FCS design, as discussed in Chapter 3 via questionnaire analysis.Accordingly, 11 biomechanical zones have been created to mark the muscle groups involved in the cycling action. The biomechanical characteristics and their differences are also discussed in detail.

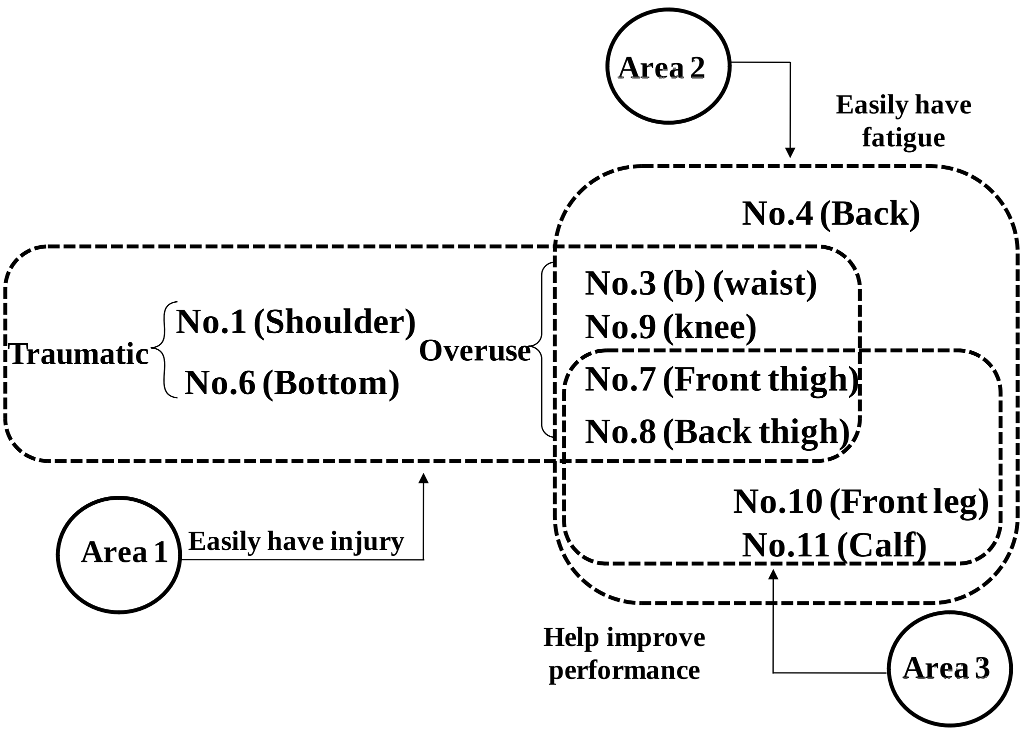


Fig. 6.12 Biomechanical zones categorized into three biomechanical design areas

To achieve an effective functional design, the 11 biomechanical zones are further categorized into three biomechanical design areas according to the biomechanical features of the muscle groups involved in the cycling action. The purpose is to realize fatigue reduction and injury prevention. In other words, area 1: easily injured; area 2: easily fatigued; and area 3: can improve muscle performance by functional design. The biomechanical zones are included in these three areas, as shown in Fig. 6.12. These biomechanical design areas on the body are shown in Fig. 6.13.

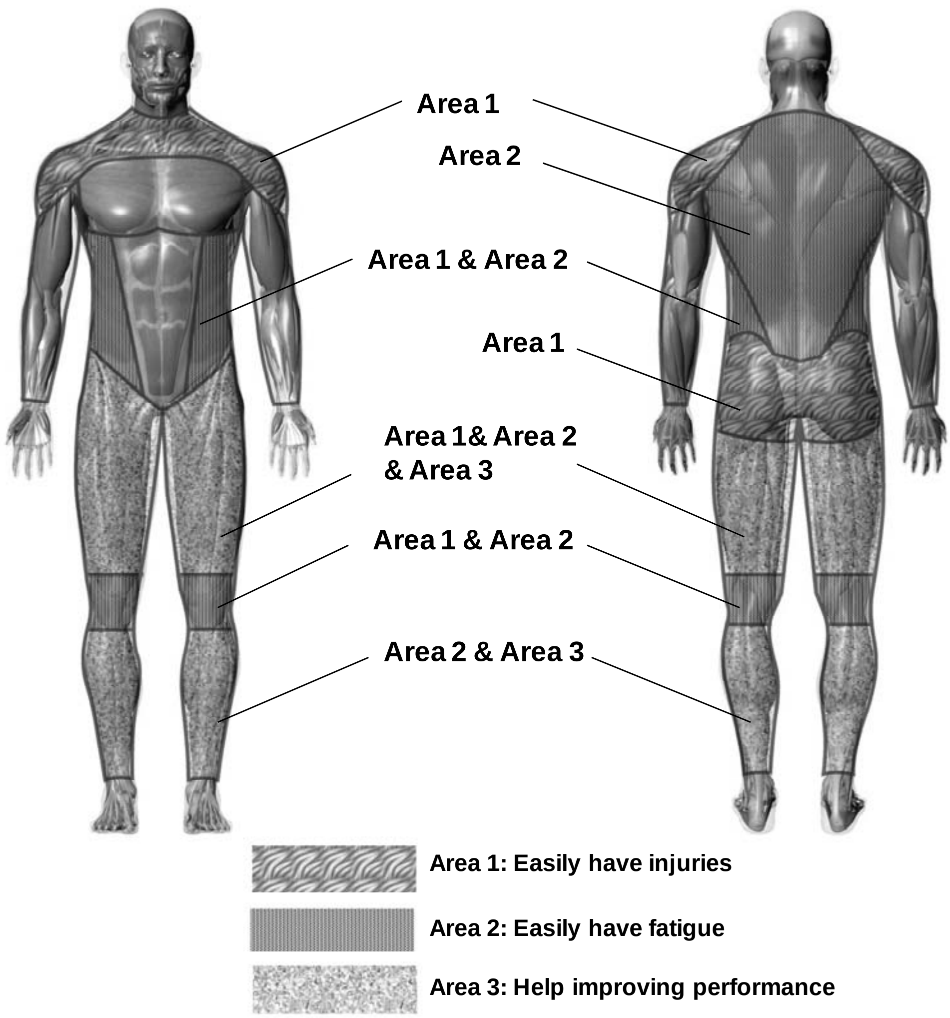


Fig. 6.13 Illustration of the three biomechanical design areas on the body

As reviewed in Chapter 2, compression garments are popularly used by athletes during training and competition to maximize competitive performance. They have many benefits such as an increased venous blood flow, reduced muscle vibration, improved proprioception, increased resistance to fatigue, and decreased musculoskeletal injuries. Moreover, compression garments worn during cycling can help increase the power output of cyclists by around 5% (Scanlan et al., 2008). Hence, FCS design can utilize the compression function of the garments to improve muscle performance and injury prevention. According to this concept, the biomechanical functional design can be realized as shown in Fig. 6.14. Generally, knitting fabrics, which are much more elastic than woven fabrics, may be adopted to provide the required compression and stretchability for cycling. The compression levels for the different areas and body parts are designed according to the compression range of different muscles presented in Table 6.3.

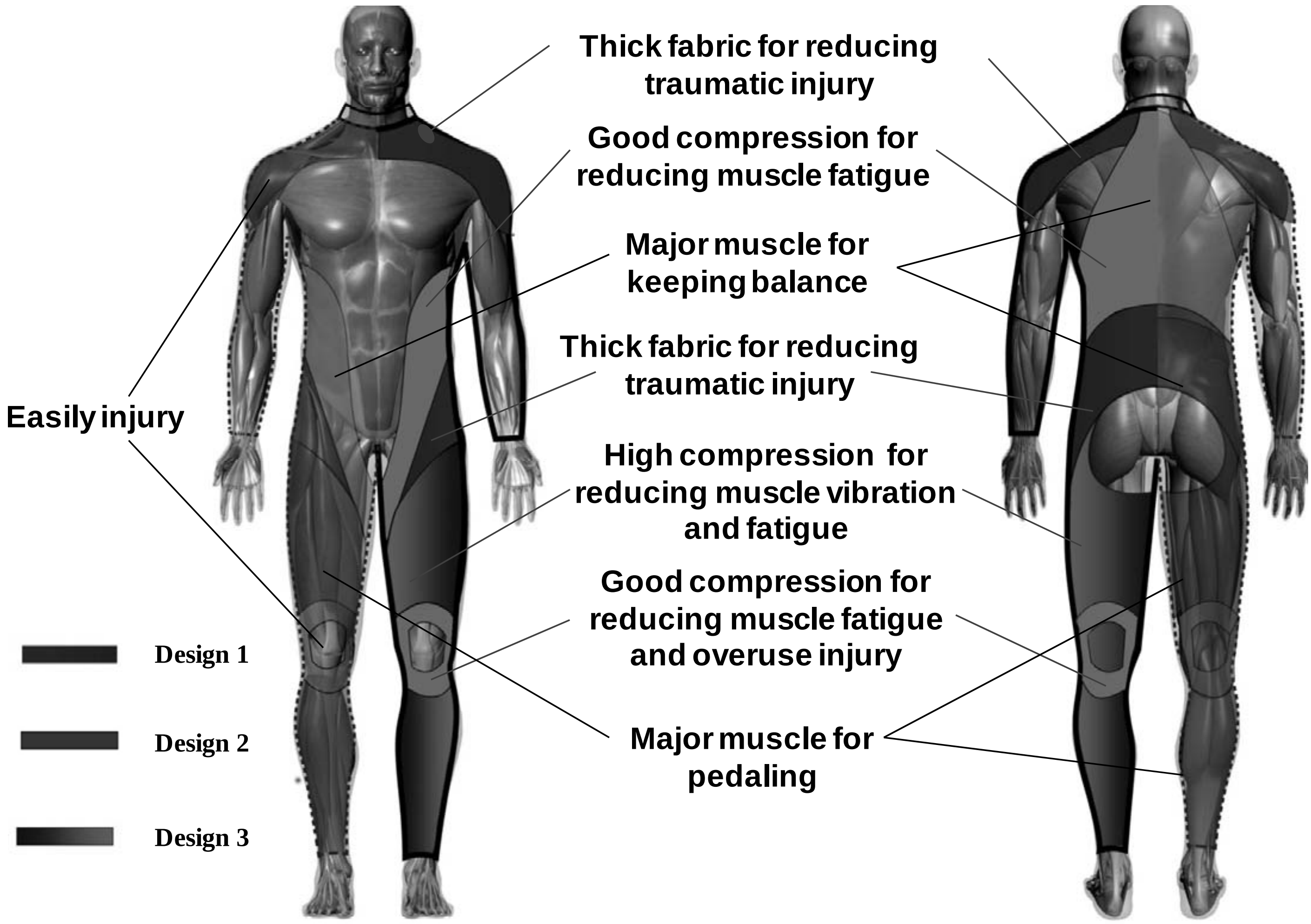


Fig. 6.14 Biomechanical functional design scheme of FCS

In design 1, the muscle groups involved in the shoulder (No. 1) and bottom (No. 6) are characterized as being prone to traumatic injuries. This finding is mostly due to collision with the ground when the body loses balance and falls. Moreover, according to the analysis of the biomechanical needs via the survey questionnaire, most respondents also strongly agreed that the shoulders and bottom need special protection from injuries. Thus, the functional design can adopt thick knitting fabrics with compressions of 9–12 mmHg to protect the shoulders and bottom from traumatic injuries in specific incidents or events. Furthermore, considering that traumatic injuries on the bottom mostly occur on the two sides of the hipbone (Tetsuo et al., 2000), and that the bottom accumulates much more sweat during cycling, the bottom design can be achieved with multi-structure fabrics. In other words, a thicker fabric can be used for the two sides of the bottom, and a thin fabric with good moisture management can be adopted for the center of the bottom. The muscle groups in the waist (No. 3(b)), back (No. 4), knee (No. 9), and thigh (No. 7 and No.8) may also suffer from overuse injury due to lengthy fatigue, which should be considered to reduce fatigue and prevent overuse, as discussed in areas 2 and 3.

In design 2, the involved body parts including waist (No. 3(b)), back (No. 4), and knee (No. 9) are characterized as being prone to fatigue and possibly result in overuse injuries. During cycling, the rectus abdominis, transverses abdominis, and abdominal obliques provide anterior and lateral support to the torso and counter the actions of back muscles. Meanwhile, the body needs to maintain the bent-over position most of the time to reduce the resistance caused by air flow during cycling. As a result, the back (No. 4) and waist (No. 3(b)), being parts of the upper limb, are the most prone to experience fatigue. Considering that these parts are kept in the same position during cycling, a fabric with good compression (8–10 mmHg) can be adopted to prevent muscle vibration of the waist and back, and keep the body stable. The flexibility offered by the stretch fabric can enable the bent-over riding position of cyclists. The knee (No.

9), which has been recognized as the most prone to overuse injury among all body parts, is also the part where sweat accumulation is high, as discussed in Chapter 4. Thus, multi-structure fabrics can be adopted for this part. A fabric with good compression (8–10 mmHg) can be designed around the knee to offer greater support to the muscles. A fabric with good breathability and moisture management can be used for the center of the knee. The generated compression can help stabilize the knee during repetitive riding and protect the knee from injury caused by over-bending and incorrect bending angle.

In design 3, the functional design is especially concerned with the lower limbs, which are active during the entire cycle of cycling action and provide power for pedaling, to improve cycling performance. The body parts involved include the front thigh (No. 7), back thigh (No. 8), front leg (No. 10), and calf (No. 11). These parts are prone to fatigue and should be considered as a group in FCS design. Thus, a knitted stretch fabric with high compression (21–25 mmHg) can be adopted for these parts. The muscle groups in these body parts keep contracting and stretching during cycling; hence, the high compression generated by the FCS may adversely result in over constraint and fatigue. Thus, an adequate amount of compression is good to reduce the vibration of muscles without having an adverse influence on muscle action. Good stretchability offers freedom for the muscle actions of the lower limbs.

6.5 Mechanical Performance Simulation

6.5.1 Mechanical Properties Measurement

The fabrics' mechanical properties (specifically bending, shearing, and tensile properties) can be measured at low levels of force using the Kawabata system, simulating actual fabric deformation during practical use. Primary hand values, such as stiffness, softness, and crispness, can also be measured using the Kawabata system, based on conversion from basic measurements of compression, shear, bending, surface, friction, and tensile properties (McKelvey, 2011). Detailed descriptions of testing instruments and standards are listed in Table 6.4.

Physical property	Testing instruments	Standards
Surface property	Automatic Surface Tester	KES-FB4-Auto-A
Compression property	KES compression tester	KES-FB3-Auto-A
Tensile property	KES tensile & shearing tester	KES-FB1
Shearing property	KES tensile & shearing tester	KES-FB1
Bending property	KES bending tester	KES-FB2
Primary hand value	KESF system	KES-FB1~4

Table 6.4 Measurement devices and standards for biomechanical properties

Table 6.5 shows the mechanical properties of some fabrics which are ready-for-use in this study and their thermal properties has been demonstrated in Chapter 5, including elastic modulus forward and return in warp, and also the values of stiffness, softness and crispness.

Mechanical properties	Fabric type				
	PP--plain	PP--plating	PP--tuck	PP--1x1 rib	PP--2x2 rib
	Original	Original	Original	Original	Original
Thickness [cm]	0.75	0.98	0.97	1.14	1.51
Elastic modulus forward warp	0.216	0.113	0.285	0.261	0.248
Elastic modulus return warp	0.079	0.060	0.139	0.095	0.088
Stiffness	6.78	5.36	8.23	10.09	11.33
Softness	12.44	10.79	11.52	11.17	10.20
Crispness	3.48	1.08	2.70	3.35	3.43

Table 6.5 Mechanical properties of some ready-for-use fabrics

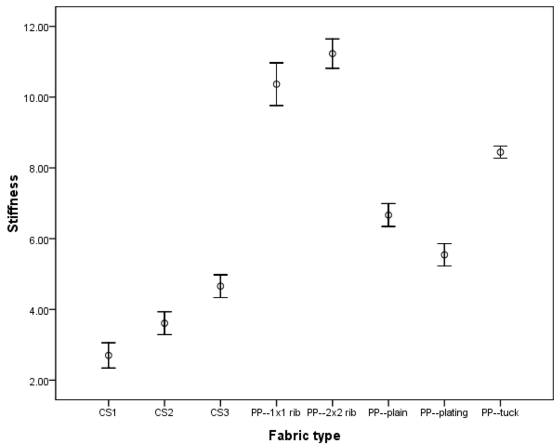
From this table, it can be observed that the PP-tuck fabric has the greatest elastic modulus forward warp, and the PP-1x1 rib and PP-2x2 rib fabrics have higher elastic modulus forward warp than the PP-plain and PP-plating fabrics. The PP-tuck fabric has the greatest stiffness and softness. Stiffness is a characteristic of high-density elastic fabrics, whereas softness is a combination of bulkiness, flexibility, and smoothness (McKelvey, 2011). These results indicate that the PP-tuck fabric has the best tensile property, followed by the PP-1x1rib, PP-2x2 rib, PP-plain, and PP-plating fabrics in descending order.

In order to evaluate the mechanical functions of these fabrics, the same three fabrics (CS1, CS2, and CS3) from the chest, back and thigh of the commercial cycling sportswear discussed in Chapter 5 was measured with the mechanical properties in terms of stiffness softness and crispness. Five samples of each fabric were tested using the measurement instruments and standards described in Table 6.4. The mean mechanical properties of these commercial fabrics are shown in Tables 6.6.

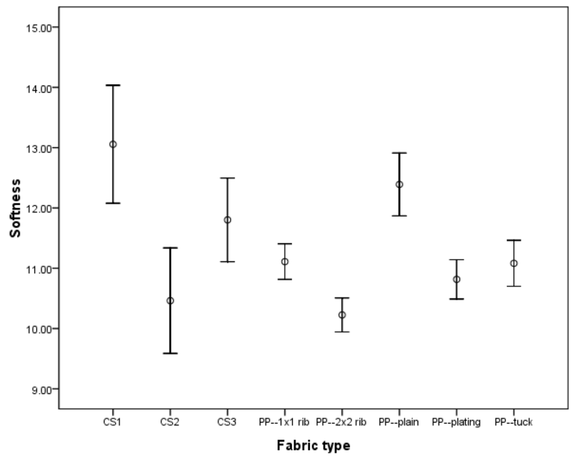
Mechanical properties	Fabric type		
	CS 1 Original	CS 2 Original	CS 3 Original
Stiffness	2.64	3.58	4.65
Softness	12.44	9.8	11.3
Crispness	0.87	2.06	1.39

Table 6.6 Mechanical properties of fabrics from commercial FCS

A comparison of measured mechanical properties was carried out between the ready-for-use fabrics, namely, PP-plain, PP-plating, PP-tuck, PP--1x1 rib and PP--2x2 rib, and CS1, CS2 and CS3. Fig. 6.15 shows the data plots of the compared mechanical properties in terms of stiffness and softness.



a) Stiffness



b) Softness

Fig. 6.15 Compared mechanical properties of the fabrics

From the data charts, it can be observed that the ready-for-used fabrics have better tensile properties than the fabrics from the commercial suit reflected by the stiffness. Furthermore, the thicker thickness of the ready-for-used fabrics, especially for the rib fabrics, can enhance the compression effect of the FCS.

6.5.2 Compression Simulation

The compression behaviour of sportswear is a form of interactive contact between the fabric and the body. Factors influencing sportswear compression capabilities include tensile and geometric properties of the fabric and friction between the fabric and the body (Lin et al., 2012). In general, a fabric's tensile property is the predominant factor in its compression performance. Thicker fabrics may undergo more tension and stress, whereas denser fabrics may enhance the body's force against it, potentially increasing the sportswear's compression capabilities.

Contact pressure, a key issue in compression garment design, can be simulated using Laplace's law and the finite element method (FEM) (Thomas, 2003). FEM can facilitate parametric design using different configurations of mechanical properties, such as tensile, thickness, density, and friction. Compression garments of varying geometry and materials can be numerically designed by these parameters, and their compression performance can be simulated and evaluated without tedious experimental trial and testing.

An optimized compression sportswear fabric design approach using numerical simulation was developed by Lin et al. (2012). The commercial FE software package ABAQUS was modified to perform this simulation, where 3D compression FEM was developed in the form of a nonlinear fabric tube and cylinder base. The numerical simulation consisted of two stages: the fabric tube was pulled up the support cylinder base in the first stage, and then in the second stage, friction was added between the fabric and the cylinder through surface-to-surface contact. Using this numerical design approach, the compression of the knitted fabric ready-for-use in this study can be predicted by inputting the appropriate tested mechanical parameters. Fig.6.16 shows the predicted compress distribution on the thigh and leg. As demonstrated in this picture, the range of compression on the leg and thigh in tight compression status can reach 18-25 mmHg, which indicates the fabric being able to generate high compression effect is required.

