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Design and engineering of functional clothing

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The process of design and engineering of functional clothing design is based on the outcomes of an objective assessment of many requirements of the user, and hence tend to be complex and iterative. In this paper, the user requirements (besides the primary requirement of functionality) have been classified under four subtitles, namely physiological, biomechanical, ergonomic and psychological. The correlation between various characteristics of clothing and these requirements has been discussed. Subsequent steps involved in the ergonomic design process such as selection of materials, size and fit determination, pattern making, assembling and finishing have been listed out. Influence of technological advancements in related fields on each of these activities is discussed with a view to emphasise how the process of functional clothing design is different from design of everyday apparel. The fast developing field of functional clothing represents the future of textile and apparel industry, particularly in growing economies like China and India who will be the largest producers as well as consumers of these high tech products. Challenges being faced by this sector and a road map to meet the same have also been proposed.

Keywords: Clothing engineering, Comfort, Clothing design, Ergonomic design process, Functional clothing

1 Introduction

Unlike fashion clothing, which is essentially a product of the designer's creative instincts, the process of designing functional clothing begins and ends with the user specific requirements. These requirements, whether for performance or for comfort, are determined by the environment in which the user operates, and the activities that he or she performs.

Clothing, by its nature has a restrictive effect on body movement as well as on transport of heat and moisture from the body. Clothing can be abrasive, noisy, smelly or unattractive. Clothing designed specifically for certain functionalities has been shown to cause heat stress, reduce task efficiency as well as range-of-motion[1] of the wearer. The process of design therefore begins by first establishing the many requirements of the user. Subsequent processes are based on meeting, to the best possible extent, these user requirements. Figure 1 shows the flow chart of steps involved in the design of functional clothing. In this paper, the user requirements (besides the primary requirement of functionality) have been classified under four subtitles and the correlation between various characteristics of clothing and these requirements are discussed. Subsequent steps involved in the ergonomic design process such as selection of materials, size and fit determination, pattern making, assembling and finishing have also been listed out.

2 Requirements from Functional Clothing

Each class of functional clothing has a well defined functionality which distinguishes it from the other classes. However, in addition to this specific functionality, all functional clothing classes must fulfill certain requirements which are common to all users. These considerations can be classified into the following categories: physiological, biomechanical, ergonomic and psychological considerations. Effective functional wear is based on the integration of all of these considerations into the design of a clothing system.

2.1 Physiological Requirements

These relate to the human physiology and anatomy – shape, size, mass, strength and metabolic activities of the body or the need of the human body to feel comfortable in a clothing system. To what extent these needs are met is determined by the shape, size, feel and design of the garment, materials selected and their response to internal and external stimuli such as extreme cold, heat, rain, sand or snow. Ease of use, wear and removal has to be considered in case of first responders, motor disabled and elderly groups.

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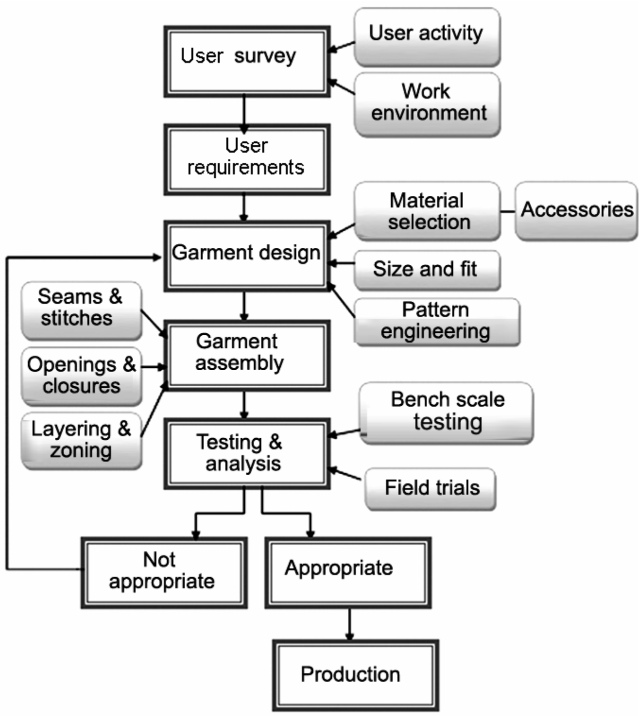

Fig.1—Flow chart showing the steps involved in design of functional clothing

The primary factors affecting the physiological needs are the energy metabolism, clothing thermal properties (as determined by the heat and mass transfer characteristics of clothing assemblies) and the ambient climatic conditions. Given the multitude of responsible variables, it is extremely complex to predict the comfort aspects of a garment accurately. These are affected by clothing penetration by solar and thermal radiation, interactions with moisture in clothing, effective latent heat of evaporation in clothing, heat and vapour resistance and clothing ventilation (through fabrics and specialized openings at optimal body areas).

2.2 Biomechanical Requirements

Biomechanics deals with the mechanical characteristics of human body as well as the kinematic, dynamic, and behavioral analysis of human activity. Its applications address mechanical structure, strength, and mobility of humans for engineering purposes — the unusual postures and movements of the users , such as crawling, crouching, fire fighting, flood relief, climbing, zero gravity and manipulating objects. As clothing forms an intimate covering of the human body, mechanical interactions take place between clothing and muscles, skin and tissue at different parts of the body, while the body is moving and working. The shape and fit of the garment vis a vis the human body, pressure and friction exerted by the garment on the body are some of the factors which affect this aspect.

Depending on the design and fit, all clothing exerts some pressure on the body. Pressure may also be intentionally applied on specific body parts for therapeutic and rehabilitation applications in the form of compression garments. Distribution of this pressure is determined by the mechanical properties of body parts, e.g. fleshy parts sustain pressure better than bony parts. Biomechanical considerations form the basis of design of specialized clothing classes, e.g. sportswear, where compression may be applied on selected muscles to enhance performance and reduce fatigue. Similarly, clothing for body sculpting is designed to preferentially compress, lift or support body parts based on anatomical and biomechanical considerations.

Application of too little pressure is ineffective while too much pressure can restrict the blood supply and cause edema or severe debilitation[2]. Designer must know that body parts where major blood and lymph vessels lie, are more sensitive to pressure than the rest. Disregard for these considerations can lead to the wearer experiencing unpleasant and sometime debilitating sensations such as thermal discomfort, rubbing, chafing, localized pressure development and restriction of movement.

2.3 Ergonomic Requirements

Ergonomics is defined as the science of work: of the people who do it and the ways it is done, of the tools and equipment they use, the places they work in, and the psycho-social aspects of the working situation [3]. It has been shown that compared to a semi-nude body, the movement, speed, accuracy, and range of motion may be reduced in a clothed body, while muscular exertion may be increased, e.g. the integral joint mobility of an astronaut can be reduced to 20% of normal in a typical space suit[4]. The ability to receive visual and auditory feedback may also be compromised when performance wear is worn[1].

Ergonomic considerations dictate that the mechanical characteristics of clothing match the motion, degree of freedom, range of motion and force, and moment of human joints. The working postures, materials handling, movements, workplace layout, safety and health considerations should be given due consideration while developing the style, cut and features of a functional garment.

Size of a garment vis a vis the size of body or 'fit' is another critical consideration in design of functional garments. Clothing which is too loose can get caught during work and may impede movement but that which is too tight will be uncomfortable to work in. Either way, an ill fitting garment can severely compromise the safety and performance of the wearer. In applications where monitoring devices/sensors are built into the clothing, the fit is even more critical as the sensors have to be in intimate contact with the body in order to be effective. The ergonomic efficiency of a clothing system can be evaluated objectively by using specially devised human mechanics and operational performance tests[5].