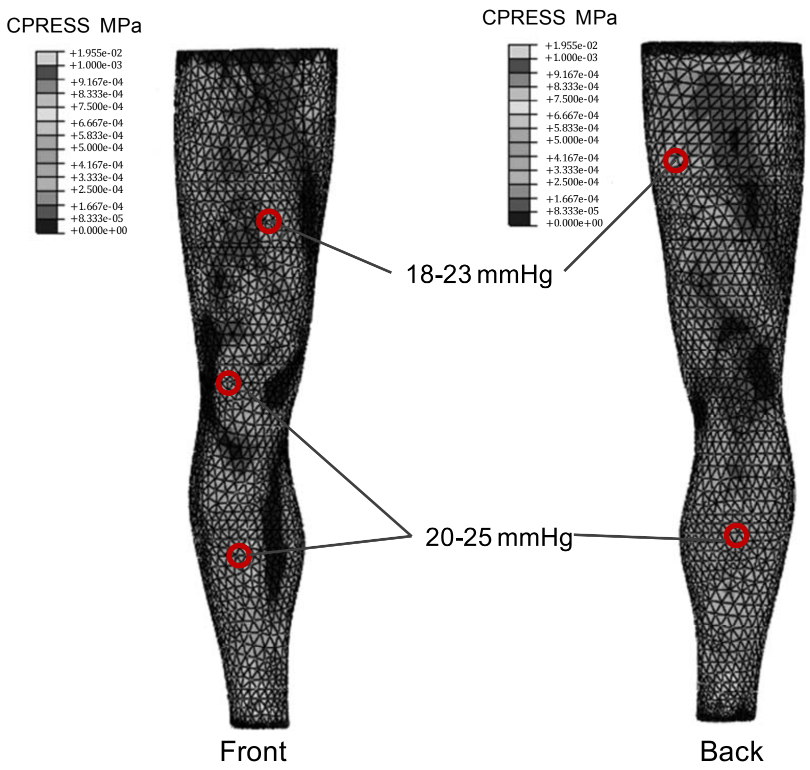


Fig. 6.16 Numerical design of compression sportswear fabric (Lin et al., 2012)

In this simulation experiment, it was verified that the average pressure of the PP-plain fabric reached the range of compression (10 mmHg to16 mmHg), as did the average pressure of the PP-tuck fabric (18 mmHg to 22 mmHg). As listed in Table 6.5, the tensile properties of PP-tuck structure are better than those of the plain structure reported by previous research. These results indicates the pressures of the PP-1x1 rib and PP-2x2 rib fabrics, which are thicker than other structures, are also able to reach and exceed the range compression (10 mmHg to 16 mmHg). Thus it can be predicted that all these five structure fabrics can achieve the required levels of compression for different groups of muscles, as shown in Table 6.3.

6.5.3 Fabric Selection for Biomechanical Functional Design

Since the tensile and thickness of the fabric are the main factors influencing the compression capabilities of sportswear (Lin et al., 2012), the tensile modulus and thickness can be considered as the main mechanical properties to choose the fabrics with different levels of compression effect. Fig. 6.17 shows the fabric selection scheme for the biomechanical functional design of FCS. The detail is discussed as follows:

1) The design 1 is characterized as being thicker for reducing traumatic injury. The fabric with thicker thickness, such as PP-2x2 rib, can be adopted for this design;

2) The design 2 is characterized as being good compression for reducing muscle fatigue. The fabric with good tensile property, such as PP-1x1 rib, PP-2x2 rib, PP-plain and PP-tuck, can be considered in this design.

3) The design 3 is characterized as being high compression for reducing muscle vibration and fatigue. The fabric with thicker thickness and good tensile property, such as PP-tuck, can be selected to achieve the desired compression effect.

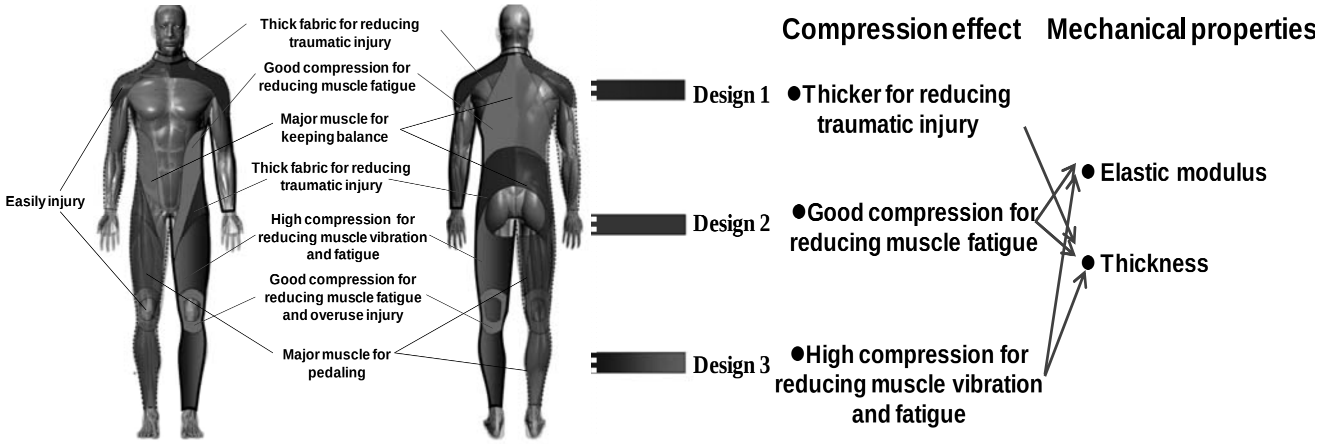


Fig. 6.17 Fabric selection scheme for biomechanical functional design

6.6 Conclusion

This chapter has reported on the biomechanical functional design of FCS. The basic biomechanical mechanisms of skeletal muscles, muscle fatigue, and injuries, as well as sport injuries are first studied and summarized to develop basic background knowledge. Subsequently, the required knowledge for the biomechanical functional design of cycling sportswear is established. Muscle group recruitment in cycling pertaining to four quarter cycles are illustrated for FCS design based on cycling anatomy. The body parts covered by clothing that need to possess injury protection were identified by analyzing cycling injuries. Furthermore, the detailed biomechanical needs of the body for the FCS design are obtained via questionnaire data analysis. Subsequently, the biomechanical requirements of FCS design are identified by creating biomechanical zones to express and compare the different biomechanical requirements of each body part. With such basic work, the biomechanical functional design scheme is developed by utilizing the compression effect of fabric. Finally, by measuring the mechanical properties of fabrics and numerical simulation of the compression effect of fabric, the scheme of fabric selection for biomechanical functional design is described.

CHAPTER 7 REALIZATION OF FUNCTIONAL CYCLING SPORTSWEAR DESIGN

7.1 Introduction

The aesthetic, thermal and biomechanical functional designs of cycling sportswear have been described in Chapters 4, 5 and 6, respectively. Based on these efforts, the functional cycling sportswear (FCS) design can be fused and realized with the creation of prototypes according to the theoretical design framework discussed in Chapter 3, as shown in Fig.7.1. The creation of FCS prototypes is an important way to collect and combine available information and technologies, as well as to explore new knowledge and potential applications in practice, because it is a practice-led stage in the design cycle (Kathryn, 2011). This chapter focuses on how to realize the FCS design for different applications.

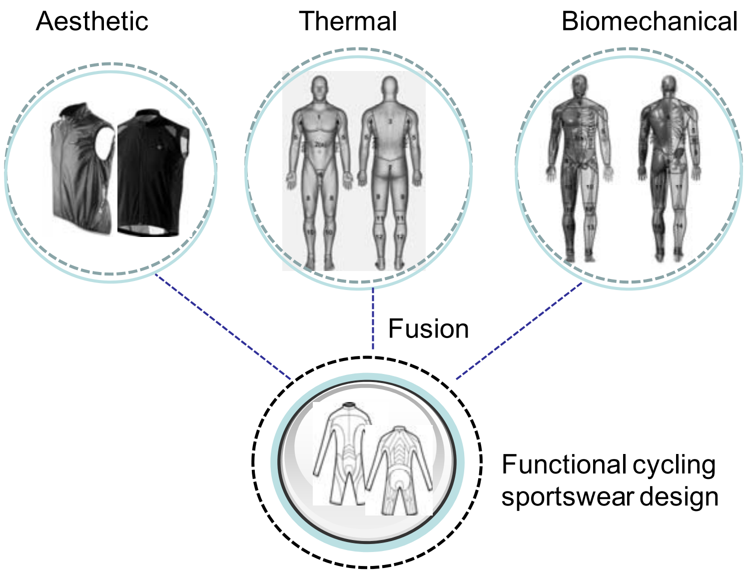


Fig. 7.1 Functional cycling sportswear design

In this chapter, the creation procedure of the design prototypes is initially discussed. The process, technology, and machines involved to create FCS prototypes are introduced. As a demonstration of the realization process, the creation of FCS prototypes respectively for competition and training are described in detail in collection I, including design inspiration, design scheme, fabric, garment pattern and design demonstration. With the purpose of promoting this design innovation into more applications, collection II and III are designed and realized respectively for 2008 SMART Convection and 2012 Olympic Games.

7.2 Creation Procedure of Design Prototype

The general procedure for garment creation includes development of design inspiration and sketch, specification of fabric and color, cutting and construction, and pattern making and refinement (McKelvey, 2003). During garment creation, the fabric acts as the basic element, which enables the garment to have varied effects. Functional performance is the main concern for sportswear. The advances in the production of fibers and fabrics with unique functional properties facilitate creation of sportswear with performance characteristics, such as thermal insulation, moisture management, breathability, injury protection, and biomechanical fit and prevention.

The creation of FCS prototypes, which aims to achieve multi-functional requirements, collects the design process for sportswear, current production technology, and advanced machines. Fig.7.2 illustrates a typical procedure of creating an FCS prototype with the process, technology and machines involved. The whole procedure that starts from design inspiration and design scheme may be repeated and will only end when the desired FCS product is successfully created.

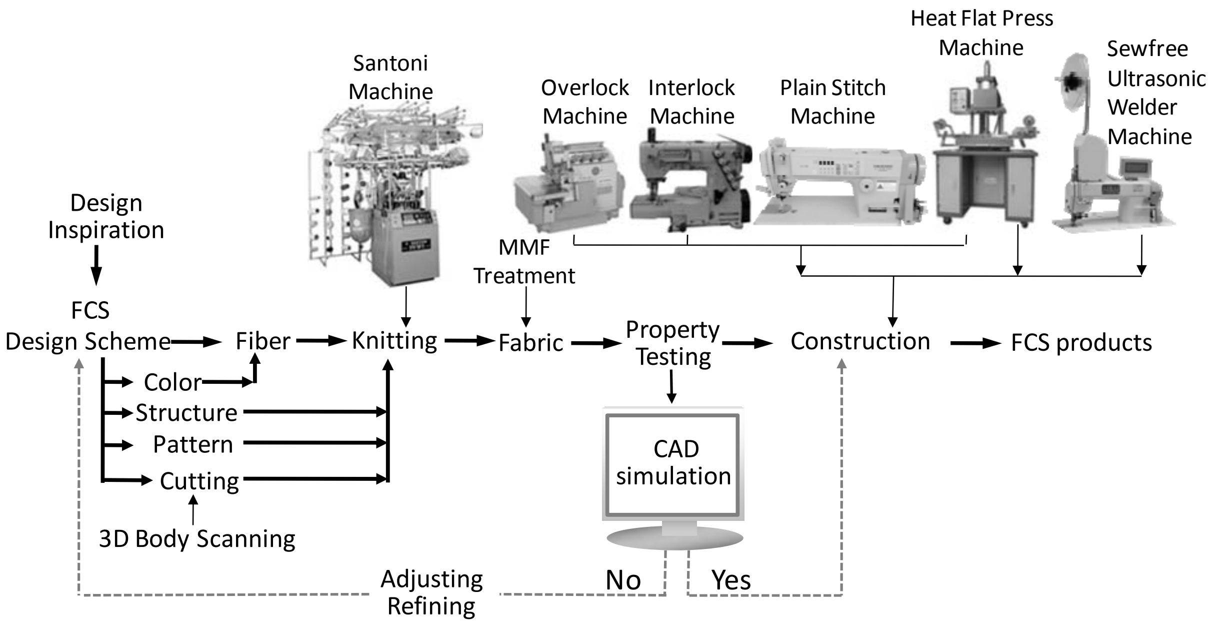


Fig. 7.2 Typical creation procedure of FCS prototype

The creation of FCS products starts from fabric selection, which predominantly affects the required aesthetic effect, thermal and biomechanical functions of the final product. The fabrics made by different fibers characterized by different functional properties may differ significantly from each other in terms of performance. For instance, cotton has a different thermal and mechanical performance compared with synthetic fabric. Synthetic fibers are generally considered the best choice for sportswear because they provide a good combination of moisture management, softness, and thermal insulation

(Anon, 2001). They absorb less water than cotton and wool but can still wick moisture rapidly through the fabric. The synthetic fibers, such as polyester, polypropylene, nylon, acrylics, and elastane, are usually used for sportswear and active wear (Kathryn, 2011). Besides the fiber components, the color, texture and pattern may be also concerned in the fabric selection to create different aesthetic effects.

In order to achieve better functional characteristics for sportswear, the fabric are usually created by knitting technology, which supports the free transposition of loops and easily achieves different structures. The knitted fabric may help achieve the required breathable function in thermal functional design and the required stretch function in biomechanical functional design.

Currently, two basic forms in knitting technology exist, namely, warp knitting and weft knitting. Although these two knitted fabrics are massively manufactured in the market, the weft-knitted fabric is generally more elastic than the warp-knitted fabric (Reichman et al., 1967). Considering that the fabric required in the biomechanical functional design of FCS needs to be stretchable, the weft knitted fabric is more preferred. Currently, the main manufacturers of weft knitting machines include Shima Seiki, Stoll, and Santoni (Wang, 2010). Shima Seiki and Stoll manufacture V-bed flat knitting machines, whereas Santoni provides circular knitting machines. The Santoni machine (SM8-Top2s 14”/28G) is used in the knitting of fabrics for this study, since it can create different fabric structures and patterns by seamless knitting technology. Different knitting structures may lead to distinct thickness, stretch, and breathability of the fabrics, which are required to achieve different levels of thermal and biomechanical requirements. Information of 3D body size needs to be considered during knitting because the Santoni machine produces fabric by circular and seamless knitting.

The body size measured by 3D body scanning is generally regarded as more accurate and more sophisticated than traditional body size measurement by hand (Loker et al., 2004; Simmons and Istook, 2003). In this procedure, the primary cutting size for the body is derived from 3D body scanning data, which is measured by a 3D body scanner (VOXELAN LPW-2000FW) based on identified anthropometric measuring points and lines on the body surface. The detail body size information has been illustrated in Chapter 4. Furthermore, sizes can be expanded for different types of wearers with different shapes.

Meanwhile, MMF treatment may be performed on the fabric to improve the rate of moisture wicking and breathability of the fabric (Li, 2001). The fabrics can then be dried quickly and can release moisture from the skin to the outer surface of the fabric.

With the selected and MMF-treated fabrics, the physical properties of the fabrics are measured to illustrate their thermal and mechanical characteristics. These characteristics are the primary bases for designers to recognize the different levels of functional characteristics of the fabrics. Furthermore, these characteristic data of the fabrics can be input into the CAD tools, which perform numerical simulation to predict the functional performance of FCS designed by these fabrics and offer indication for fabric selection in the design. The detail information about the functional properties measurement and numerical simulation, as well as an indication for fabric selection has been reported in Chapter 5 and 6, respectively. The designers are thus able to refine their design before real production starts.

However, the success of a garment is largely decided by whether the parts are sophisticatedly joined together (Mansfield, 1974). Cutting and construction of garment patterns is the crucial process of creating the final prototype. During this process, the body size information is also concerned for cutting. Both seam and seamless technology may be adopted in the practical production. Though seamless technology seems more preferred, the seams may also create line interest and delightful space divisions (Shields, 2011). In the construction of an FCS product, three seam machines are used, including overlock machine for seaming, interlock machine for hemming, and plain stitch machine for zipper stitching. A sew-free ultrasonic welder machine (H&H, US-004) is used to seal fabrics by ultrasonic and reinforced seam sealing by bonding line to produce a seamless effect. Meanwhile, a Pneumatic cool and heat flat press machine (H&H, CS-500T) is used to coat the fabric with tape. Final FCS products can be constructed using these machines.

Based on this design procedure, the following collections were created for international design contest, exhibition and Olympic Games, respectively. As a demonstration of the realization process, the two prototypes for competition and training in the collection I are described in detail.

7.3 Collection I: Speed

7.3.1 Design Inspiration

The design inspiration of the FCS comes from ‘speed’: different international design trends for concept cars, as shown in Fig. 7.3, which shows the smooth fusion of high-tech and modern fashion. It has advanced technology and functionalities, which offer drivers more safety and a faster driving experience. Additionally, concept cars have creative and unique design, which presents a shape with a strong streamline feeling with its geometric illusions of lines, distances, angles, and space. People find it easy to appreciate the features of high-tech and speed when viewing its appearance. The ‘speed’ collections presenting modern concepts offer the inspiration for the functional cycling sportswear design. The main color for this collection adopts blue, which has higher likelihood of winner, as discussed in Chapter 4. The other colors adopted include red and silver. The samples of the colors are shown in Fig.7.4.

Fig. 7.3. Inspiration for the collection I

Fig. 7.4. Colors for the collection I

7.3.2 Design Brief

Based on the fused aesthetic, thermal and biomechanical functional design, basically, two FCS prototypes in this collection, called Speed-pro, were created respectively for competition and training according to the practical requirements. Due to this collection aimed to participate in the 5th Qiaodan cup international sport equipment design contest, another two FCS prototypes, called Speed-power, which create more visual effect, were expanded in this collection.

Speed-pro for Competition

According to the convention, cycling sportswear with long pants is not allowed in international competitions (Switzerland, 2005). Therefore, the FCS for competition was designed in the style of the all-in-one-suit with long sleeves and short pants, in a tight fit, conforming to the design preference of professional athletes, as reported in Chapter 4.

- ***Design scheme***

To create a new FCS prototype for competition, the inspiration of design is depicted by sketching, as shown in Fig. 7.5. The FCS worn by the cyclists is demonstrated with the front-view, side-view and rear-view. Given the multi-functional properties of the FCS, design schemes that take into consideration the thermal and biomechanical functions are reported individually in Chapter 5 and Chapter 6. This sketch focuses on the aesthetic elements, which are also fused with the functions of the FCS. The main color of the FCS is blue, abstracted from the design inspiration. The streamline line shows the feeling of 'speed' in the sketch.

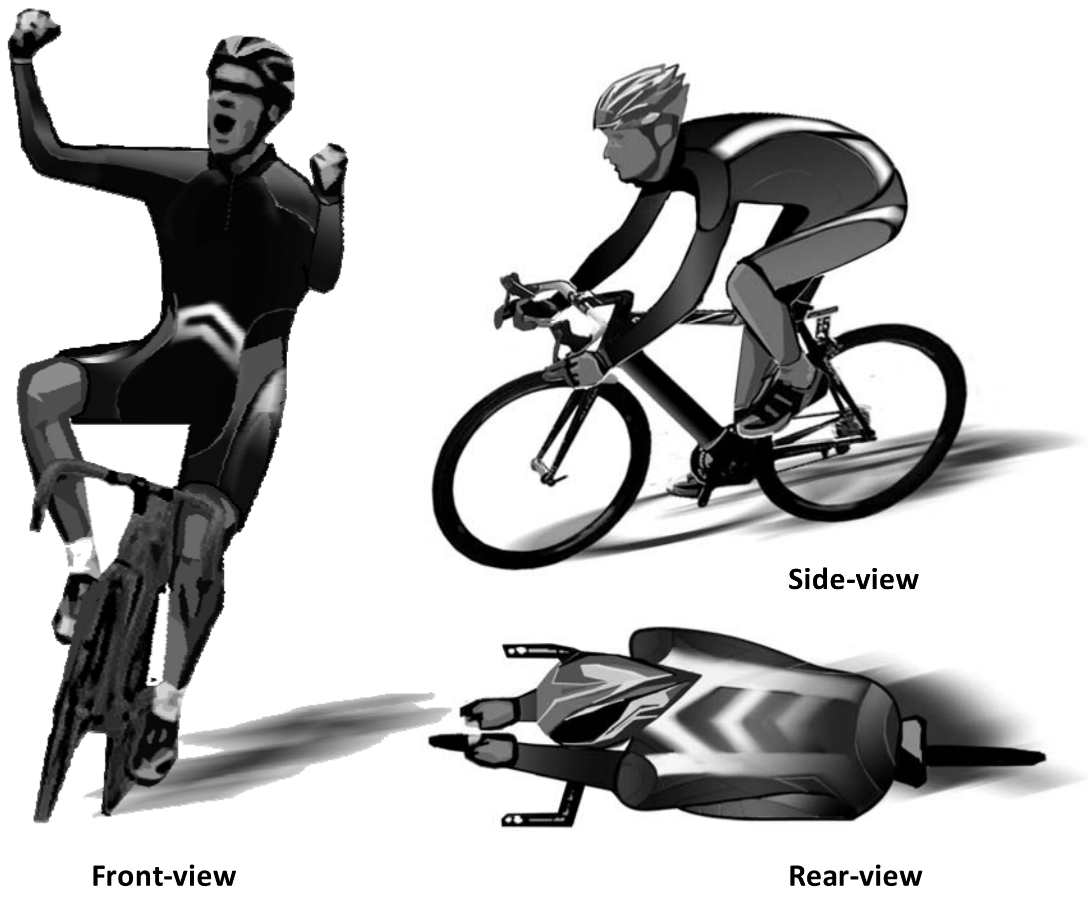


Fig. 7.5 Design sketch of the Speed-pro for competition

Fig. 7.6 is the design scheme of the Speed-pro for competition. The cutting lines wind at the parts of the chest, abdomen, waist, and thighs according to the anatomical structures of muscles. The back, body side, and shoulders do not have seam lines as the knitting technology is adopted. The knitted fabrics with different structures are described as fabric1 (PP-2x2 rib), fabric2 (PP-1x1 rib), fabric3 (PP-tuck), and fabric4 (PP-plain) for the different body parts to afford the required thermal and biomechanical functions. According to the thermal and biomechanical functional characteristics of these fabrics, the fabrics with different structures are adopted to different body parts.