2.4 Psychological Requirements

Psychological aspects relate to how human beings feel, think, act, and interact under a given set of circumstances. As clothing is an extension of one's persona, strong feelings are often associated with its appearance and aesthetics. Considerations in terms of users' psychological and social behavior in response to events, people and/or environments e.g. acceptance by peer group, pride, identification, etc becomes important. Clothing items which are perfect in comfort and function may be completely rejected by the users if they do not 'look right' or are not perceived as smart and conveying the proper image. Psychological expectations and preferences of the user must therefore be given due consideration so as to create functional clothing which is in tune with their social and cultural background, geographical location, age, sex, activity and work profile.

These considerations are of vital importance when clothing is designed for special groups such as disabled or elderly. Clothing items have been known to be often not accepted by the target groups as it makes them stand out from the rest. These groups prefer clothing which has enabling features for their needs but does not look different and helps them to appear "normal". In other words, people prefer the functionality to be *unobstrusive*.

For other user groups, aesthetic requirements are secondary in importance to functional requirements in design of functional clothing, but are nevertheless important. It has been reported that medical clothing which looks good can actually facilitate effective social acceptance and lead to an improved quality of life for the disabled. Aesthetics of the clothing are as important as performance aspects in some sports such as tennis, skiing, motorbiker's clothing and swimming. Assessment of psychological aspects of clothing can be done through subjective methods based on user surveys, feedback and preferences as well as study of cultural and demographic features.

3 Process of Clothing Design

Once the user requirements have been established, the next step is to identify and select appropriate materials, followed by the design of clothing assembly, pattern engineering and the final assembling of these heterogeneous materials to create multilayer or composite assemblies in a manner that allows them to adequately fulfill the requirements of comfort, protection and functionality[6].

3.1 Material Selection

The material properties of fabrics can be extremely complex and difficult to predict. Textile fabrics are made up of a series of yarns produced from fibres, which interact with each other in many ways. The constituent fibre or yarn properties, weave or knit patterns and geometry of yarn and fabric structures, affect the overall material properties. Anisotropy, non- linearity and hysteresis are some characteristic features of textile structures. The stresses and strains to which textiles would be subjected by the working body need to be considered while choosing materials. Some requirements common to all functional clothes are that they should be light in weight, thermoregulatory, elastic, antimicrobial, aesthetic and durable. Specialised applications require materials that are anti UV, anti ballistic, anti impact, fire retardant, abrasion resistant, cut resistant, water repellent, high visibility and NCB (nuclear, chemical and biological) barrier.

Innovative fibres with special properties, special fabric and web forming technologies and developments in chemical and mechanical finishes make high performance textiles an important element of functional clothing design. A variety of materials with widely varying properties are now available due to rapid progress made in the field of technical textiles. Specific functional needs may require the use of judicious combination of materials ranging from polymers and metals to ceramics, composites, laminates and membranes[7]. Some innovative developments in material science, which are expected to play an increasingly important role in the design of functional clothing, are discussed below.

3.1.1 Stretch Fabrics

Stretch fabrics are integral to design of functional clothing. From additional comfort to enhanced mobility, muscle support, muscle alignment and body part compression—all are now possible by strategic use of stretch fabrics. The efficiency and performance of textile sensors and electrodes, in particular, depends on the nature of contact with the body which can be controlled by the stretch characteristics of the fabric. Fabrics with 1 way, 2 way and 4 way stretch are being developed to offer controlled stretch and functioning. Pattern pieces have to be suitably engineered to provide the required stretch and fit in a product.

3.1.2 Smart Textiles

Smart textiles are materials that sense and react to environmental conditions or stimuli, such as those from mechanical, thermal, chemical, electrical, magnetic or other sources. Examples include chromatic materials which change colour with change in environment, phase change materials for thermoregulation and shape memory polymers which change shape with change in temperature.

3.1.3 Biomimetic Textiles

Biomimetics is a field which deals with development of materials which are inspired by natural phenomenon. From mimicking skin's function to enhancing skin performance, more and more materials are being developed which imitate living systems. Breathable wet suits - based on the pores of leaves, self cleaning effects based on the lotus leaf and sharkskin effect (Fig. 2) for better hydrodynamics in water are some concepts which have already been commercialized.