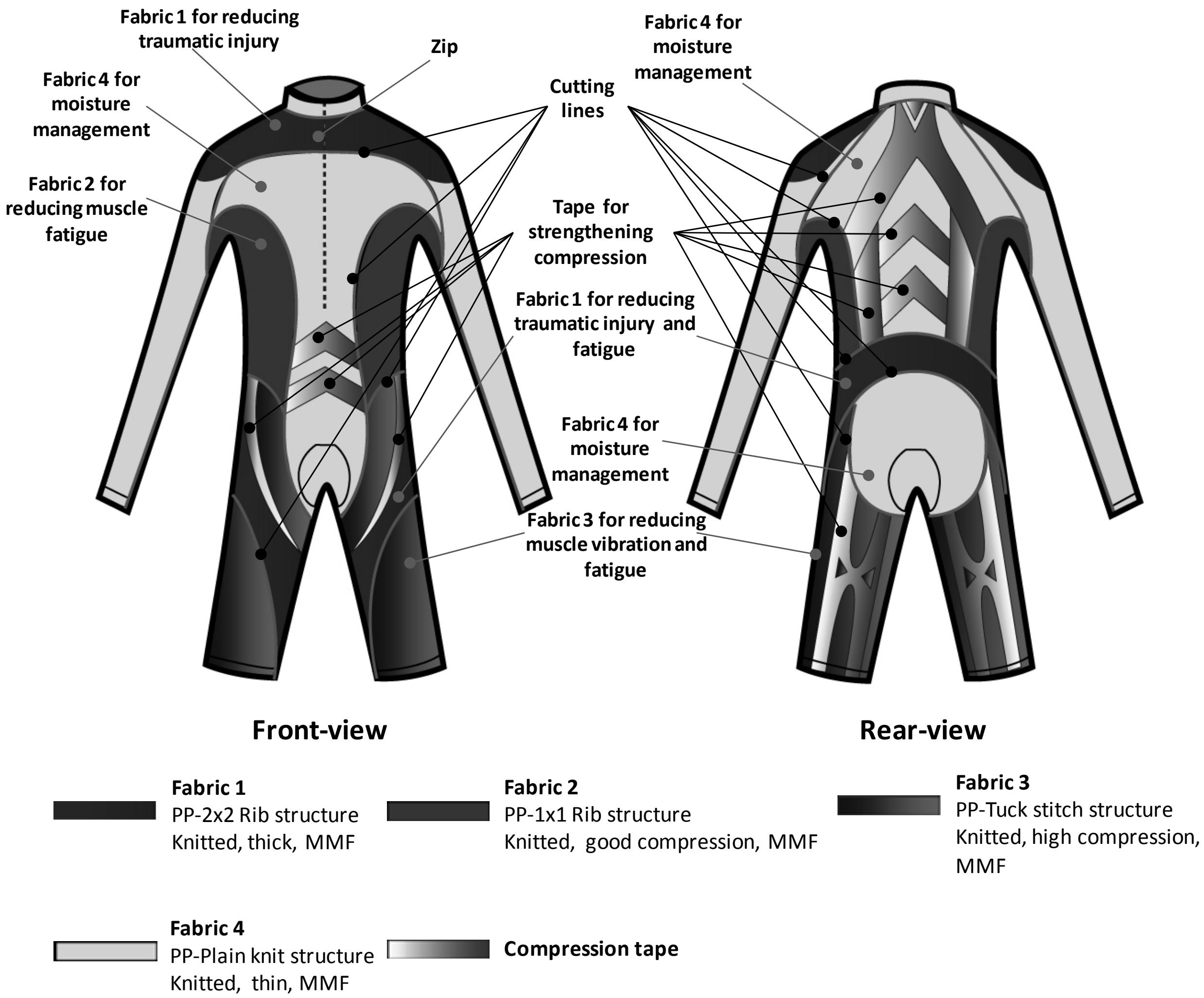


Fig. 7.6 Design scheme of the Speed-pro for competition

As the shoulders are prone to traumatic injury during cycling, the fabric 1 (PP--2x2 rib), which is the thickest one in the five fabrics, is adopted to prevent injury and designed with raglan sleeves to avoid seam line. Fabric1 is also used for the bottom to prevent traumatic injury and fatigue, and is extended to the front thigh for better compression. For the purpose of reducing fatigue of the main muscles involved in the cycling action, the stretch fabric is used to generate the required compression for biomechanical protection. At the back side, the fabric2 (PP--1x1 rib) with good stretch and compression is adopted, and extended to the armpit in order to reduce air resistance during cycling competitions since the sparse mesh fabric is efficient in sucking air. The fabric3 (PP--tuck) with high stretch and compression is adopted for the thigh, which has the most active muscle groups in cycling, to reduce muscle vibration and fatigue and improve performance during competitions. Furthermore, in order to strengthen the compression of the FCS, thermoplastic coating with polyurethane (PU) tape is used based on the cycling anatomy. One is designed starting from the back, crossing the waist and the abdomen, and ending at the thigh, and another is used on the back of the thigh. These tapes also create a strong feeling of streamline, which can offer a speed experience to viewers. The fabric4 (PP--plain), which is thin and good at moisture management, is used for the other parts, such as the chest, back and arm where have intense sweat accumulation.

- ***Fabric***

The basic properties, knitting structures and images of the selected fabrics for this prototype are listed out in Table 7.1. The thermal and biomechanical properties of these fabrics have been illustrated in Chapter 5 and Chapter 6 respectively.

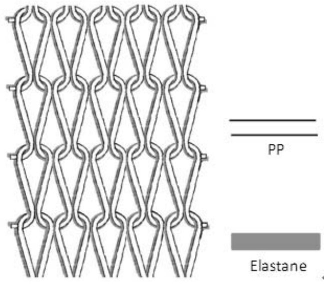
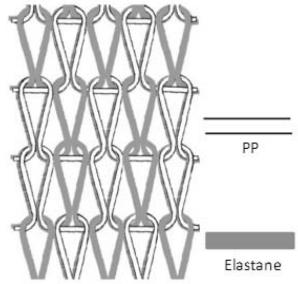
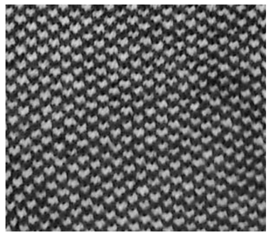
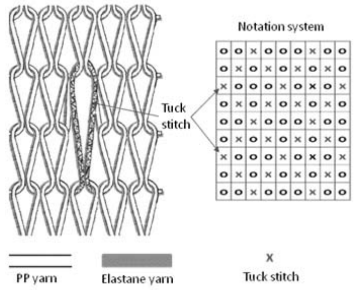
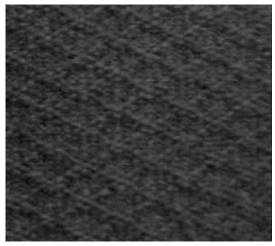
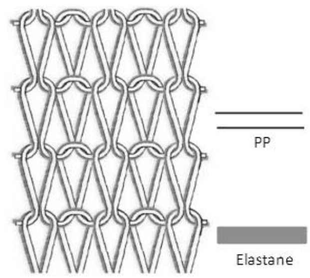
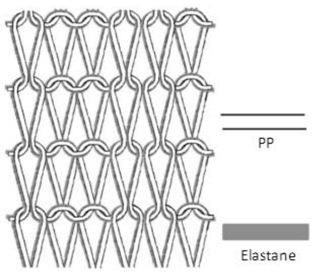
Fabric	Fibers	Density [g/m3]	Thickness [cm]	Knitting structure	Image
PP-plain	PP Elastane	153.7	0.75		
PP-plating	PP Elastane	144.2	0.98		
PP-tuck	PP Elastane	168.3	0.97		
PP-1x1 rib	PP Elastane	210.9	1.14		
PP-2x2 rib	PP Elastane	243.4	1.51		

Table 7.1 Basic prosperities, knitting structures and images of the selected fabrics

Since elastane is a synthetic fiber that can revert to its original form after being stretched, it is adopted in many types of apparel requiring a high degree of permanent elasticity, such as tights, swimwear, sportswear, and knitted fabrics. All these five fabrics are knitted by mixing elastane with polypropylene to achieve excellent stretchability.

Plain knit is the simplest structure for weft-knitted fabric, which is stretchable in width, breathable, and thinner compared with other fabrics (Raz, 1993). The plating knitted fabric is thin and sparse, thus, has excellent breathability. It has similar breathability as mesh, but can shield the skin from exposure. The 1x1 rib fabric is characterized with being most tensile along the width and has better extension ability compared with other rib structure fabrics (Liu and Wang, 2009). Similarly, the 2x2 rib structure has good tensile strength and expansive ability, which, however, are declined compared to 1x1 rib structure. The tuck stitch structure is characterized being thick and compressive and is widely used in the production of sportswear, since it increases the weight and thickness of the knitted fabric, meanwhile has more compression than plain, plating, and rib structures (Lin, 2012).

- ***Garment pattern***

The FCS prototype for competition is designed with long sleeves and short pants, consists of six pattern pieces, and is cut based on cycling anatomy analysis and 3D body scanning data. Fig. 7.7 shows the garment patterns for different parts, namely, arm (P1), back (P2), armpit and waist (P3), chest, abdomen, and bottom (P4), waist and parts of thigh (P5), and thigh (P6). The cutting employs curved lines designed according to the shape of the most active muscles during cycling, and takes into account the design preferences of the professional athletes surveyed in Chapter 6. For example, the cutting lines on the thighs wind with the shape of the sartorius muscle, the cutting lines on the upper body consider the shape of abdominal muscles, and the cutting lines on the back are curved according to the shape of the latissimus dorsi muscle. These cutting lines are built around the distribution and shapes of the main muscle groups, stretching over them smoothly and greatly increasing their dynamic fit, resulting in increased comfort for the wearer during cycling.

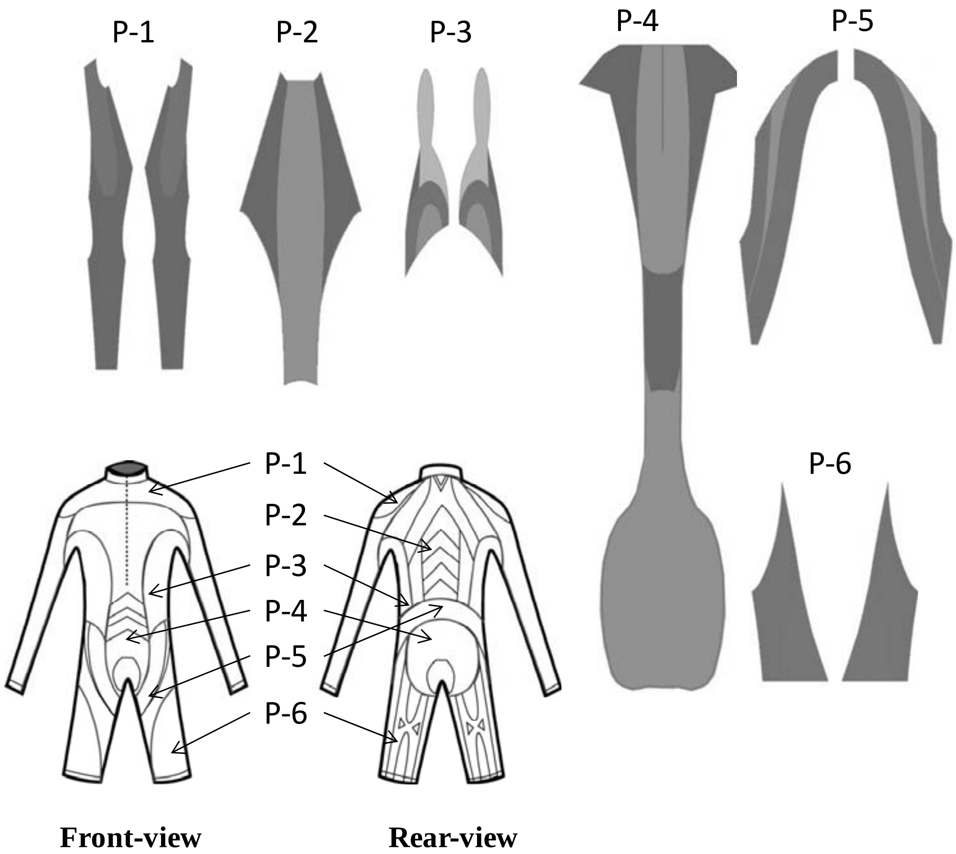


Fig. 7.7 Garment patterns of the Speed-pro for competition

The prototype of FCS is constructed by joining these six pattern pieces together. It is very importance of the quality of seam in terms of strength, flexibility and elasticity, which may have significant influence on the functional quality of the sportswear (Green and Patla, 1992). Therefore, the correct choice of seam technology is crucial for the functional active wear (Anon, 2001).

Currently, the overlock machine is the mostly widely-adopted tool for seaming knitted sportswear (Allen et al., 2007). The thread used in the seaming process is textured polyester (cotton count 60's/2). The interlock machine can be utilized for hemming to strengthen the seam and make it more flat and aesthetic, so that the seams lie neatly and do not cause friction against the wearer's skin (Liu and Wang,2009). Furthermore, the PU cover tape aiming to strengthen compression is coated on the back and thighs parts according to the design scheme with the Pneumatic cool and heat flat press machine (H&H, CS-500T). The detailed construction specifications of the FCS prototype for competition are listed in Table 7.2.

- ***Design demonstration***

The prototype is realized in blue in the style of an all-in-one-suit, as demonstrated in Fig. 7.8. At the front, the seams' contrasting colors curving with the shape of muscles add a decorative effect. The silvery PU tape coating on the thigh along the sartorius muscles offer biomechanical support for the quadriceps femoris group and creates a fashionable contrast between the fabrics. The PU tape can also be applied in an arrow shape or pattern on the abdominal area and back to give a visual perception of speed.

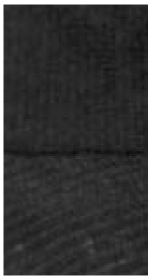
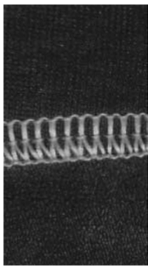
Machine	Type	Specification	Application	Photos
Overlock machines	**Pegasus EX-series**	2 needles 4 threads	Seam pattern pieces together	  **Front** **Back**
Interlock machine	**Yamato VC2700-150M**	3 needles 5 threads	Hemming	  **Front** **Back**
Plain sewing machine	**Brother EXEDRA**	1 needles 1 threads	Seam zippers	
Flat press machine	H&H CS-500T	120 – 130℃ 10s – 12s 4kPa	Heat sealing PU cover tapes	

Table 7.2 Construction specification of the Speed-pro for competition

Front-view Rear-view

Fig. 7.8. Prototype of the Speed-pro for competition

Speed-pro for Training

- ***Design scheme***

Based on the same design inspiration, the prototype of Speed-pro for training can be designed, with more consideration on the training conditions that all the active muscles in the lower limb should be protected during lengthy practice. Similar to the Speed-pro for competition, the style also adopted the all-in-one-suit with long sleeves but long pants in tight fit. The design sketch is shown in Fig.7.9 with the front-view, side-view, and rear-view. The color blue was also adopted as the main color for this prototype.

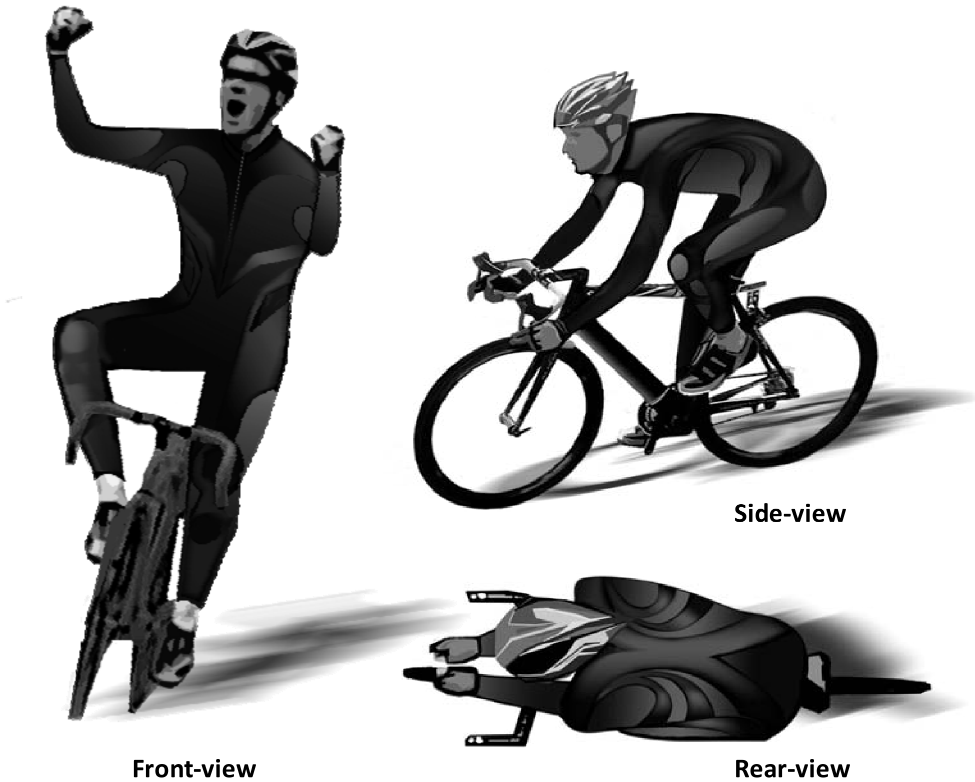


Fig. 7.9 Design sketch of the Speed-pro for training

Fig. 7.10 shows the design scheme of Speed-pro for training. Similarly, the multi-structure knitted fabrics (fabric1, fabric2, fabric3, fabric4, and fabric5) are also adopted for the different body parts to offer desirable thermal and biomechanical functions. Considering that the contacting friction between the skin and seam lines during lengthy training may lead to strong discomfort, this prototype is cut mostly by seamless technology, with only four seam lines in the whole suit. The back, body side, shoulders, waist, and thighs do not have seam lines, thanks to the knitting technology used.