3.1.4 E-textiles

Incorporation of ICT components into textiles has added a whole new functionality to this field. These sophisticated materials can exhibit complex multidirectional behaviour by sensing, reacting and activating a specific function. Conductive yarns, flexible and elastic sensors, wireless tools and alternate power sources form an area of intensive research for the development of electronic textiles. Textile based wearable products for health and fitness monitoring in patients and athletes are available. Research continues to expand the applications of use and develop products which are lighter and more comfortable to use.

3.1.5 Nanotechnology in Textiles

Developments in nano fibres (electrospinning), nano finishes, nano membranes and nano composites can be used to impart functionalities which were

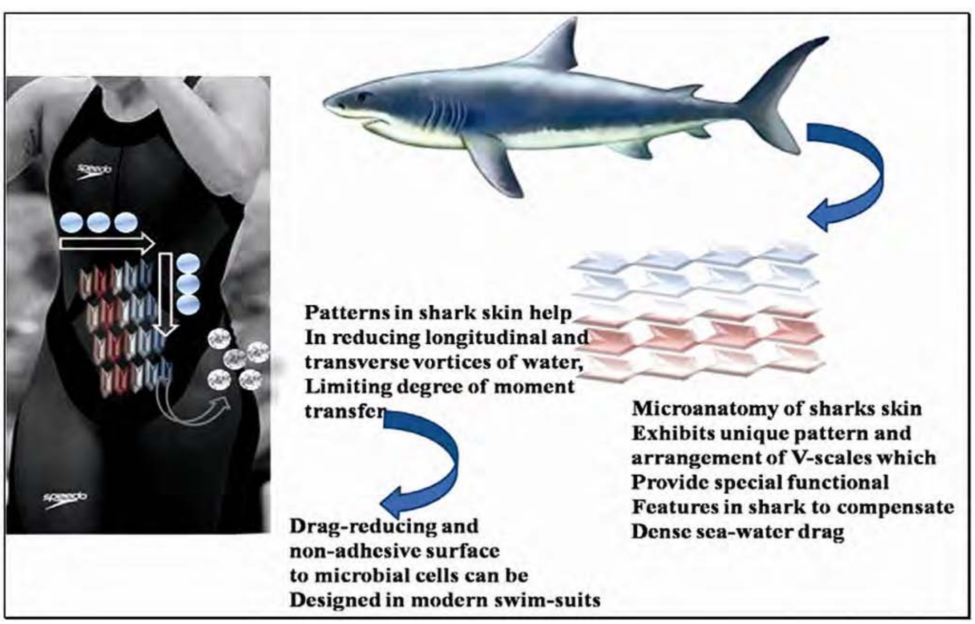

Fig. 2—Biomimetic fabric for low hydrodynamic surface drag for swimsuit inspired by shark skin[8]

hitherto not possible to achieve in textiles. Antimicrobial, anti UV, stain repellent, fire resistant, antistat, moisture control and thermoregulation properties can be imparted at the molecular level without affecting the inherent flexibility and comfort of fabrics. Progress in this field is expected to yield multifunctional fabrics which are flexible, lightweight and comfortable, making them the ideal choice for complex functional clothing applications.

3.1.6 Use of Air in Textiles

Another innovative development, specifically relevant to the design of functional clothing is the increasing use of air in protective and medical clothing to keep the systems light in weight. Hollow core fibres, woven spacer fabrics, raised knits and 3D fleece fabric are all means of introducing air in the system for cushioning, insulation or moisture transport. Double layer fabrics with a 3D spacing structure between the inner and the outer fabric face offer superb moisture management and great thermal insulation or ventilation, depending on the construction[9]. These fabrics are used in medical field for applying compression, providing support or transport of fluids[10,11]. They can also be used instead of foams in protective gear for shock absorption.