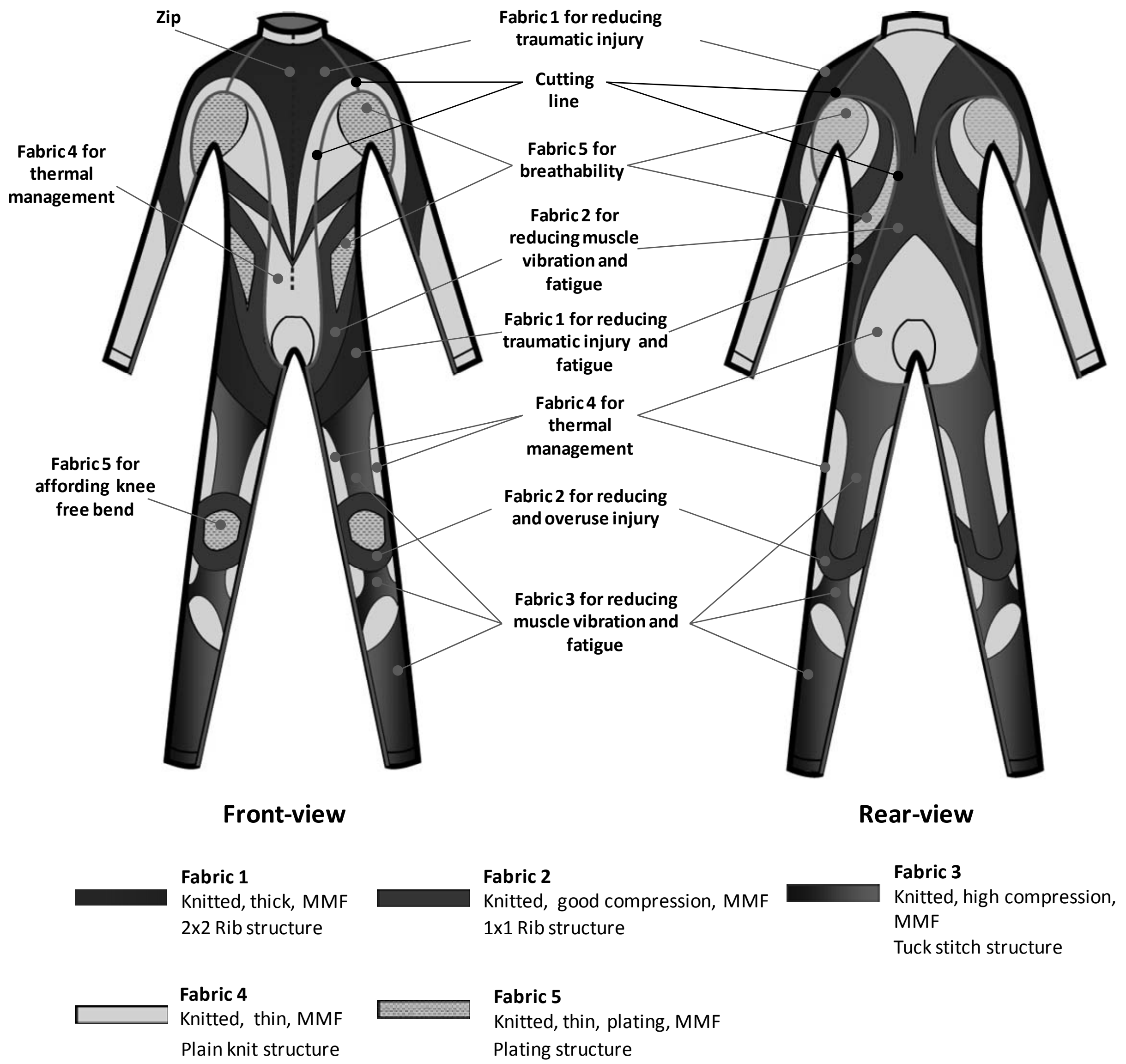


Fig. 7.10 Design scheme of the Speed-pro for training

Given the intense sweat accumulation at the back, waist, and armpit during lengthy training, the sparse mesh fabric 5 (PP--plating) is adopted for the purpose of quick sweat release and air breathability. The fabric2 (PP--1x1 rib), which has good stretch and compression, is adopted for the back and waist to reduce muscle fatigue. Since the knees are covered by the long pants and are the most prone to overuse injury, the fabric2 with good compression can also be designed around the knees for better muscle support, meanwhile the fabric5 (PP--plating) can be used on the centre of the knee for good breathability and free bent. The fabric3 (PP--tuck), which has high stretch and compression, is adopted for the whole lower limb to improve performance, as it contains major active muscles during cycling. Furthermore, in order to increase moisture management capability and avoid possible discomfort caused by high compression fabric during lengthy training, the thin fabric4 is used for the lower limb together and create a curved pattern. The fabric4 (PP-plain) is also used for the other parts which have intense sweat accumulation.

- ***Fabric***

The basic properties, knitting structures and images of the selected fabrics for this prototype refer to Table 7.1 and the discussion in the part of Speed-pro for competition.

- ***Garment pattern***

This prototype is designed with long sleeves and long pants, and only consists of three pattern pieces because too many seam lines may cause friction against the skin and generate resistance to muscle movement during prolonged training. The knitted patterns are based on cycling anatomy analysis and 3D body size, as shown in Fig. 7.11.

They consist of the chest, abdomen, bottom and back (P1), arm (P2), armpit, side of waist, and lower limbs (P3). Fabric structures are similar to those of the Speed-pro for competition to meet with functional requirements; the difference is that the number of seam lines is reduced to a minimum by the application of seamless technology.

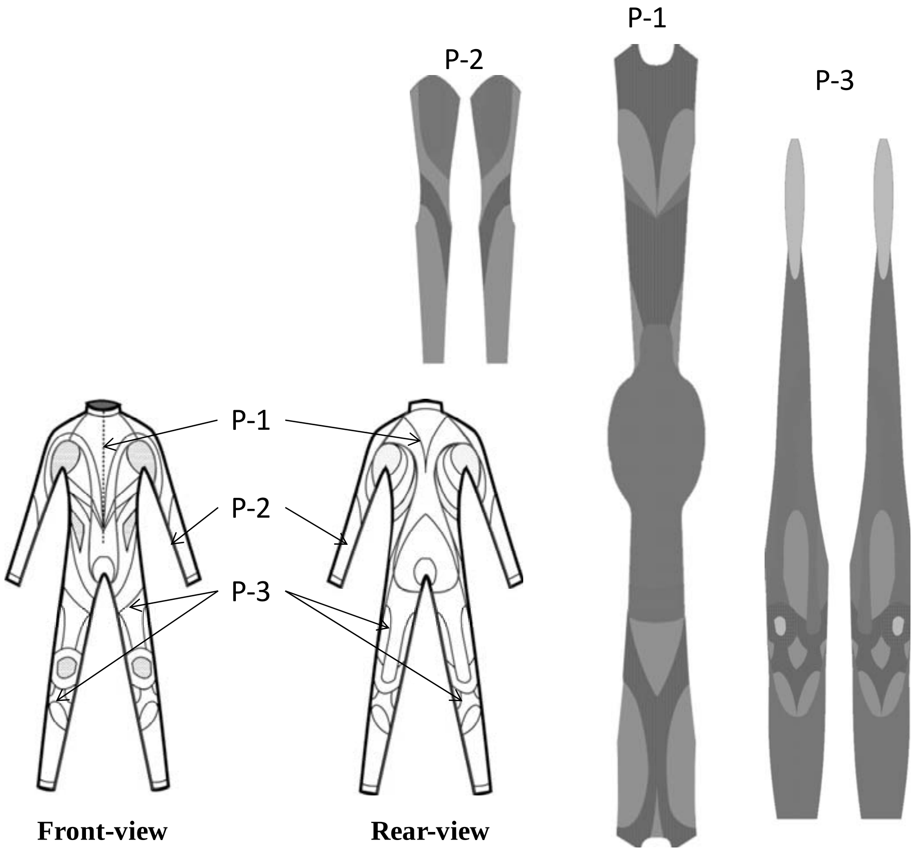


Fig. 7.11 Garment patterns of the Speed-pro for training

Welding technology has a special place in garment production due to its ability to bind thermoplastic materials without the use of adhesives, binders, staples, and threads, thereby allowing seamless seaming (Prabir, 2011). Synthetic polypropylene (PP) fabric is also quite suitable for seamless fabrication (Jana, 2011). The sew-free ultrasonic welder machine (H&H, US-004) was used to achieve seamless seaming for this FCS prototype. It seals fabrics through ultrasonic line bonding. The detailed construction specifications for the training FCS prototype are listed in Table 7.3.

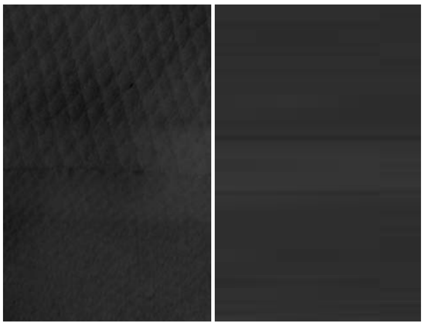
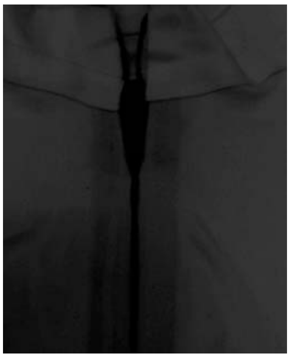
Machine	Type	Specification	Application	Photos
Ultrasonic welder machine	H&H, US-004	40KHz Ultrasonic System	welding and bonding pattern pieces together	 **Front** **Back**
Flat press machine	H&H CS-500T	120 – 130 °C 10s – 12s 4kPa	Heat sealing zipper	

Table 7.3 Construction specification of the Speed-pro for training

- ***Design demonstration***

The final prototype of Speed-pro for training is displayed in both the front and back views, as shown in Fig. 7.12. It is a product of seamless technology, offering a smoother fabric and reducing friction during cycling. This prototype is designed with long sleeves and long pants which cover all the main muscles involved. Thus it is able to provide injury protection for all the main muscles during prolonged training.

Front-view

Rear-view

Fig. 7.12 Prototype of the Speed-pro for training

Speed-power

- ***Design scheme***

The two prototypes of Speed-power were designed with the style of jersey and bib pants, as illustrated in Fig. 7.13 in terms of front-view and rear-view. The multi-structural fabrics are cut with smooth lines and used in the different parts to achieve thermal and biomechanical functions. The PU cover tapes cut with hollowed patterns was coated on the fabrics to generate a contrast effect.

- ***Fabric***

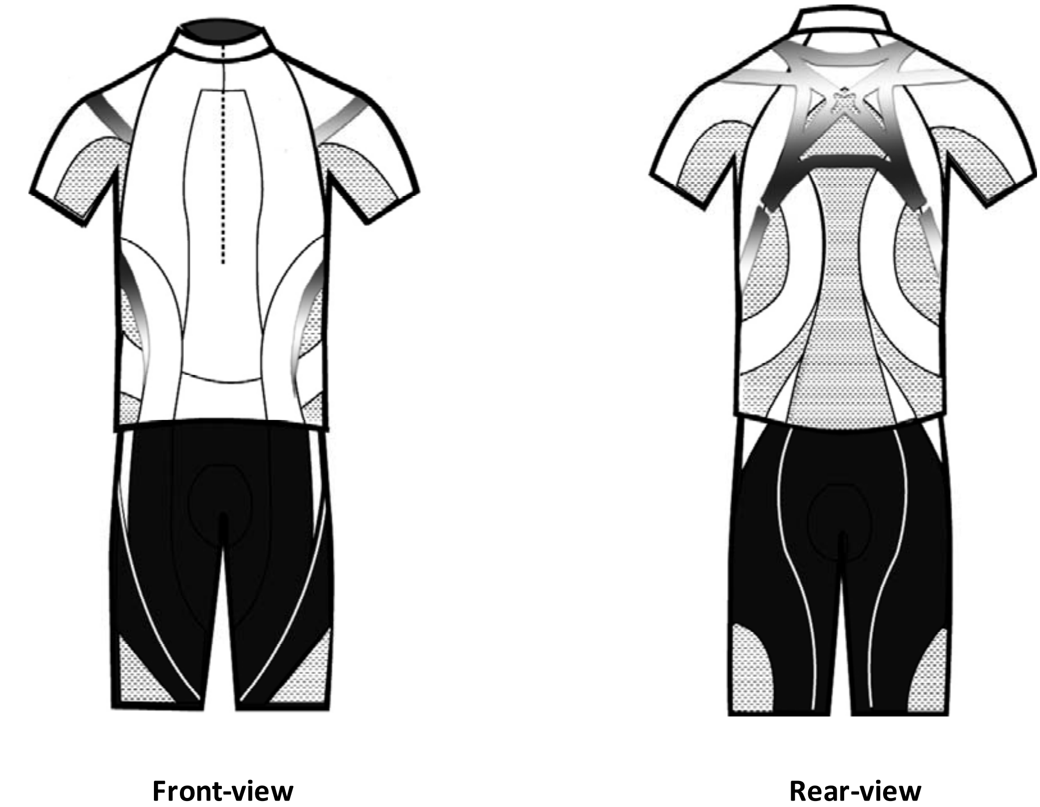
Similarly, the fabrics adopted for these two prototypes include PP-plain, PP-tuck, PP-plating, PP-1x1 rib and PP-2x2 rib. The basic properties, knitting structures and images of the selected fabrics for this prototype refer to Table 7.1 and the discussion in the part of Speed-pro.

- ***Garment pattern***

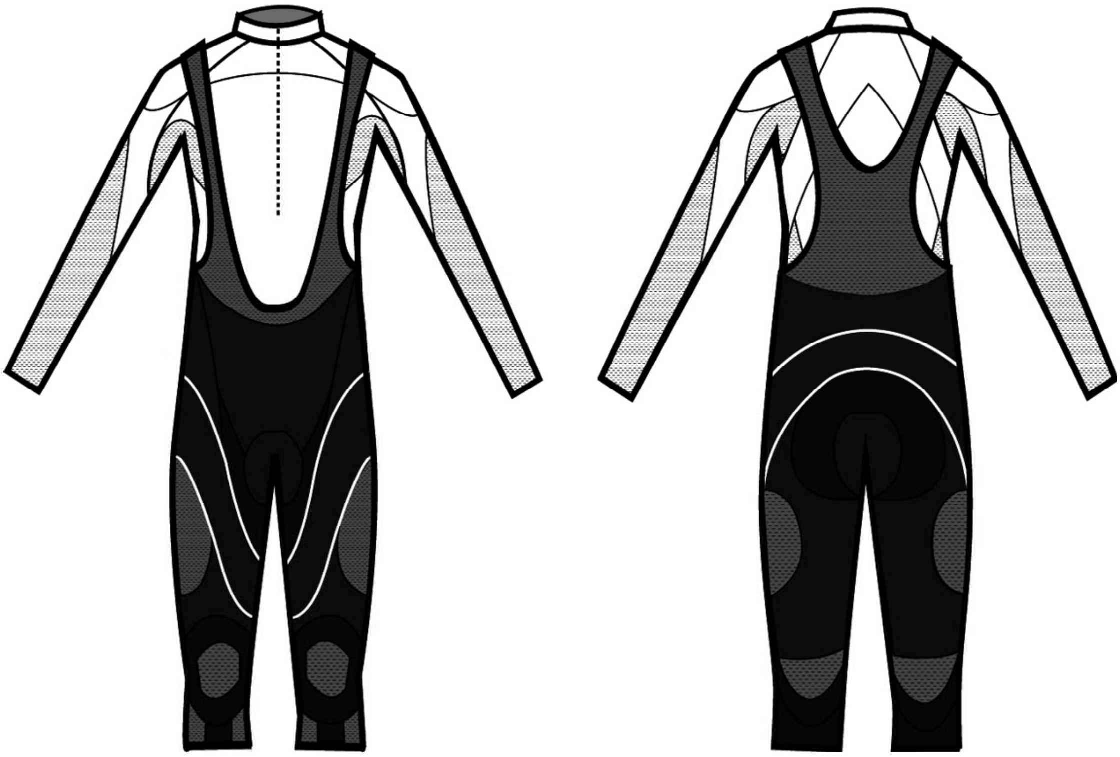
These two FCS prototypes were made up with five and six pattern pieces, respectively, aiming to reduce the number of seam lines, which may cause evident friction and resistance to the muscle. The detail garment patterns for these two suits of prototypes are demonstrated in Fig. 7.14.

- ***Design demonstration***

The final two prototypes of Speed-power are displayed in Fig. 7.15. The pictures demonstrate both the front view and back view of the prototypes.

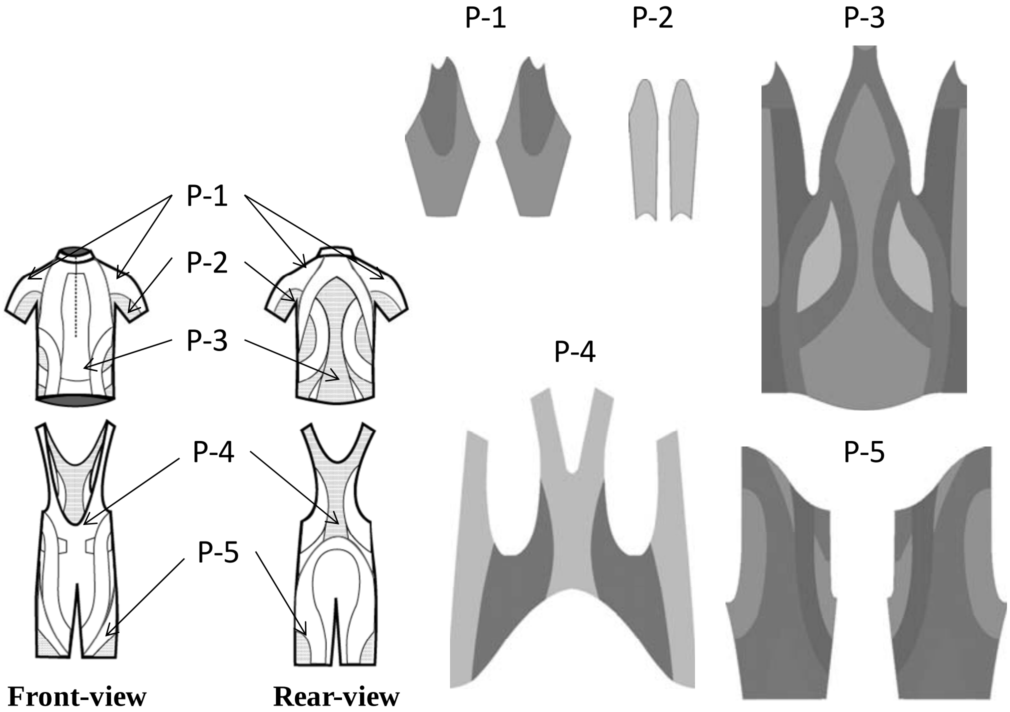


a) Speed-power 1

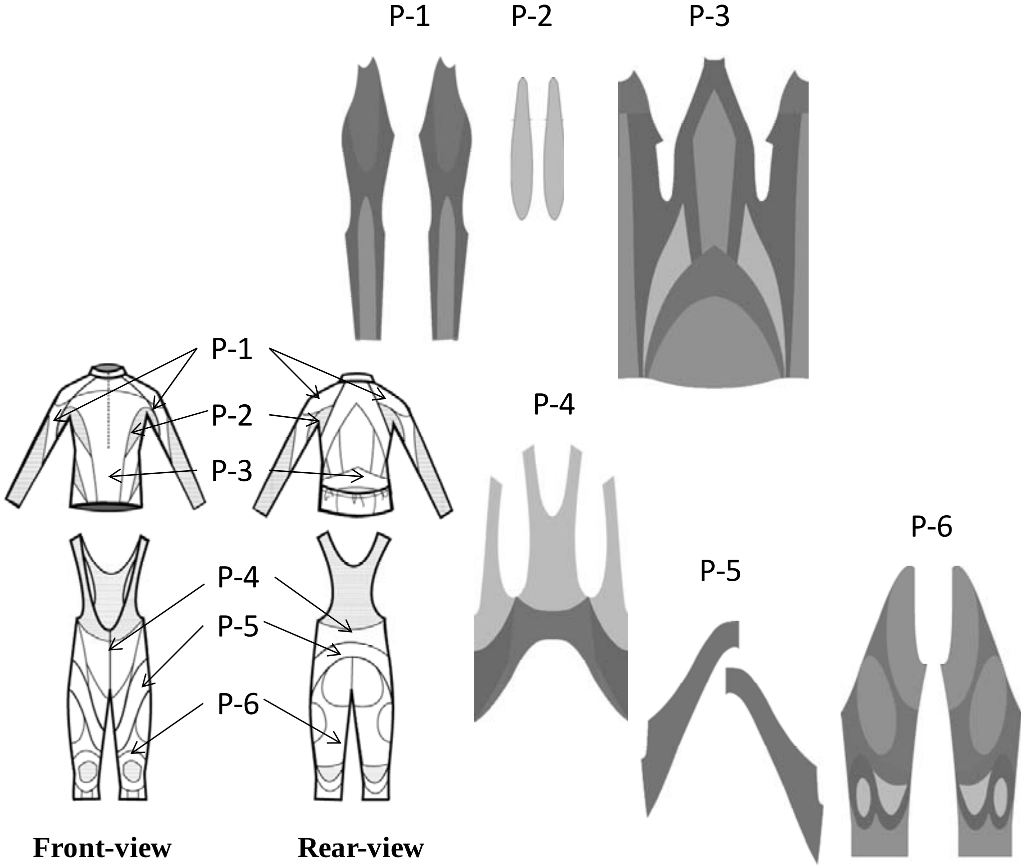


b) Speed-power 2

Fig. 7.13 Design schemes of Speed-power



a) Speed-power 1



b) Speed-power 2

Fig. 7.14 Garment patterns of Speed-power

Front-view Rear-view

a) Speed-power 1

Front-view Rear-view

b) Speed-power 2

Fig. 7.15 Design demonstration of Speed-power

7.3.3 Public Event

This collection participated in the 5th Qiaodan Cup International Sport Equipment Design Contest and won the Golden Prize. This competition encourages the players enjoy themselves in sports equipment to show the creative design, not only closely linked to the international sports equipment to the popular trend, but also reflects the Chinese culture, heritage and heritage, the sports, technology, fashion, innovation, internationalization and localization of integration, to create their own characteristics. The photos of catwalk and certification are show in Fig.7.16.

a) Collection I in the catwalk

荣誉证书

罗洁在“乔丹杯”第 5 届中国运动装备设计大赛运动装组中荣获金奖，特发此证。

中国服装设计师协会

二[illegible]年十月二十[illegible]日

b) Certification of Golden Prize

Fig. 7.16 Photos of catwalk and certification of collection I

7.4 Collection II: Angle

7.4.1 Design Inspiration

The design inspiration of this collection came from the silhouettes of a series of architectures, called ‘angle’, as shown in Fig. 7.17. The architectures with special sculpts demonstrate strong but smooth feeling of lines. The angles between lines varying from acute to obtuse range show an aesthetic sense of pursuit. The color yellow, which is according to the yellow jersey for the champion of Tour of France, was adopted as the main color for this collection (shown in Fig.7.18).

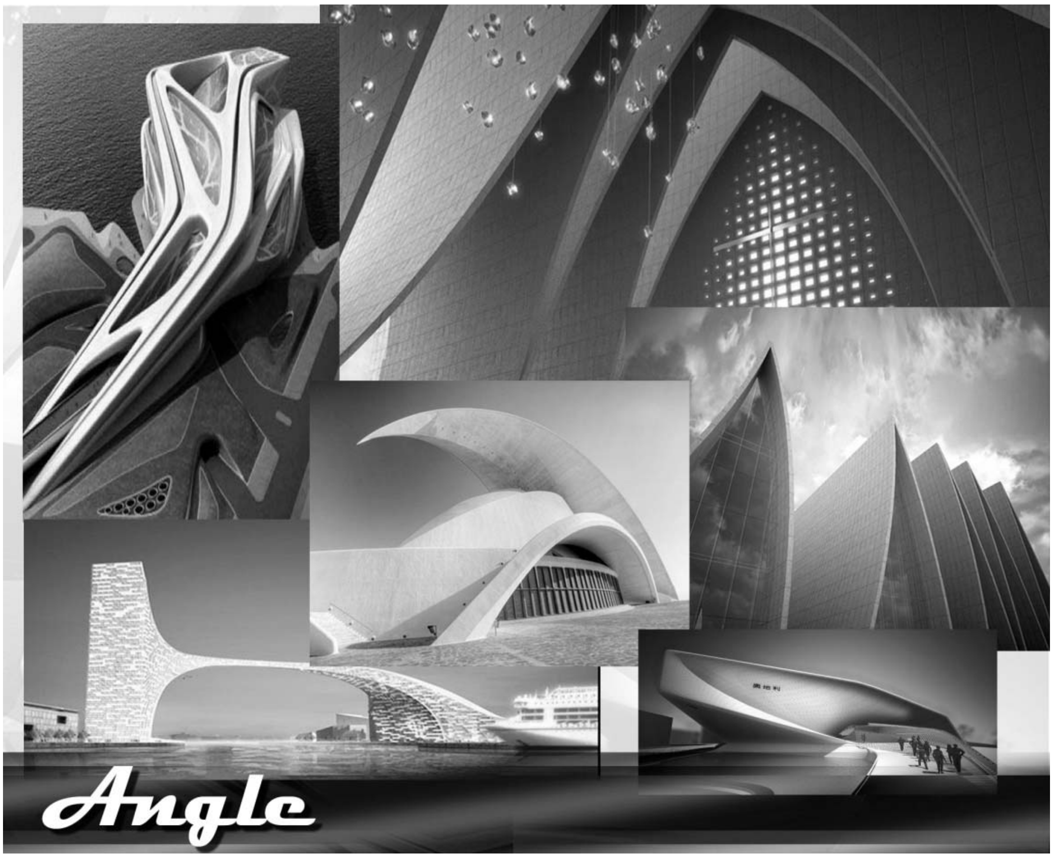


Fig. 7.17 Inspiration for the collection II

Fig. 7.18 Colors for the collection II

7.4.2 Design Brief

- ***Design scheme***

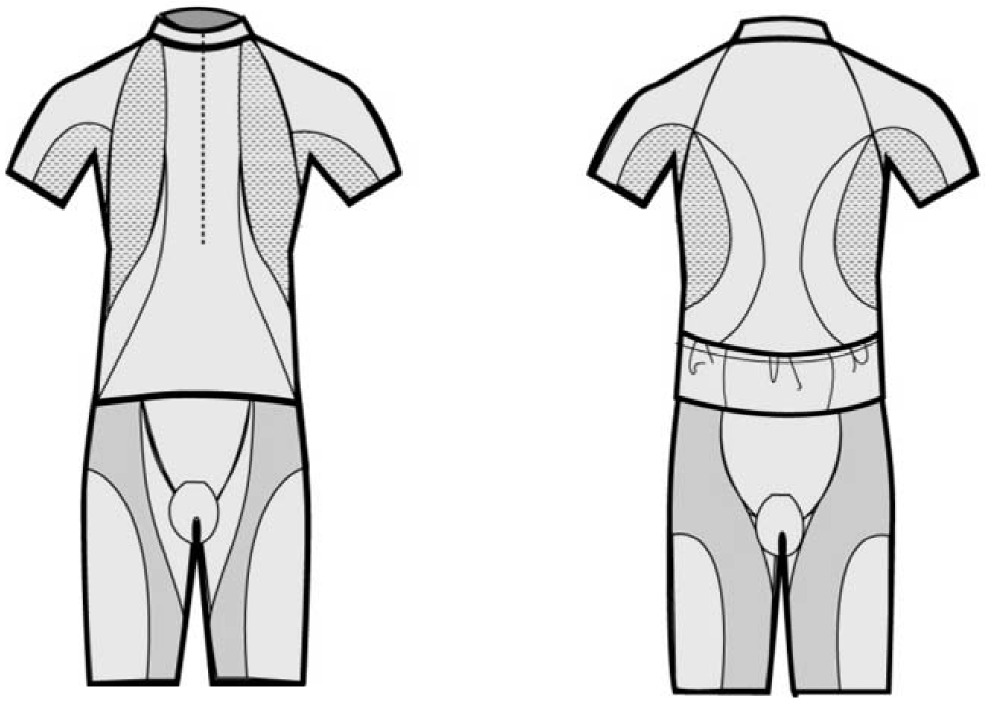
There are total two suits of FCS in this collection, which were both designed with the style of jersey and bib shorts. Fig. 7.19 shows the design sketch for these two suits of FCS. The curved lines were adopted in the design of this collection to demonstrate aesthetic sense of pursuit and strength by varying angles.

- ***Fabric***

The adopted fabrics for this collection include the ones with plain structure, tuck stitch structure, plating structure, 1x1 rib structure and 2x2 rib structure, as shown in Fig. 7.20.

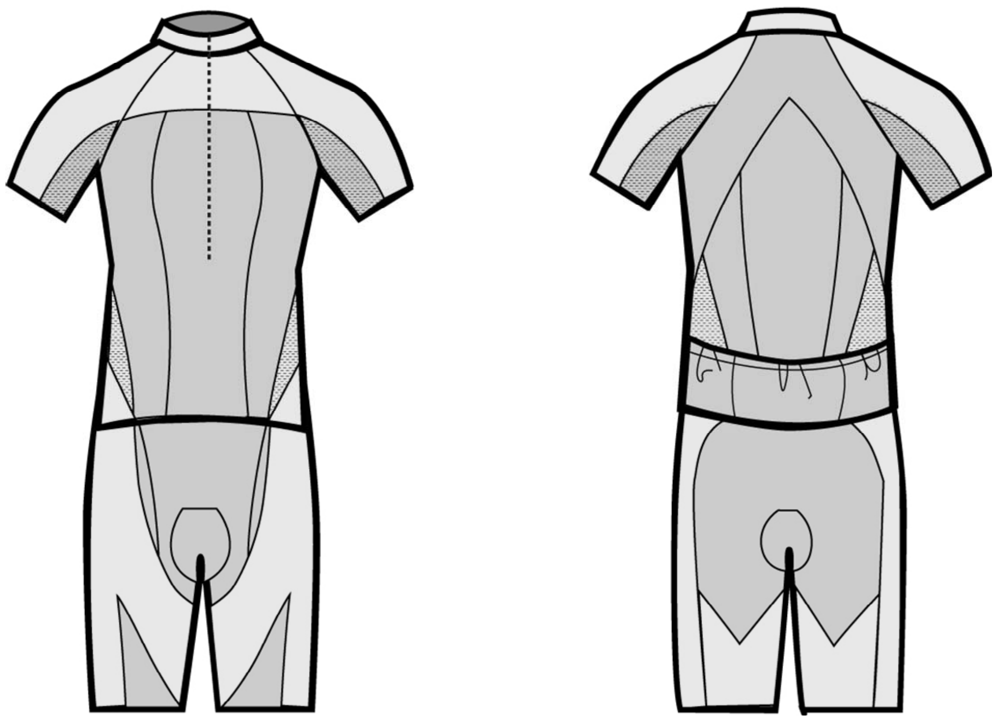
- ***Garment pattern***

Both of these two FCS prototypes were made up with three pattern pieces to reduce the number of seam lines and generate varied angels with curved lines. t friction and resistance to the muscle. The detail garment patterns for these two suits of prototypes are demonstrated in Fig. 7.21.



Front-view **Rear-view**

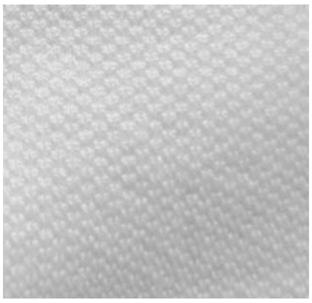
a) Suit 1



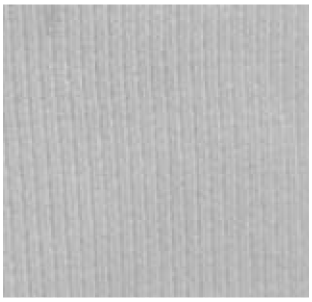
Front-view **Rear-view**

b) Suit 2

Fig. 7.19 Design sketches of the collection II



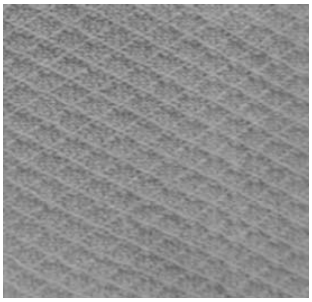
Plating structure
Polypropylene
(70/72/1 PP)
Elastane
(20/20/1 Nylon cover Lycra)



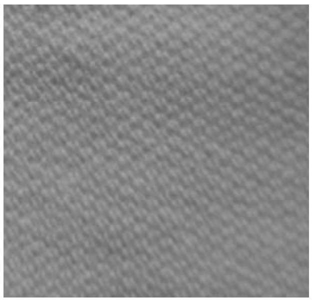
1x1 Rib structure
Polypropylene
(70/72/1 PP)
Elastane
(20/20/1 Nylon cover Lycra)

2x2 Rib structure
Polypropylene
(70/72/1 PP)
Elastane
(20/20/1 Nylon cover Lycra)

1x1 Rib structure
Polypropylene
(70/72/1 PP)
Elastane
(20/20/1 Nylon cover Lycra)



Tuck stitch structure
Polypropylene
(70/72/1 PP)
Elastane
(20/20/1 Nylon cover Lycra)

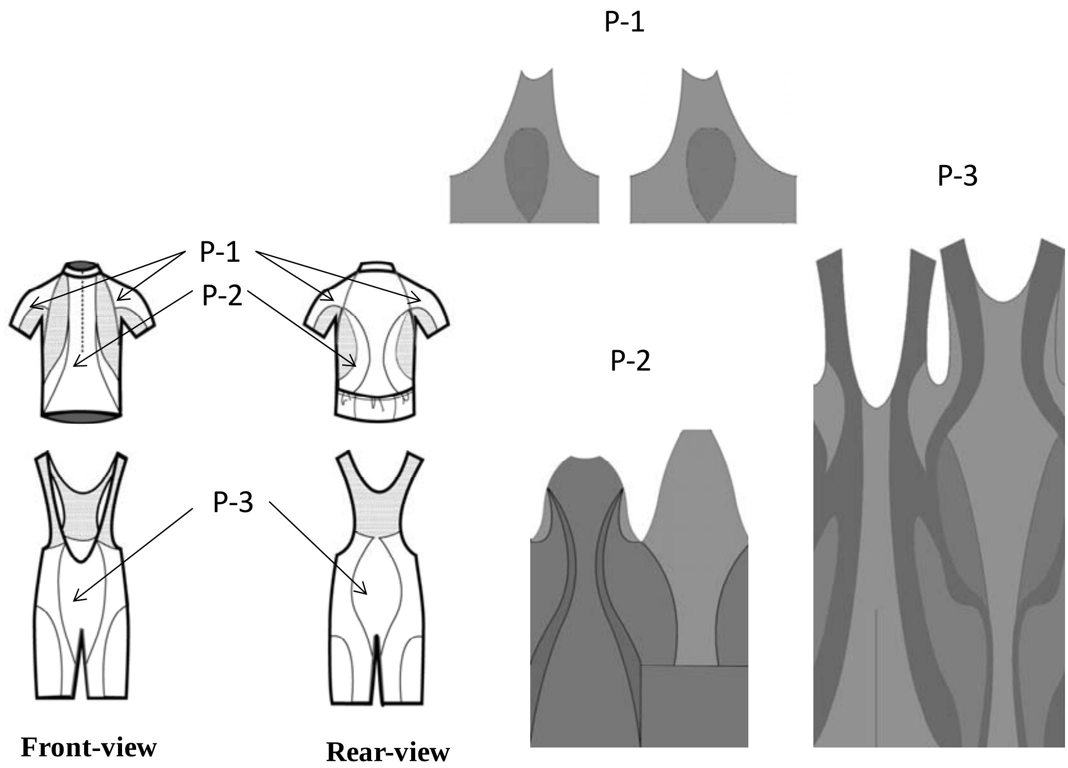


Plating structure
Polypropylene
(70/72/1 PP)
Elastane
(20/20/1 Nylon cover Lycra)

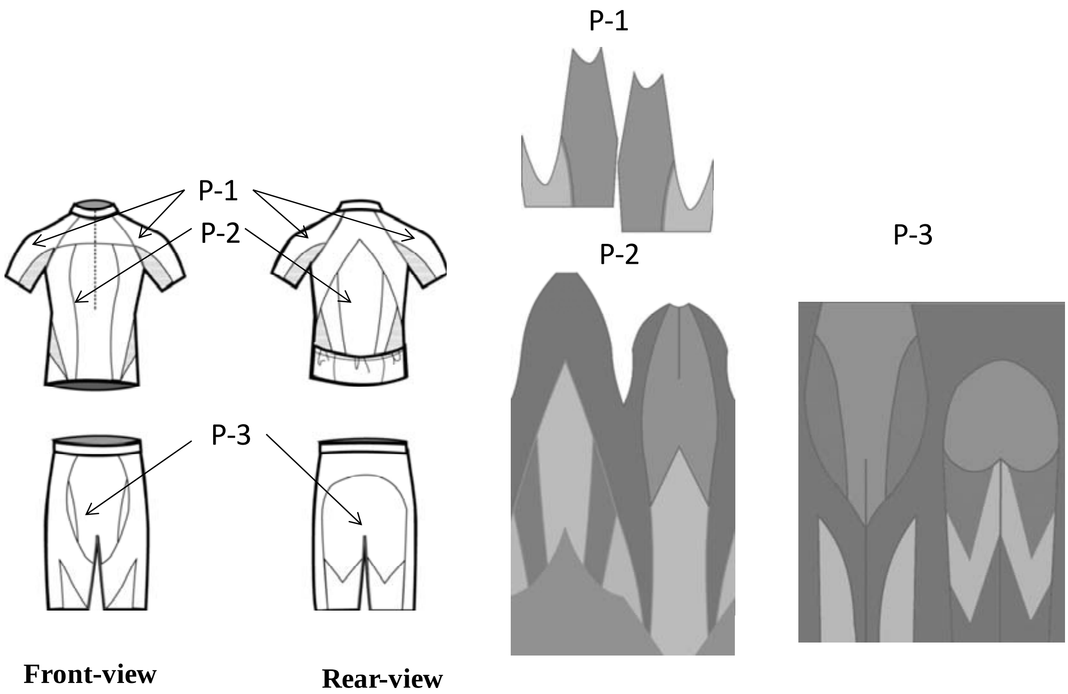
Fig. 7.20 Fabrics for the collection II

- ***Design demonstration***

The final FCS prototypes of this collection are displayed in Fig. 7.22. The pictures demonstrate both the front view and back view of the prototype.



a) Suit 1



b) Suit 2

Fig. 7.21 Garment patterns for the collection II

a) Suit 1

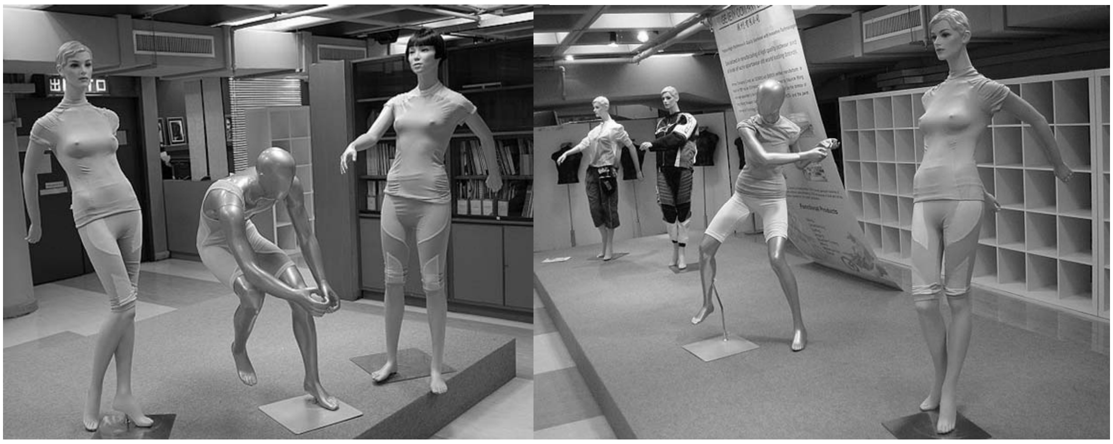
b) Suit 2

Fig. 7.22 Design demonstration of the collection II

7.4.3 Public Event

This collection was selected for the exhibition of the SMART Convention 2008, which was one of the highlight of the 'CUHK Olympic Carnival' held in Hong Kong with the central theme of 'in support of Olympic Spirit'. The photos of this collection in the exhibition are shown in Fig. 7.23

a) Photo 1



b) Photo 2

Fig. 7.23 Photos of the collection II in exhibition

7.5 Collection III: Glory

7.5.1 Design Inspiration

The national, regional or even club's cultures often impose an important influence on the design of sportswear (McCann, 2005). Especially, in the international competition, for instance, the Olympic Games, the sportswear often adopts the representative pattern or the elements from the national flag for easily identifying the country or region of the athletes. This collection was especially designed for the Hong Kong cycling team for the London Olympic Games in 2012. The inspiration of this collection came from the aspiration of the champion, which offers cyclists the feeling of speed, perfection and great honour. This aspiration can be expressed by the element of Bauhinia, which is the regional flower of Hong Kong, and can be regarded as a symbol representing the culture and feature of Hong Kong, as shown in Fig. 7.24.

Red, which is the color of the regional flag of Hong Kong, was adopted to be the main color for this collection, combined with white symbolizing the cercis and blue symbolizing high-tech, as shown in Fig. 7.25.

Fig. 7.24 Design inspiration for the collection III

Fig. 7.25 Colors for the collection III

7.5.2 Design Brief

- ***Design scheme***

There are total two suits of FCS in this collection, in which one was designed with long sleeves and the other was designed with short sleeves. However, both of these two prototypes are in the style of all-in-one suit and short pant. Fig. 7.26 shows the design schemes of this collection. The artwork design was determined by the Hong Kong Cycling Association and was realized by Champion System Ltd. with their company logo as the sponsor.