3.2 Membranes and Coatings

Breathability is an overriding factor in material selection today. Coatings while imparting special properties often make a fabric non breathable. Developments in membrane technology over the last few decades allow the fabric to remain breathable on the inside while being impenetrable on the outside. Membranes have micro pores which provide a barrier against wind, water, chemicals, microbes and harmful vapours present in the environment while allowing vapour (perspiration) to escape. Other properties that can be imparted by membranes include transparency, flexibility, elasticity, oil resistance and high tensile and abrasion resistance. They are being increasingly used to provide breathability to otherwise water or wind proof clothing used in high-performance sports apparel, foul weather clothing, military and industrial uniforms and medical clothing.

3.3 Accessories and Trimmings

While fabrics form the major component of functional clothing, an equally important component is the accessories that go into making up of the complete assembly. Today, it is possible for a garment to be made up of up to 25 different materials that include buttons, zippers, pullers, snaps, fasteners, tapes, cords and braids, high visibility strips, labels, wadding, padding, belts and buckles. Suitable selection and placement of accessories can go a long way in providing multiple looks, ease of donning, opening, maintenance, handling, improved comfort and safety to the user. Special fasteners for motor disabled, water proof and fire retardant zips for specific applications are some such examples.

4 Clothing Design

As discussed above, technical textile materials are the primary building blocks of functional clothing. However, to capitalize on the special functionalities provided by high tech materials, it is important to club them with equally innovative methods and techniques of clothing design and manufacturing. New materials require newer methods of cutting, sewing and joining to handle and convert them into performance clothing systems. Design of clothing must move away from the conventional domain of designing in 2D (material centric) to designing in 3D (garment shells). Availability of advanced CAD/CAM technologies in the last few years has made this possible to a large extent. For example, 3D body scanning technology allows the creation of anatomically accurate models of the human body which can be used as a base for virtual or real designing as well as fit testing of garments in actions and postures which closely simulate real life usage of clothing. Once finalized, CAD systems are further able to translate the final design into patterns, pattern grades and markers while CAM systems including computerized sewing machines take care of the sewing process[12].

4.1 Steps in Clothing Design

Development of a piece of clothing takes place in several interdependent yet disparate processes with its final appearance, fit and functionality being influenced by each one of these steps[13]. The following paragraphs discuss the steps employed in design of functional clothing and the way in which modern technologies and advances are transforming the same.

4.1.1 Body Measurement and Sizing

Generating body measurements of the target group tend to serve as the first step in clothing design. Conventional standardized size charts used for traditional apparel design cannot be used for design of functional clothing as those are based on traditional anthropometry, where the body measurements are taken in fixed, static poses and the data available is one dimensional in nature. Such data contains measurements which indicate the size but do not yield any information about the complex human body shape in curvature or postures.

Ergonomic block development requires 3D anthropometric data captured in multiple realistic postures. 3D body scanners can be used to measure the population in static as well as dynamic mode to capture the shape, size and posture data. Ergonomic measures such as the range of motion also need to be collected and considered in designing. For more accurate understanding of the change in body shape or the restrictions posed by clothing while performing specific activities like swimming, jumping, crouching, human motion analysis systems can be used.

The issue of sizing is further made complex by the fact that since the type and nature of measurements required varies from one type of application (swimming, skating, cycling, skiing) to another, independent size charts will be needed for each type of clothing. The size roll in each case will also have to be developed depending on the type of clothing being designed.

4.1.2 Pattern Engineering

Making of patterns is the next step in the development of a garment. It is the process of converting a 3D garment design into flat 2D constituent pieces. These flat irregular shapes represent various sections of a garment which when joined together using a process such as sewing will yield the 3 D garment shape[14,15]. Making of patterns currently is a multi-step process which is largely iterative, empirical and based on trial and error approach[16,17]. A lot of tweaking, adjustment or fitting is required in this 3D-2D-3D process to achieve the desired fit and performance.

Functional clothing design needs to be based on a system that accurately represents the geometry of the human body not only in a static mode but also in the kinetic mode during work and motion. It is because of this, that the traditional pattern making approach of working on flat front/back/sleeve panels is found to be limiting. Pattern shapes of ergonomic garments need to follow the 3D contour and physiology of the human body and correspond exactly to the size and posture of the user. Functional clothing patterns are therefore best designed in 3D, i.e. on the body itself.