- ***Fabric***

As demonstrated in Fig. 7.27, three MMF-treated fabrics, which are characterized as being thick, high compression and thin, respectively, were adopted for this collection. Fabric 1 is characterized as having the surface alike to the golf ball, which can reduce wind resistance during cycling, and having thick thickness to prevent traumatic injury. It was used for the parts of arms and shoulders; Fabric 2 is characterized as having high compression function, which can reduce muscle vibration and improve performance during competitions. It was used for the parts of back, waist and thighs; Fabric 3 is characterized as having thin thickness and MMF capability to release the heat and sweat moisture quickly. It was used for all the other parts. Meanwhile, these fabrics were dyed, and printed with Bauhinia by thermal transfer to illustrate the culture of Hong Kong.

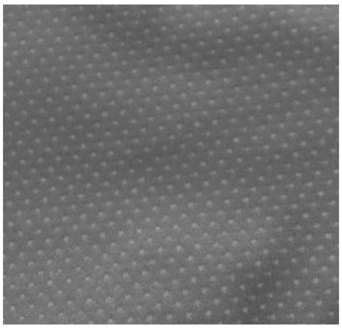
Front-view **Rear-view**

a) Suit 1

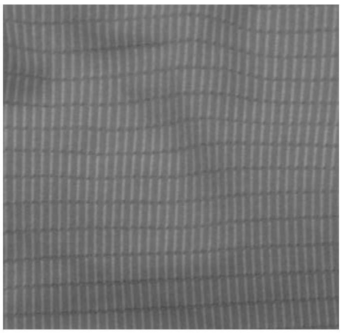
Front-view **Rear-view**

b) Suit 2

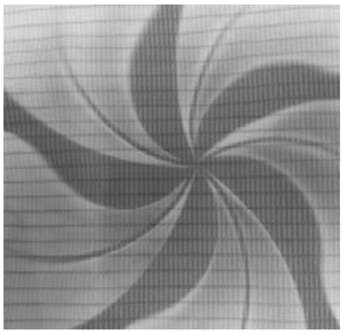
Fig. 7.26 Design schemes for the collection III



Fabric 1
Thick, MMF
80% Nylon
20% Elastane



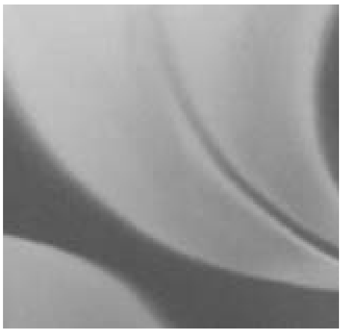
Fabric 2
High compression, MMF
80% Nylon
20% Elastane



Fabric 2
High compression, MMF
(with thermal transfer printing)
80% Nylon
20% Elastane

Fabric 3
Thin, MMF
80% Nylon
20% Elastane

Fabric 3
Thin, MMF
80% Nylon
20% Elastane

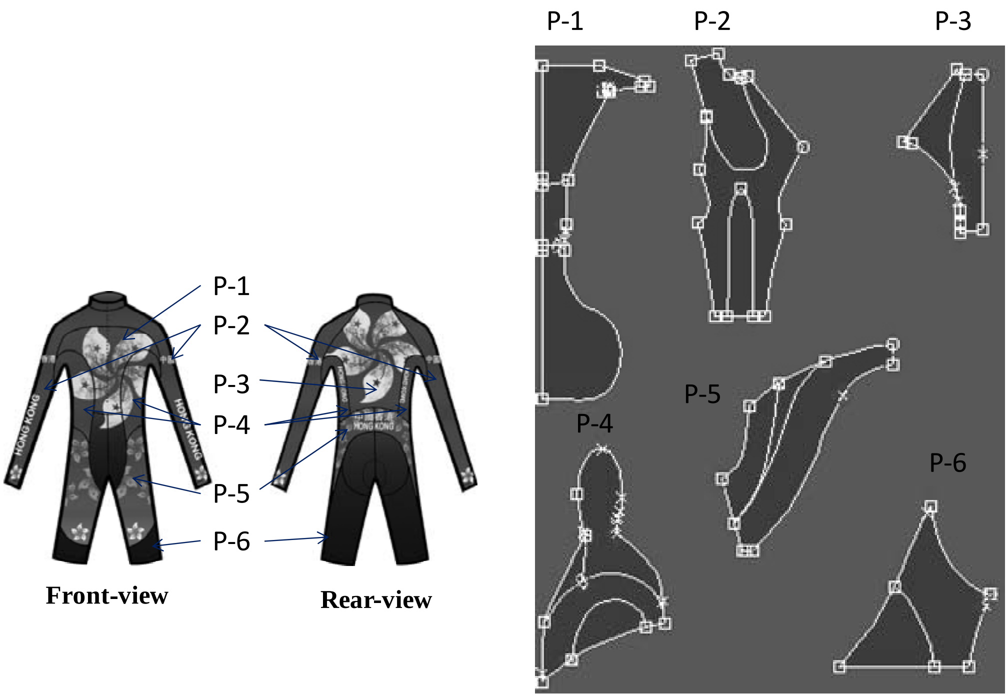


Fabric 3
Thin, MMF
(with thermal transfer printing)
80% Nylon
20% Elastane

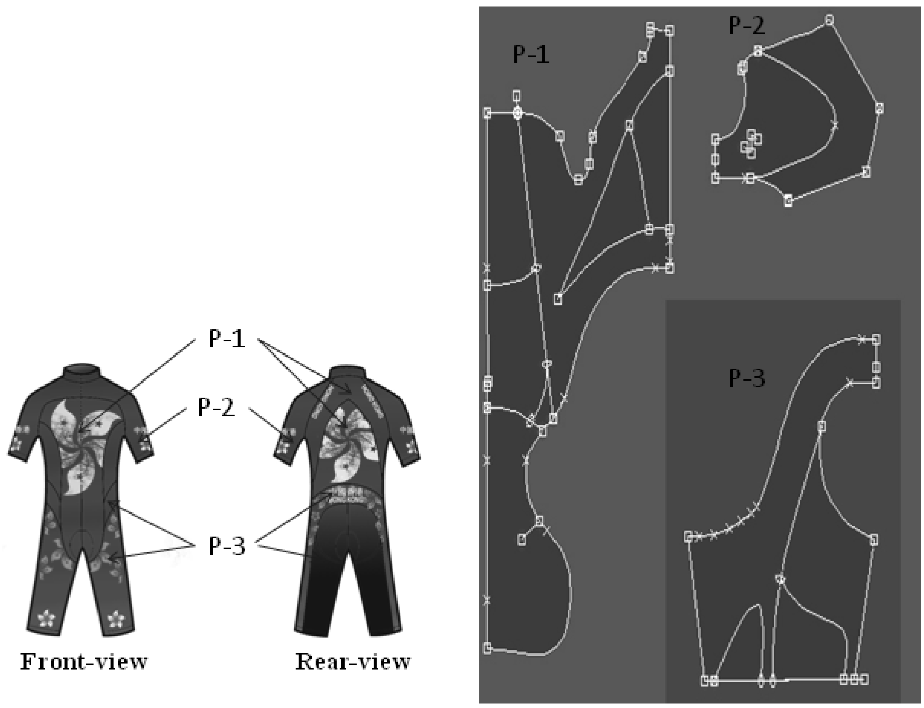
Fig. 7.27 Fabrics for the collection III

- ***Garment pattern***

The two FCS prototypes consist of six and three pattern pieces, respectively. The detail garment patterns for these two suits of prototypes are demonstrated in Fig. 7.28.



a) Suit 1



a) Suit 2

Fig. 7.28 Garment pattern for the collection III

- ***Design demonstration***

The final prototypes for this collection are displayed in Fig.7.29. The pictures demonstrate both the front view and back view of the prototypes. The prototypes, designed with short pants but long and short sleeves respectively, is in accordance with the common styles adopted for the cycling competition.

a) Suit 1

b) Suit 2

Fig. 7.29 Design demonstration for the collection III

7.5.3 Public Event

With the corporation with the Champion System Ltd. and Hong Kong Sports Institute, this collection was designed and developed especially for the Hong Kong team for their competition uniform in the 2012 London Olympic Games. Fig.7.30 shows the photos of this collection worn on the elite cycling athlete in the training process.

Fig. 7.30 Collection III worn by the elite cycling athlete

7.6 Conclusion

This chapter has described the realization of the functional cycling sportswear design. Firstly, a typical creation procedure of the designed prototypes is presented, including the process, technology and machines involved. According to this creation procedure, the collection I is designed and created for the 5th Qiaodan Cup International Sports Equipment Design Contest and awarded with Golden Prize. In this collection, the creation of the prototypes respectively for competition and training is introduced in detail to illustrate the realization process of FCS design. The design inspiration, design scheme, fabric selection, garment patterns and design demonstration are described accordingly. Based on the method of this design innovation, collections II and III are designed and created with prototypes respectively for the exhibition of SMART Convention 2008 and the 2012 Olympic Games.

CHAPTER 8 CONCLUSION AND FUTURE WORKS

8.1 Conclusion

This research study aims to formulate a design innovation model of functional cycling sportswear (FCS) that is able to fulfill the wearers' aesthetic needs and functional requirements of cycling sportswear. The final functional cycling sportswear is achieved by fusing the aesthetic design with thermal and biomechanical functional requirements. By applying this design innovation method, various FCS products are created with desired functional performance in terms of thermal comfort, muscle fatigue reduction, and muscle injury prevention.

With the findings reported in individual chapters, the five objectives of this research have been achieved, namely: 1) a multi-disciplinary framework of FCS design, 2) aesthetic design of cycling sportswear, 3) thermal functional design of cycling sportswear, 4) biomechanical functional design of cycling sportswear, and 5) realization of FCS products for different applications.

Specifically, this study is able to contribute the following new knowledge:

1) The characteristics of cycling sport and the mechanisms involved in related disciplines, such as thermal physiology, biomechanics, and aesthetics have been investigated in detail and become available knowledge for FCS design. The

aesthetic elements in terms of fabric, cut, and color have been studied and their functional influences of physiological and psychological effects on game performance have been investigated. The thermal mechanisms of cycling sports in terms of thermal conditions and thermal comfort has been illustrated. Furthermore, the biomechanical mechanisms in terms of skeletal muscles, muscle fatigue and injuries, as well as sport injuries have also been examined.

2) The multi-disciplinary framework developed in this study not only provides a methodology to achieve the functional cycling sportswear design, but it also provides theoretical foundation of developing design innovation models for other sportswear designs, such as running, rolling and badminton. This multi-disciplinary framework illustrates how to accomplish the systematic procedure for achieving the functional design FCS. Besides, the functions of cycling sportswear have been analyzed by investigating the multi-functional needs of the body, and the functional requirements of cycling sportswear have been identified. The knowledge from different fields of thermal physiology, biomechanics, and aesthetics has been systematically integrated.

3) The integrated process between the aesthetic and functional design demonstrated in this study is the key issue in the realization of this FCS design innovation. It is the first time that the integrated process of design and technology has been clearly discussed through the design elements in terms of fabric, cutting and color. In

these design elements, the fabric takes the basic role of achieving different styles and fulfilling various thermal and biomechanical functional design requirements. The color of the fabric is decided by its influence on performance as well as the influence of culture. The cutting is based on the cycling anatomy and 3D body information. It concerns the biomechanical requirements of body by reducing the seam lines and achieves the best fit for different body parts. A theoretical model for integrating aesthetic and functional design in sportswear has been presented and is available for developing design innovation of sportswear.

4) The thermal functional design and biomechanical design realized in this study illustrate the theoretical methods and procedures in achieving the required functions of sportswear. The identification method of thermal physiology of cyclists can be applied to identify the thermal requirements of the body during other sports. The demonstration of muscle group recruitments in cycling can guide the muscle group analysis of body for other sportswear. The creation of thermal and biomechanical zones in this study presents a comprehensive method to express the functional requirements on different body parts. The appropriate pressure range for individual muscle groups provides helpful indication to achieve optimal compression effect in muscle injury prevention and fatigue reduction. Furthermore, the PU tape coating to strengthen the compression effects used in this study can be applied in producing other sportswear.

5) The procedure of creating prototype of FCS has been presented to illustrate the process, technology, and machine involved in the realization of the functional design of sportswear. The design inspiration, design scheme, color combination, fabric selection, garment pattern and construction specification have been discussed in detail. This procedure also offers a solid reference for the creation of other sportswear.

In summary, the design innovation of FCS presented in this study concretely demonstrates how design and technology are fused smoothly and systematically to achieve high quality functional sportswear. The integration of knowledge from different disciplines namely, thermal physiology, biomechanics and aesthetics generates new knowledge, methods, procedure and technology for FCS design. Furthermore, they can be applied for the innovative design of sportswear for other sports, such as running, rolling and badminton.

8.2 Directions for Future Works

As discussed above, the objectives of this study have been fully achieved. The design innovation of FCS has been realized by carrying out the aesthetic, thermal and biomechanical functional designs simultaneously. In addition, two prototypes of FCS for competition and training respectively have been produced by using current materials, equipment, and technologies. These prototypes have good functional characteristics and performance that are able to meet wearers' functional requirements. Future research work can be continued to improve the functional performance of FCS by: i) using advanced fabrics and technologies, ii) creating more FCS products for various applications, and iii) even expanding this technique of design innovation into the design of sportswear for other performance sports. The directions for future works are discussed as follows:

1) To further improve the functional perfromance of FCS. The functions of sportswear are practically determined by the textile materials, technologies, and even equipment, which hopefully improve the functions of FCS in this study. For example, the new fiber with better tesnsile and moisture properties can be adopted; the fabric can be knitted with more structures to achieve different functional characteristics in terms of compression and breathability; the fabric can also be used with more functional treatments for better heat dissipation, sweat release, and UV-protection; and the new technologies of seamless seaming and tape coating can be aided by advanced equipiment.

2) To create more FCS products for commercial applications. In this study, three collections were created for design contest, an exhibition and the Olympic Games. However, this design innovation technique can also be applied for design and production of commercial FCS products. The commercial FCS products can adopt

this technique to achieve superior functional characteristics by meeting the thermal, biomechanical, and aesthetic requirements of the wearers. These requirements have already become important factors influencing the buying decision of consumers, as surveyed in chapter 2, and it can also help manufacturers to seize the market by increasing their brand value.

3) To expand the new design innovation model for other kinds of performance sportswear. Although this design innovation places the focus on sportswear for cycling by investigating the characteristics of the sport and the cyclists during cycling, the systematic technique may be extended to other performance sports. The multidisciplinary framework that illustrates the integration of thermal, biomechanical, and aesthetic knowledge can also be applied as the basic framework for the design innovation of other performance sportswear. The mechanisms of thermal physiology, biomechanical protection of muscles, aesthetic elements, and fusion of the aesthetic design and functional design also lay solid theoretical fundamentals for the expansion of this design innovation. With this framework and theoretical fundamentals, the new design innovation can thus be smoothly realized the performance sportswear of other sports, such as running, swimming, and badminton.

APPENDIX A: QUESTIONNAIRE FOR THIS STUDY

THE HONG KONG
POLYTECHNIC UNIVERSITY
香港理工大學

自行车服装调查问卷/Questionnaire for cycling sportswear

请填写您的基本资料，并以√表示您的选择/ Please tick (√) your particular information:

- 性别/ Gender: （）男/Male （）女/Female
- 年龄/Age(year): （）18~20 （）21~23 （）24~26 （）27~29 （）above 30
- 体重/Weight (kg): （）below 55 （）56~60 （）61~65 （）66~70 （）71~75 （）above 76
- 身高/Height (cm): （）below 165 （）166~170 （）171~175 （）176~180 （）181~185 （）above 186
- 你进行自行车运动年限/How many years do you have experience of cycling exercise? :
  （）1~2 （）3~4 （）5~6 （）7~8 （）above 9
- 你的国籍/What's your nationality ?:____

Declaration

纺织及制衣学系 / Department of Institute of Textiles & Clothing
香港理工大学/The Hong Kong Polytechnic University
红磡/Hung Hom，九龙/Kowloon，香港/Hong Kong
T 852-34008920 | http://www.itc.polyu.edu.hk

RESEARCH PROJECT: FUCTIONAL CYCLING SPORTSWEAR DESIGN

Explanation of Research:

My name is Jie Luo and I am a PhD's student in the Department of Institute of Textiles & Clothing. You are being asked to fill out this questionnaire related to your functional cycling sportswear requirements. The significance of this study is to know what requirements are involved for functional cycling sportswear design. The objectives of this study included identifying professional functional cycling sportswear expectation, assessing the importance of professional functional cycling sportswear attributes and assess satisfaction with selection, fit, comfort, and style of garment for professional functional cycling sportswear different levels of professional cycling race commitment.

Your participation in this study is voluntary. There are no foreseeable risks or benefits to you for your participation in this study. The information you give is anonymous. You will not lose any benefits or rights you normally have is you choose not to participate. The questionnaire will take about 10 minutes to complete. You are free to skip any question or stop at any time. If you have any questions about this research project, please contact: Prof. Yi Li, at (852) 2766 6479 or the Hong Kong Polytechnic University research office (RO) at (852) 3400 3635 or by email at roro@inet.polyu.edu.hk

THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

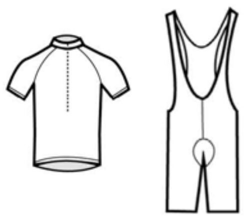
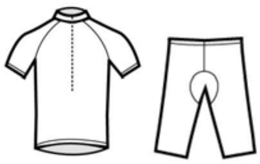
自行车服装调查问卷/Questionnaire for cycling sportswear

请根据您的认同度对以下各项进行评价（请用 5 分制打分，1=极不同意，2=不同意，3= 中立，4=同意，5=非常同意）/ Please grade your satisfactory level on the following items (from 1 to 5, 1=Strongly disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly agree)

Part Ⅰ 自行车运动服的功能性需求/Functional requirements on the cycling sportswear						
1. 你对专业自行车运动服的需求/Your requirements on the high performance cycling sportswear include:						
	保持身体干爽、凉爽（提供热湿舒适感）/ Can keep body cool and dry（Provide thermal comfort）	(1)	(2)	(3)	(4)	(5)
	可以提升肌肉运动状态/Can increase muscle power output	(1)	(2)	(3)	(4)	(5)
	可以防止肌肉受伤/Can prevent muscle from injury	(1)	(2)	(3)	(4)	(5)
	可以降低肌肉疲劳/Can reduce muscle fatigue	(1)	(2)	(3)	(4)	(5)
	能建立专业形象/ Have professional image	(1)	(2)	(3)	(4)	(5)
2. 以下设计元素对你骑行成绩会产生积极地影响/ The following factors in cycling sportswear design have positive influence on cycling performance:						
	提高运动状态的压力设计/Use compress design improving cycling performance	(1)	(2)	(3)	(4)	(5)
	采用快速排汗、干爽的面料/Use fabric keeping body cool and dry（thermal regulating fabric）	(1)	(2)	(3)	(4)	(5)
	色彩对情绪的影响/Consider psychological influence of colors	(1)	(2)	(3)	(4)	(5)
	参照自行车运动生物力学的裁剪/Design sportswear cutting based on cycling biomechanics (Will NOT reduce the muscles performance during cycling)	(1)	(2)	(3)	(4)	(5)
3. 你选择自行车运动服时主要考虑以下因素/You usually select cycling sportswear according to the following factors:						
	品牌/Brand	(1)	(2)	(3)	(4)	(5)
	热湿舒适度（保持干爽、凉爽）/ Keep body cool and dry(Thermal comfort)	(1)	(2)	(3)	(4)	(5)
	可提升运动状态的高科技纺织品和工艺/Hi-tech textiles and technology for improving cycling performance	(1)	(2)	(3)	(4)	(5)
	剪裁/Fit (cutting)	(1)	(2)	(3)	(4)	(5)
	款式/Style	(1)	(2)	(3)	(4)	(5)
	色彩/Color	(1)	(2)	(3)	(4)	(5)
4. 请指出你对这次大运会比赛中所穿的自行车运动服的各项设计的满意度（1=极不满意，2=不满意，3= 中立，4=满意，5=非常满意）/Please rate your satisfactory level on your cycling sportswear for the UNIVERSIADE 2011 SHENZHEN in following aspects **(from 1 to 5, 1=Not satisfied at all, 2=Mostly dissatisfied, 3=Neutral, 4=Satisfied, 5= Highly satisfied)**						
	热湿舒适度（保持干爽、凉爽）/Can keep body cool and dry (Thermal comfort)	(1)	(2)	(3)	(4)	(5)
	可以提升运动状态/Can increase muscle power output	(1)	(2)	(3)	(4)	(5)
	可以防止肌肉受伤/Can prevent muscle from injury	(1)	(2)	(3)	(4)	(5)