Further, functional garments would require "zoning" of patterns, i.e. several different fabrics to make up a pattern piece such as front or side panel, mesh fabric for ventilation in the underarm area, compressive fabric for applying pressure on specific muscles, stretch fabric for providing additional joint mobility, spacer fabric for insulation or impact resistance in the chest area and so on (Fig. 3). Thus, pattern blocks may need to be developed in totally new ways to allow for use of multiple pieces in a block. Based on the study of a moving body, patterns need to be engineered for ergonomic design in such a way that they allow enhanced mobility and reach in areas that show strain during vigorous activity (crotch, under arm, knee and elbow). Articulated knee and elbow designs need to be worked out. There are number of current research efforts in the field of 3D body modeling and computerized pattern making systems using 3D data[18-21].

Availability of 3D body scans and corresponding advances in pattern engineering has made it possible to design in 3D keeping the above considerations in mind. Pattern shapes are drawn directly on the 3 D scan of the body in action, conforming to the surface contours as shown in Fig. 4. These selected 3D regions are flattened to produce 2D patterns. Mechanical properties of fabrics can be factored in the 3D pattern and a coloured simulation of the deformation stresses and strains when the garment is worn can also be seen. Such research will hopefully lead to reduction in development times and improvement in fit, besides reducing the uncertainties inherent in the current design process [22-24].

4.2 Assembling of Garment Components

Pattern engineering involves the process of determining the shape and size of each 2D pattern that

Fig. 3—Garments showing zoning of patterns (a) first gear Kilimanjaro motorcycle jacket, and (b) 2XU men compression shorts

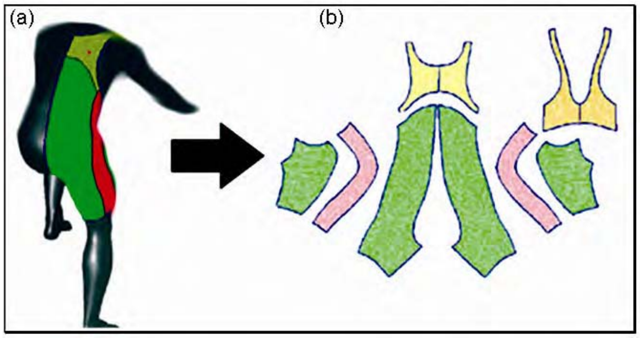

Fig. 4—Designing in 3D (a) drawing patterns on a cyclist in motion, and (b) flattening of the 3D patterns [24]

will be put together to create a 3D shell. Once these patterns have been created, they have to be cut, assembled and joined. They also have to be connected to the means of opening and closing the garment (buttons, zippers, fasteners) and such other accessories that go into the making up of a complete garment assembly. The shape of patterns as well as the selection of joining and assembling technologies (sewing, bonding, fusing) is again dictated by the activity, posture and environment in which the user will be operating as well as the properties of materials used.

Assembling of multiple fabric panels having varying properties requires sophisticated handling techniques. Traditionally sewn seams can sometimes compromise the integrity and functionality of engineered clothing. New techniques of joining materials such as taped seams, welding (high frequency, ultrasonic and laser) and adhesive bonding are often used to assemble these systems. 3D moulding is another technique used in contoured garments used for body shaping and support. Because of these trends, the new age garments are looking cleaner, fitting better, they are also lighter in weight and less bulky (Fig. 5).

5 Testing of Clothing for Functionality

Once an assembly has been created, it has to be tested extensively for performance. Test methods such as EN469, 1995 are available for testing of performance clothing, particularly protective clothing for certification purposes and quality control. However, these methods continue to test the properties of constituent materials such as material heat and vapour resistance, flammability, tensile behaviour, etc. No matter how good the properties of fabric are, poor garment design or construction can compromise its functionality

Fig. 5—Women's mountain hardwear effusion power jacket having clean lines, non bulky appearance and better fit

severely. Hence, methods that test the whole garment assembly rather than just the fabric are required[25]. The compatibility of materials with each other, their durability and robustness of construction are also important considerations. Other aspects of concern relate to the interaction of garment with the human body, effect of garment design, size, fit and manufacturing processes on material properties, etc. Hence, holistic test procedures which test for physiological load, heat protection, loss of performance, rain/moisture protection and conspicuity/visibility of the clothing under actual conditions of use are the need of the hour.