	可以降低肌肉疲劳/Can reduce muscle fatigue	(1)	(2)	(3)	(4)	(5)
	能建立专业形象/ Have professional image	(1)	(2)	(3)	(4)	(5)
	防太阳辐射/Have UV protection	(1)	(2)	(3)	(4)	(5)
	参照自行车运动生物力学的裁剪/Have sportswear cutting based on cycling biomechanics (Will NOT reduce the muscles performance during cycling)	(1)	(2)	(3)	(4)	(5)
	色彩/Color	(1)	(2)	(3)	(4)	(5)

请根据您的认同度对以下各项进行评价（请用 5 分制打分，1=极不同意，2=不同意，3= 中立，4=同意，5=非常同意）/ Please grade your satisfactory level on the following items (from 1 to 5, 1=Strongly disagree, 2=Disagree, 3=Neutral, 4=Agree, 5=Strongly agree)

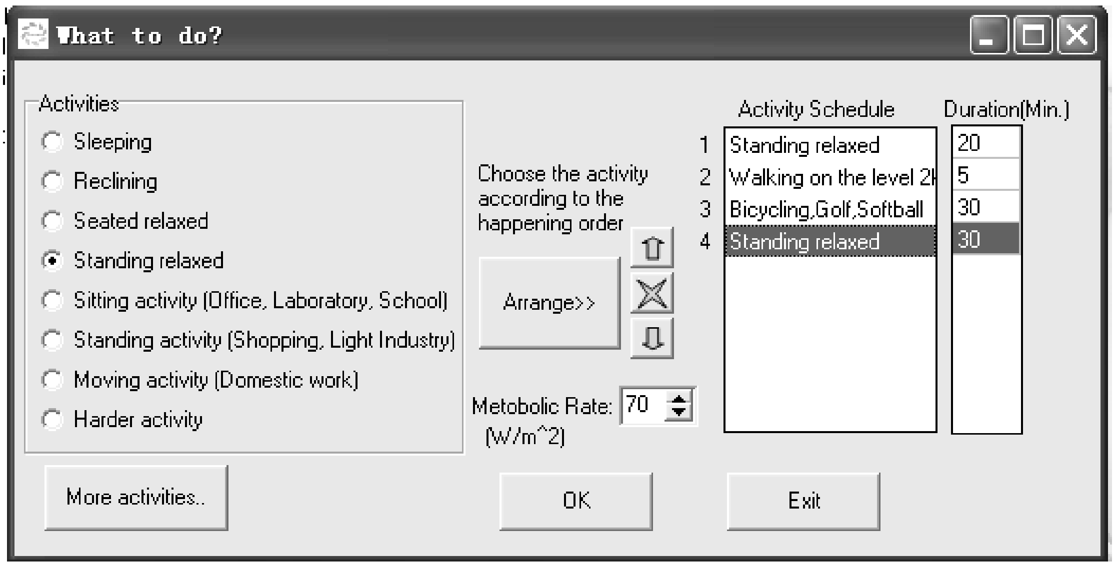
Part Ⅱ 自行车运动服的设计需求/ Design requirements on cycling sportswear						
5.	你对自行车运动服松紧度的认同度/You are more satisfied with the cycling sportswear fit status:					
	很紧身/Very tight fit	(1)	(2)	(3)	(4)	(5)
	紧身/Tight fit	(1)	(2)	(3)	(4)	(5)
	合身/Just fit	(1)	(2)	(3)	(4)	(5)
	宽松/Loose	(1)	(2)	(3)	(4)	(5)
6.	你对自行车运动服款式的认同度/ You are more satisfied with the cycling sportswear style:					
	 背带款/Jersey and bib shorts	(1)	(2)	(3)	(4)	(5)
	 上下分体款/ Jersey and shorts	(1)	(2)	(3)	(4)	(5)
	 连体款/All-in-one suit	(1)	(2)	(3)	(4)	(5)

7. 骑行时以下身体各部位将会被太阳辐射晒伤/ During cycling the following body parts are easily injured by solar radiation						
	脸/Face	(1)	(2)	(3)	(4)	(5)
	颈部和肩部/Neck and shoulder	(1)	(2)	(3)	(4)	(5)
	手臂/Arm	(1)	(2)	(3)	(4)	(5)
	背/Back	(1)	(2)	(3)	(4)	(5)
	腹部/Abdomen	(1)	(2)	(3)	(4)	(5)
	大腿/Thigh	(1)	(2)	(3)	(4)	(5)
	小腿/Calf	(1)	(2)	(3)	(4)	(5)
8. 在骑行中以下身体各部位容易疲劳/During cycling the following body parts are easy to have fatigue and influence on cycling performance						
	肩膀/Shoulder	(1)	(2)	(3)	(4)	(5)
	手臂/Arm	(1)	(2)	(3)	(4)	(5)
	背部/Back	(1)	(2)	(3)	(4)	(5)
	腹部/Abdomen	(1)	(2)	(3)	(4)	(5)
	腰部/Waist	(1)	(2)	(3)	(4)	(5)
	臀部/Bottom	(1)	(2)	(3)	(4)	(5)
	大腿/Thigh	(1)	(2)	(3)	(4)	(5)
	膝盖/Knee	(1)	(2)	(3)	(4)	(5)
	小腿/Calf	(1)	(2)	(3)	(4)	(5)
9. 以下各身体部位在自行车服设计中应该采取特殊设计以防止运动中的损伤/The following body parts need to be especially protected from injury during cycling in the cycling sportswear design						
	肩膀/Shoulder	(1)	(2)	(3)	(4)	(5)
	手臂/Arm	(1)	(2)	(3)	(4)	(5)
	背部/Back	(1)	(2)	(3)	(4)	(5)
	腹部/Abdomen	(1)	(2)	(3)	(4)	(5)
	腰部/Waist	(1)	(2)	(3)	(4)	(5)
	臀部/Bottom	(1)	(2)	(3)	(4)	(5)
	大腿/Thigh	(1)	(2)	(3)	(4)	(5)
	膝盖/Knee	(1)	(2)	(3)	(4)	(5)
	小腿/Calf	(1)	(2)	(3)	(4)	(5)
10. 以下各个部位的裁剪会对你的骑行产生负面影响（红圈内部）/The cutting and seam lines on the following parts may have negative influence on your cycling performance（marked with red circle)						
	 肩、袖子裁剪/Cutting on sleeve part	(1)	(2)	(3)	(4)	(5)

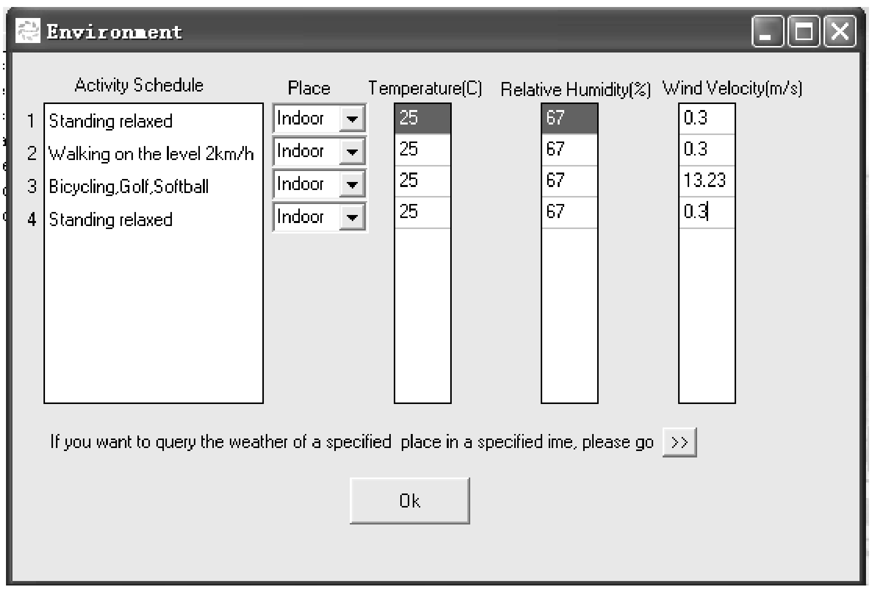
	 侧面裁剪/ Cutting on body sideseam	(1)	(2)	(3)	(4)	(5)
	 腰部裁剪/ Cutting on waist part	(1)	(2)	(3)	(4)	(5)
	 腿部裁剪/ Cutting on front thigh part	(1)	(2)	(3)	(4)	(5)
11.	你喜爱的自行车服装的颜色/ The colors of cycling sportswear you prefer					
	红/Red	(1)	(2)	(3)	(4)	(5)
	朱红/Vermilion	(1)	(2)	(3)	(4)	(5)
	黄/Yellow	(1)	(2)	(3)	(4)	(5)
	绿/Green	(1)	(2)	(3)	(4)	(5)
	蓝/Blue	(1)	(2)	(3)	(4)	(5)
	紫/Purple	(1)	(2)	(3)	(4)	(5)
	黑/Black	(1)	(2)	(3)	(4)	(5)
	白/White	(1)	(2)	(3)	(4)	(5)

APPENDIX B: SIMULATION PROCESS AND INTERFACES WITH P-SMART SYSTEM

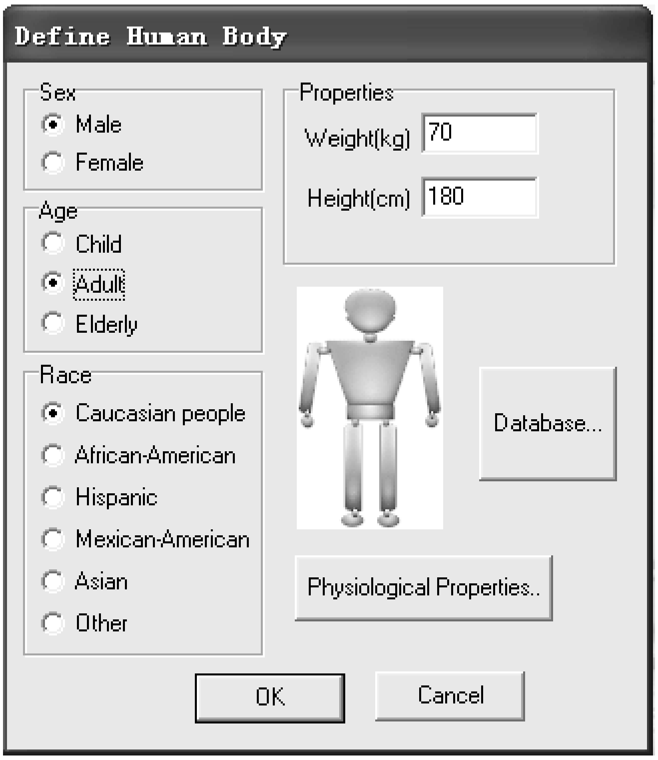
Step1: define activity schedule



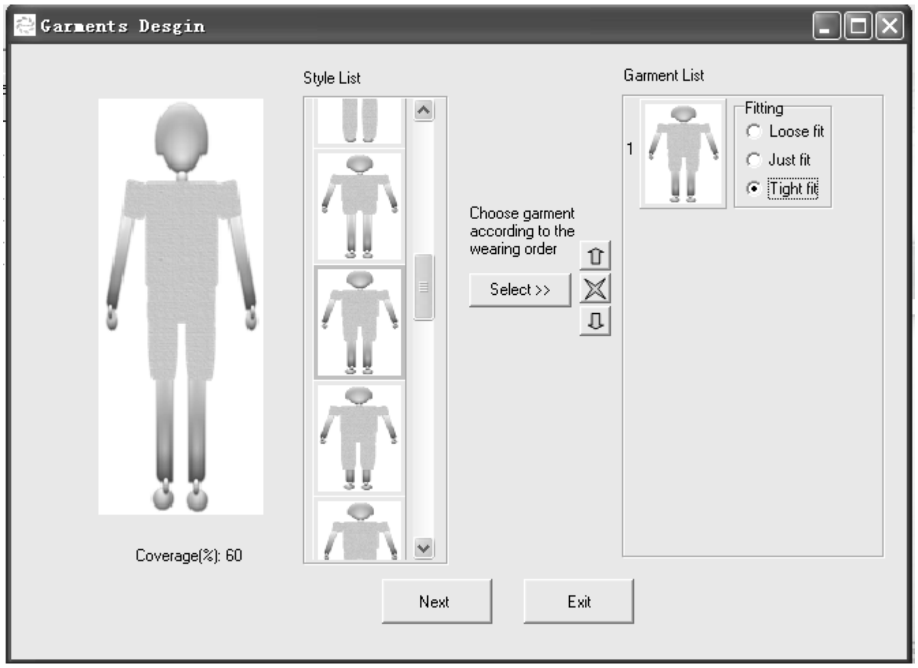
Step 2: define air temperature, relative humidity and wind velocity