Development of such test methods can be quite complex as different classes of functional clothing are designed for performing under different conditions of activity and the climatic conditions. Therefore, what may work under one set of conditions (extreme cold) will be completely unsuitable in another set of conditions (hot and humid weather). The efficiency of a functional clothing system can thus be best determined by field testing on real humans and then supported by more precise objectives measures of fabric properties that correlate to the field results[26]. Therefore, testing of each type of clothing has to be carried out under environmental conditions that simulate the actual conditions of its use. Then again, use of human subjects for testing and evaluation raises several issues. Different people will react and respond differently under identical conditions making inter and intra subject variability a major problem. Statistical considerations pertaining to comparison of different data sets as well as the ethical issues of conducting tests on humans also have to be tackled. According to Havenith *et al*.[27], standardisation on all these matters needs to be put into place, while developing what may be called as 'ergonomic test procedures'.

6 Challenges Faced by the Functional Clothing Industry[6]

The field of functional clothing is one of the fastest growing segments of technical textiles market and has seen tremendous growth in the last one decade. Yet there are following issues which need to be addressed before it can attain its real potential:

- This field requires intense R&D inputs to grow but as of now, suffers from a lack of adequate research data base, scientific guidelines and procedures which are needed to aid the design process. Interdisciplinary nature of the field further makes research difficult and expensive.
- Though the industry has seen significant growth in developed countries, there is a total lack of information and awareness about the nature of hazards and current practices in developing countries. The problem is compounded by the fact that functional clothing design is based on geographical, psychological and socio- cultural considerations. This makes it difficult to develop generic designs which are standardized and globally relevant. First hand data for each geographical and climatic zone need to be generated.
- Many of the technological developments in the field of clothing production and assembling discussed above are still in incipient stages of adoption by the manufacturing industry. Till the time that these become mainstream, affordable and adequate numbers of workers become proficient in their use and operation, growth is going to be sluggish.
- Market forces provide another challenge, in that there is monopolization of high-tech materials (fibre /yarn /fabric/membranes/ coatings) by a few large international players. High material costs and high technological inputs make entry difficult into this sector.
- The largest buyers of functional clothing are either government bodies or large corporates who are often not the users and therefore not aware of the actual conditions and problems faced by the users. Unrealistic technical requirements are therefore put forth in such cases. Good and reliable user feedback is crucial to the design of performance wear. Direct channels of communication between the user and producer should be opened to facilitate two way flow of information to facilitate optimal design.

7 Roadmap for Future

Functional clothing industry is a Greenfield industry with tremendous prospects of growth. But in order for its true potential to be realized several steps should be taken. The first relates to an accurate estimation of the size of the various sectors particularly in the developing countries with large population and workforce. Guidelines for research need to be proposed with global and regional focus. Multidisciplinary, collaborative, multinational research groups need to be developed for working together. Technological developments across relevant sectors need to be tracked and relevant technologies integrated into the field on a continuous basis. Active support and participation by industries in research can provide a major impetus to the sector.

8 Conclusion

Design and engineering of functional clothing is a complex and challenging process. What adds to the complexity is the fact that the existing systems governing the design of fashion clothing cannot be used to design performance wear clothing and no guidelines are available for designing these high tech systems. User requirements and conditions of use play a critical role in the entire process of design, manufacture and testing. Availability of innovative materials and associated technologies for production and assembling of clothing ensembles for specialized functional applications has paved the path for development of new and innovative garments capable of providing enhanced comfort and productivity and reduced physiological strain for the users. Joint involvement of engineers, designers, physiologists and ergonomists and the user is needed to fine tune the material choice, composition, sizing and assembling issues related to designing of clothing for a specific end use.

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