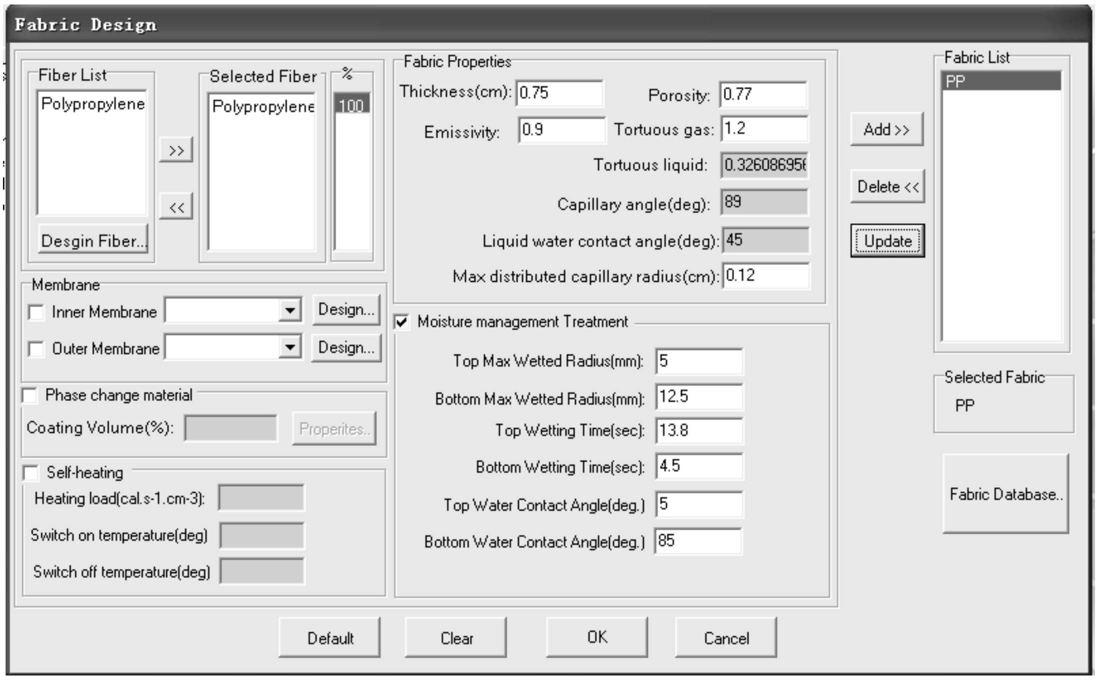
Step 3: Specify the wearer



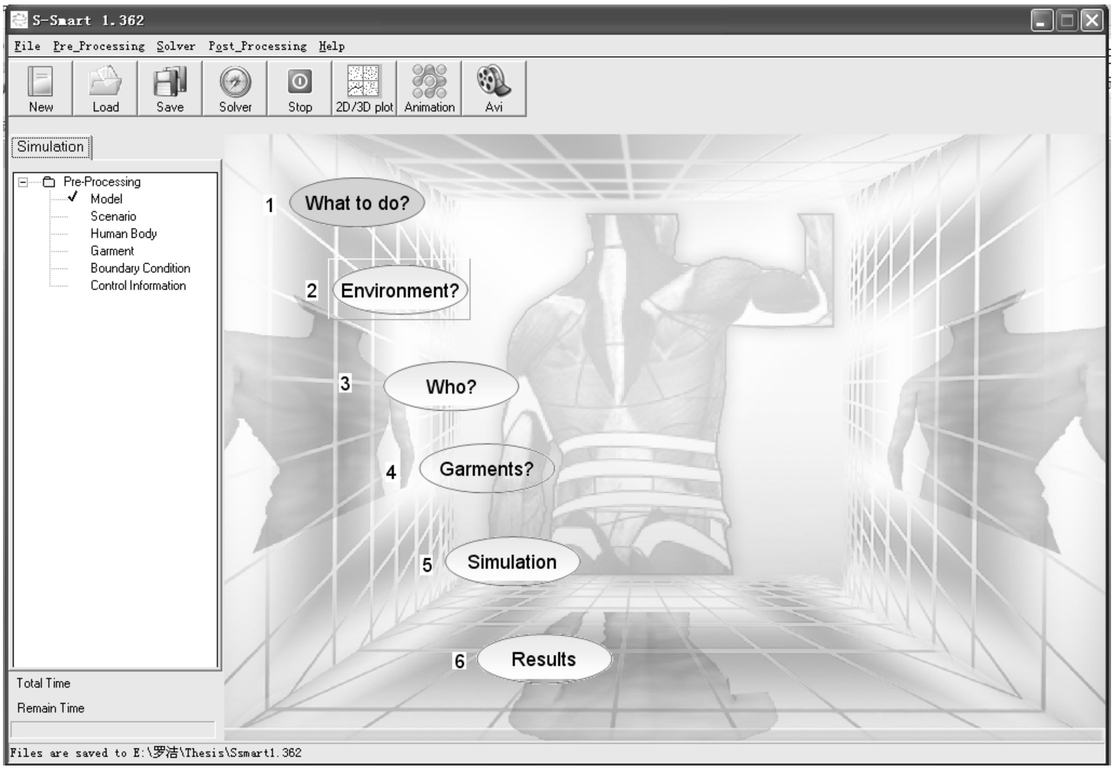
Step 4: Specify the wearer



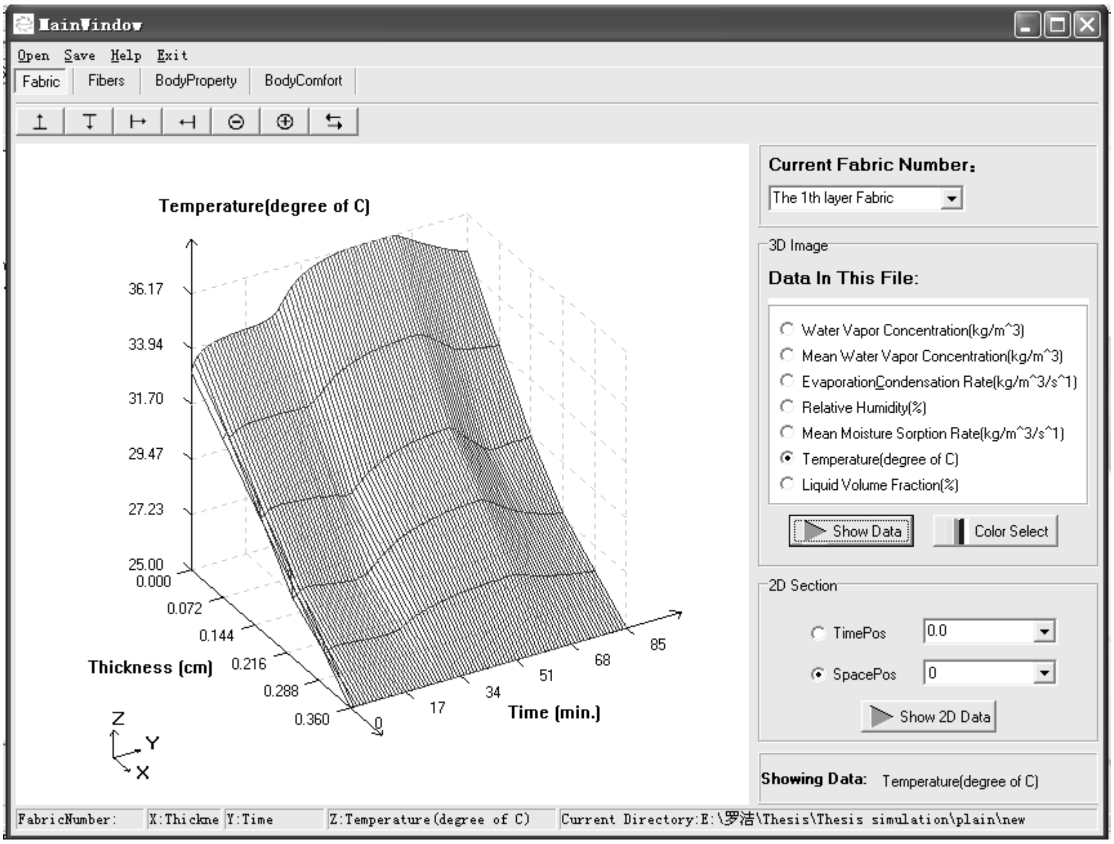
Step 4: design the fabric

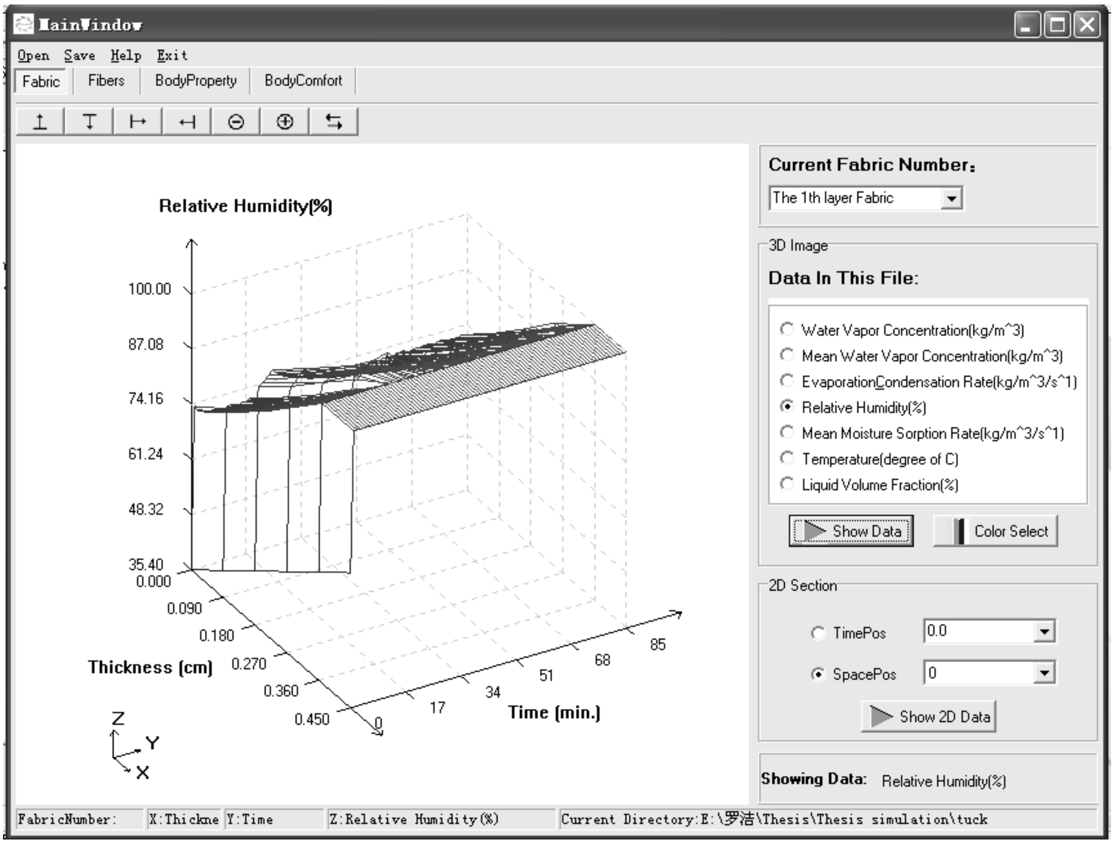


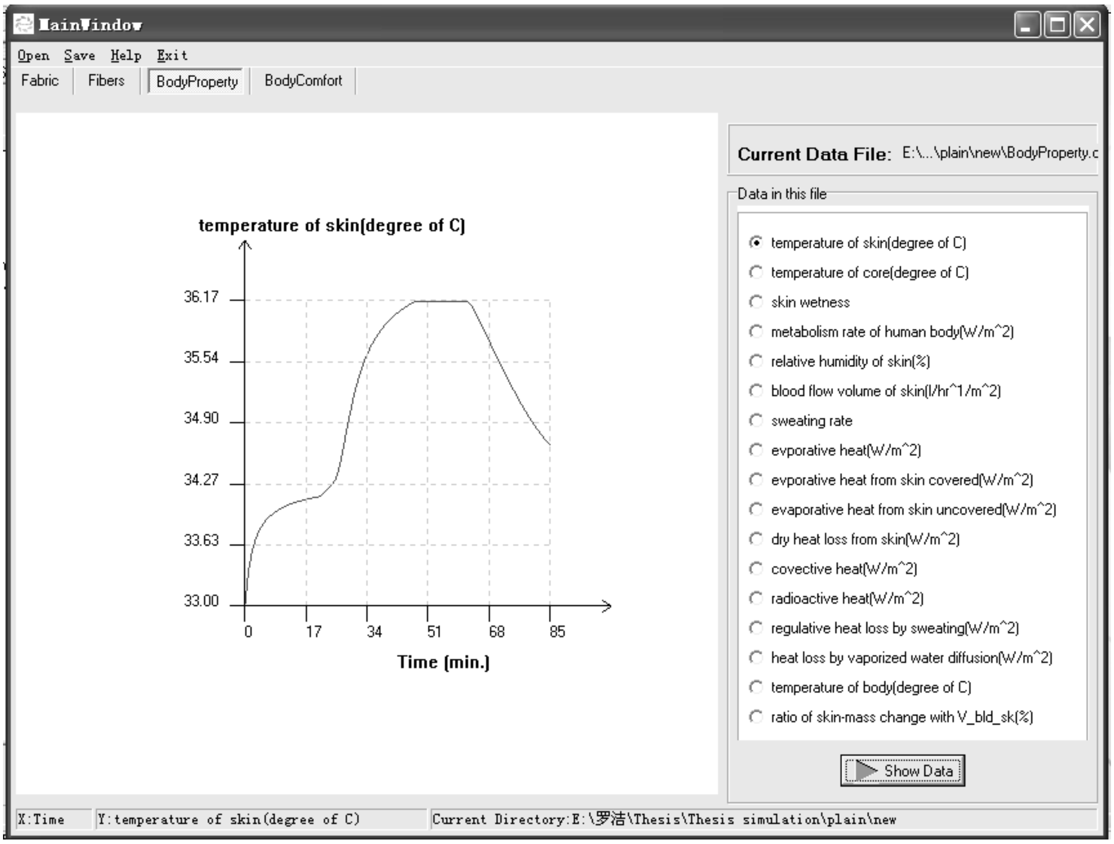
Step 5: perform the simulation

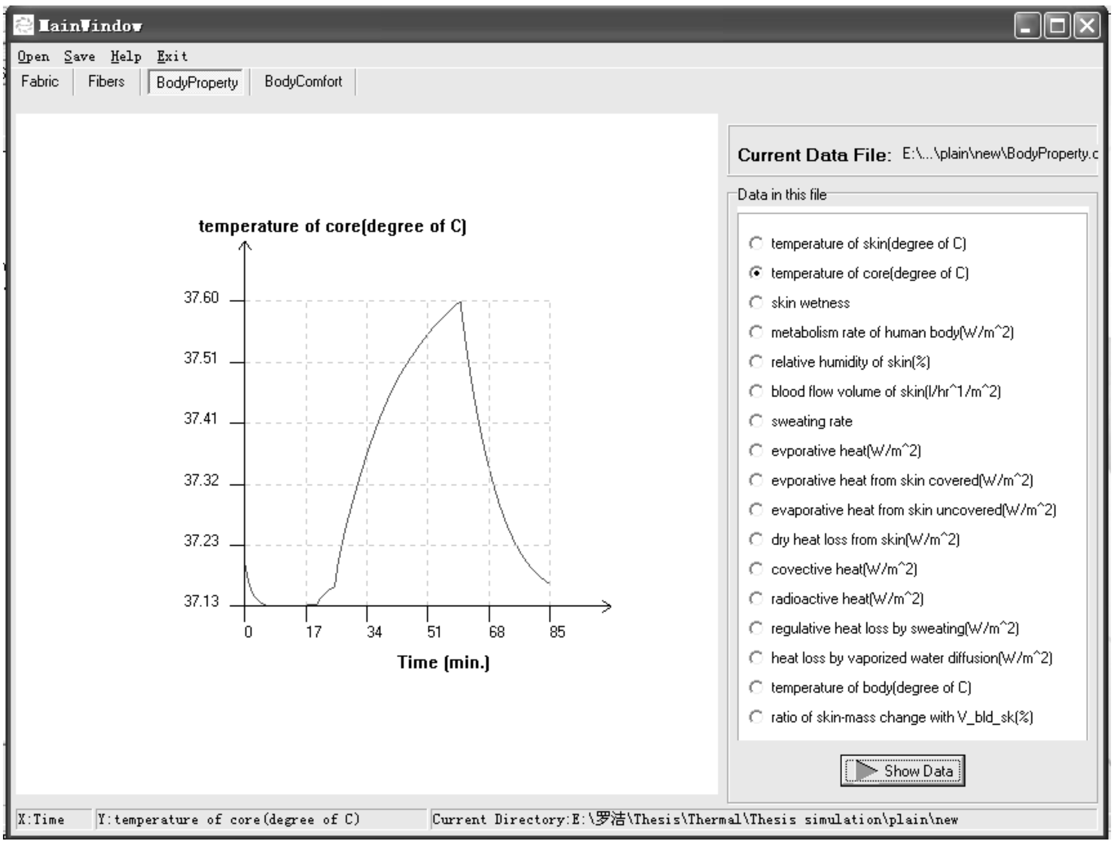


Step 5: view the simulation results


MainWindow
Open Save Help Exit
Fabric Fibers BodyProperty BodyComfort
Temperature(degree of C)
36.17
33.94
31.70
29.47
27.23
25.00
0.000
0.072
0.144
0.216
0.288
0.360
Thickness (cm)
0
17
34
51
68
85
Time (min.)
Z
Y
X
Current Fabric Number:
The 1th layer Fabric
3D Image
Data In This File:
Water Vapor Concentration(kg/m^3)
Mean Water Vapor Concentration(kg/m^3)
EvaporationCondensation Rate(kg/m^3/s^1)
Relative Humidity(%)
Mean Moisture Sorption Rate(kg/m^3/s^1)
Temperature(degree of C)
Liquid Volume Fraction(%)
Show Data
Color Select
2D Section
TimePos 0.0
SpacePos 0
Show 2D Data
Showing Data: Temperature(degree of C)
FabricNumber: X:Thickne Y:Time Z:Temperature(degree of C) Current Directory:E:\罗浩\Thesis\Thesis simulation\plain\new


MainWindow
Open Save Help Exit
Fabric Fibers BodyProperty BodyComfort
Relative Humidity(%)
100.00
87.08
74.16
61.24
48.32
35.40
0.000
0.090
0.180
0.270
0.360
0.450
Thickness (cm)
0
17
34
51
68
85
Time (min.)
Z
Y
X
Current Fabric Number:
The 1th layer Fabric
3D Image
Data In This File:
Water Vapor Concentration(kg/m^3)
Mean Water Vapor Concentration(kg/m^3)
EvaporationCondensation Rate(kg/m^3/s^1)
Relative Humidity(%)
Mean Moisture Sorption Rate(kg/m^3/s^1)
Temperature(degree of C)
Liquid Volume Fraction(%)
Show Data
Color Select
2D Section
TimePos 0.0
SpacePos 0
Show 2D Data
Showing Data: Relative Humidity(%)
FabricNumber: X:Thickne Y:Time Z:Relative Humidity(%) Current Directory:E:\罗浩\Thesis\Thesis simulation\tuck


MainWindow
Open Save Help Exit
Fabric Fibers BodyProperty BodyComfort
temperature of skin(degree of C)
36.17
35.54
34.90
34.27
33.63
33.00
0 17 34 51 68 85
Time (min.)
Current Data File: E:\...\plain\new\BodyProperty.c
Data in this file
temperature of skin(degree of C)
temperature of core(degree of C)
skin wetness
metabolism rate of human body(W/m^2)
relative humidity of skin(%)
blood flow volume of skin(l/hr^1/m^2)
sweating rate
evporative heat(W/m^2)
evporative heat from skin covered(W/m^2)
evaporative heat from skin uncovered(W/m^2)
dry heat loss from skin(W/m^2)
covective heat(W/m^2)
radioactive heat(W/m^2)
regulative heat loss by sweating(W/m^2)
heat loss by vaporized water diffusion(W/m^2)
temperature of body(degree of C)
ratio of skin-mass change with V_bld_sk(%)
Show Data
X:Time
Y:temperature of skin(degree of C)
Current Directory:E:\罗洁\Thesis\Thesis simulation\plain\new


MainWindow
Open Save Help Exit
Fabric Fibers BodyProperty BodyComfort
temperature of core(degree of C)
37.60
37.51
37.41
37.32
37.23
37.13
0 17 34 51 68 85
Time (min.)
Current Data File: E:\...\plain\new\BodyProperty.c
Data in this file
temperature of skin(degree of C)
temperature of core(degree of C)
skin wetness
metabolism rate of human body(W/m^2)
relative humidity of skin(%)
blood flow volume of skin(l/hr^1/m^2)
sweating rate
evporative heat(W/m^2)
evporative heat from skin covered(W/m^2)
evaporative heat from skin uncovered(W/m^2)
dry heat loss from skin(W/m^2)
covective heat(W/m^2)
radioactive heat(W/m^2)
regulative heat loss by sweating(W/m^2)
heat loss by vaporized water diffusion(W/m^2)
temperature of body(degree of C)
ratio of skin-mass change with V_bld_sk(%)
Show Data
X:Time
Y:temperature of core(degree of C)
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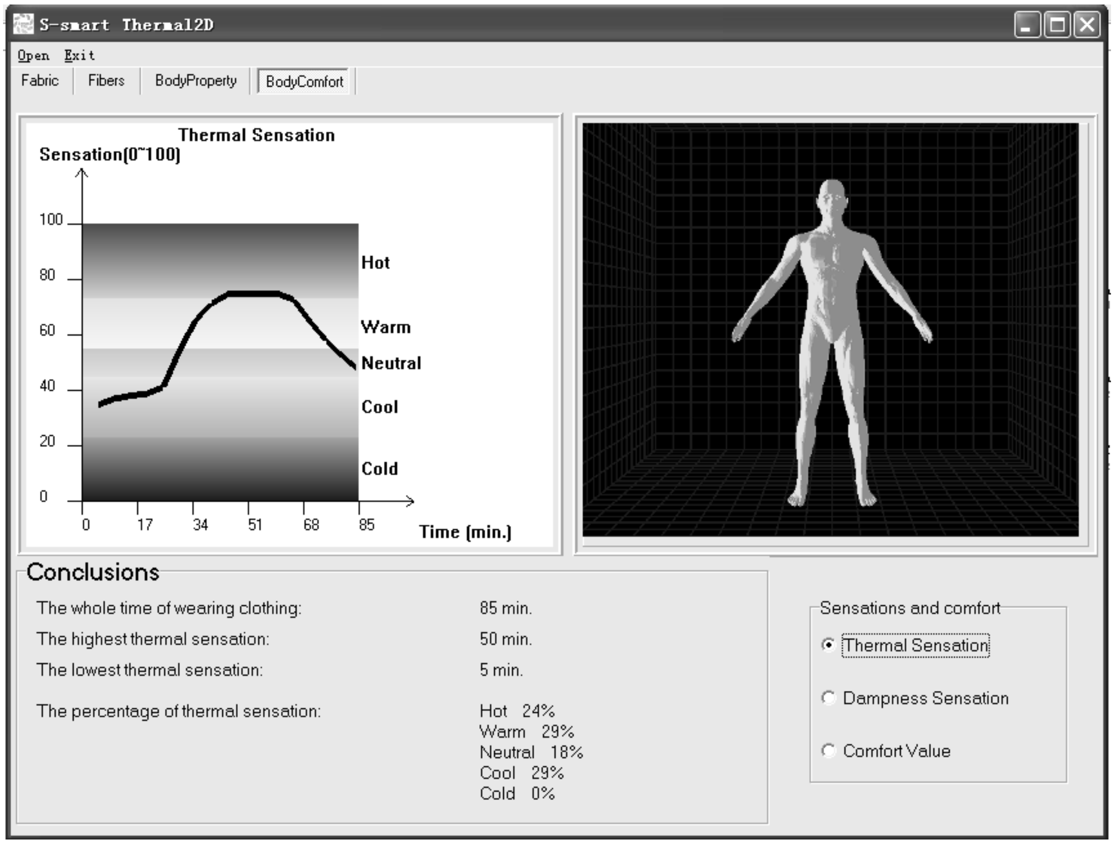
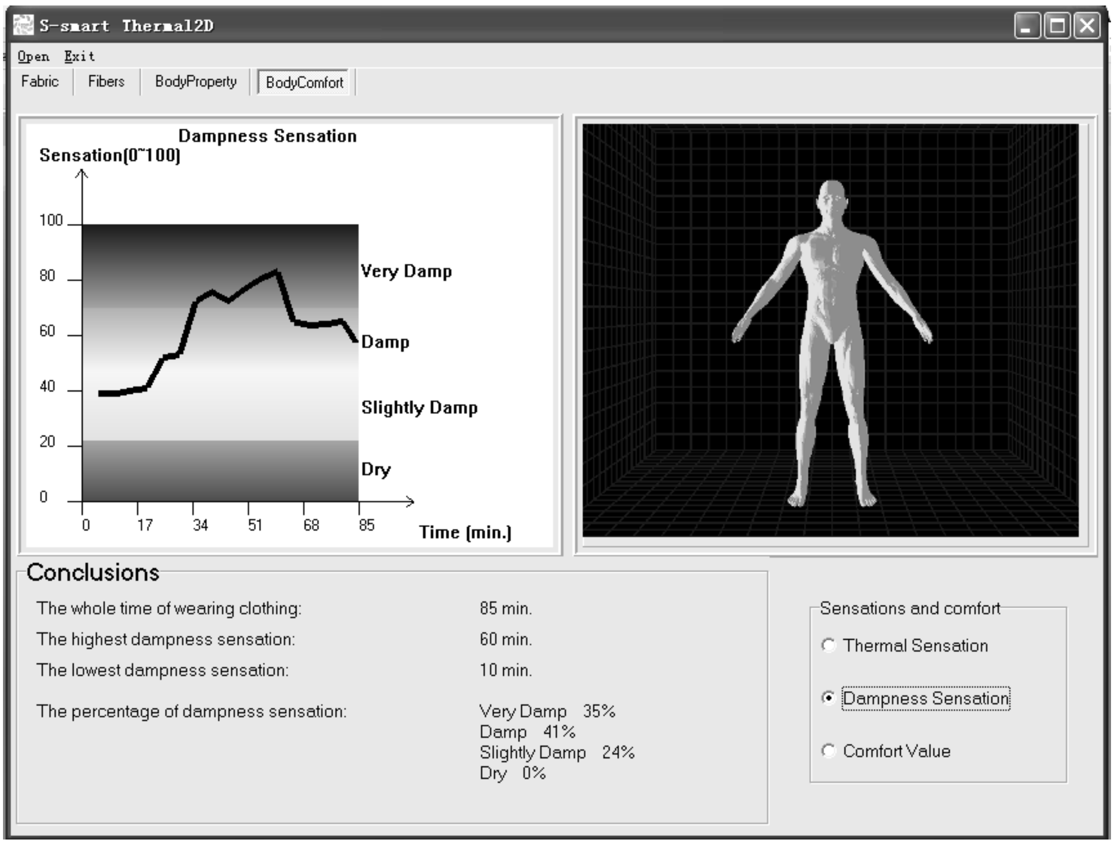

S-smart Thermal2D
Open Exit
Fabric
Fibers
BodyProperty
BodyComfort
Thermal Sensation
Sensation(0~100)
Hot
Warm
Neutral
Cool
Cold
Time (min.)
Conclusions
The whole time of wearing clothing: 85 min.
The highest thermal sensation: 50 min.
The lowest thermal sensation: 5 min.
The percentage of thermal sensation: Hot 24% Warm 29% Neutral 18% Cool 29% Cold 0%
Sensations and comfort
Thermal Sensation
Dampness Sensation
Comfort Value


S-smart Thermal2D
Open Exit
Fabric
Fibers
BodyProperty
BodyComfort
Dampness Sensation
Sensation(0~100)
Very Damp
Damp
Slightly Damp
Dry
Time (min.)
Conclusions
The whole time of wearing clothing: 85 min.
The highest dampness sensation: 60 min.
The lowest dampness sensation: 10 min.
The percentage of dampness sensation: Very Damp 35% Damp 41% Slightly Damp 24% Dry 0%
Sensations and comfort
Thermal Sensation
Dampness Sensation
Comfort Value

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