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Textile and Clothing Applications for Health Monitoring of Athletes and Potential Applications for Athletes with Disabilities

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ABSTRACT

Current technological advancements in textile development and mechanical functions of biomedical sensors allow for increased disease diagnoses, injury detection and prevention beyond the clinical environment. Athletes undergo bodily stresses brought on by the physical demands of competition and performance posing potential physical risk. Vital monitoring of an athlete throughout performance gives insight to the body's response to elevated activity and allows for preventative measures. Textile-embedded biomedical sensors can be integrated seamlessly in compression apparel for athletics without the need for wired attachments providing increased levels of comfort and long-term health monitoring. Athletes with a disability require specific functional needs that could be met through the development of specialized garments based on physiological and ergonomic demands.

Keywords: Athletic apparel, disability, biomedical textiles, specialized garments

1. Introduction

On March 17th, 2012, Bolton midfielder, Fabrice Muamba suddenly collapsed in the English FA Cup game against Tottenham, after suffering cardiac arrest. Medics were brought onto the field where unsuccessful attempts to resuscitate Muamba lasted 48 minutes. He was then removed from the field and transported to London Chest Hospital where an additional 30 minutes and 15 shocks from a defibrillator were needed for Muamba's heart to beat again on its own (Harris, 2012). According to Healthcare Global, the heart condition that led to Muambas cardiac arrest; hypertrophic obstructive cardiomyopathy (HOCM), also known as Hocum, is a condition brought upon by continuous, strenuous exercise, making footballers and other high-performance athletes far more susceptible than the average recreational athlete (Basilico, 1999; Riddington 2012; Staff, 2012). The abnormality causes the muscular walls of the heart to grow far thicker than normal, restricting blood flow. This type of strain on the heart can cause a healthy athlete to struggle with a shortness of breath like that of an unwell 80-year old (Basilico, 1999; Cheng, 2012; Harris, 2012; Rawlinson, 2012; Riddington, 2012; Staff, 2012). Due to the high physical exertion brought on by intense athletic training, the muscles of the heart become so inflamed that blood flow fails to reach the heart, resulting in cardiac arrest. In addition to adrenaline brought on by added stresses of the game, any underlying congenital heart problems can likely lead to cardiac arrest (Cheng, 2012).

In cases such as Fabrice Muamba's, athletic males under age 30 are thought to be in healthy form so heart conditions like HOCM often go undetected. The American Heart Association recommends "a thorough physical exam and detailed family and personal medical history for athletes, but not an automatic electrocardiogram, or ERG, which measures a heart's electrical activity" (Cheng, 2012). Athletes at the professional level receive a comprehensive and thorough medical screening identifying 80 percent of conditions causing sudden death (Rawlinson, 2012). Further cardiac testing of professional athletes is only required when there are occurrences of fainting episodes, heart murmurs, or a family death brought on by heart problems (Cheng, 2012). Muamba had undergone a routine screening for heart defects the previous August and once again the day following his collapse. Both tests produced "normal" results (Harris, 2012). His heart condition was never detected by the doctors of Bolton's professional soccer club, leaving Dr. Sanjay Sharma, a professor of Cardiology at St. George's Hospital in London, skeptical of the test results (Rawlinson, 2012).

Each year, misdiagnosis of cardiovascular diseases and other chronic physiological conditions in athletes result in unnecessary death and disability. In a sporting environment, athletes push their bodies to the limit in order to meet the physical demands of competition. In doing so, there is often a high risk of overexertion. Technological advancements both in textile development and mechanical functions of biomedical sensors increase disease diagnosis and illness detection and prevention beyond the clinical environment. Biomedical sensors function by converting biomedical variables into electronic signals for readable data. Textile based sensors allow for long-term monitoring through continual operation as individuals undergo clinical tests as well as practices, workouts and competition. Vital monitoring of athletes may further provide critical information in the detection of abnormalities brought on by high physical exertion. This paper plans to explore current textile-based applications for athletes and how they might be applicable in apparel product development for competitive athletes with alternative needs, such as those with disabilities.

2. Physiological Profile of an Athlete

Athletes train and develop their bodies to react to stress in competition. In doing so, their bodies change and adapt in many different ways. Identifying the physiological profile of an athlete is a critical component in determining athletic performance and predisposition to injury. Quantitative measurements of body composition, maximal aerobic power, anaerobic capacity, blood chemistry, and coronary risk factors can be key factors in determining deficiencies in the athlete, improving physical skills and decreasing risk of injury (Steinhagen, Meyers, Erickson, Noble, & Richardson, 1998).

2.1. Athletic Body Type

Athletic body type varies according to the individual sport for which the athlete is in training. The ability to modify one's body structure to meet the necessary physical demands becomes necessary in achieving optimum performance. Scientists have come up with a method of classifying anthropometric measurements of the human build into three individual body types expressed by a three-number rating representing the components of endomorphy (fatness), mesomorphy (musculoskeletal development) and ectomorphy (linearity) (Sheldon, 1954; Williams, 2012). This method is known as somatotyping, and is based on anthropometric measurements.

The anthropometric somatotype is calculated by taking measurements of ten separate dimensions: stretch stature, body mass, four skinfolds (triceps, subscapular, supraspinale, medial calf), two bone breadths (biepicondylar humerus and femur), and two limb girths (arm flexed and tensed, calf) (Carter & Heath, 1990; Sheldon, 1954). The measurements are either entered directly onto a somatotype rating form or into equations derived from the rating form (Carter & Heath, 1990). The rating form then classifies each of the three body types on a scale from 1 to 7 (1 being very low, 7 being very high). The three numbers together give the somatotype rating (e.g. 1-5-2). A two-dimensional somatochart (see Figure 1) is used to plot the numbers using X, Y coordinates derived from the rating. Calculations from the coordinates are as follows (Carter & Heath, 1990):

X = ectomorphy – endomorphy

Y = 2 x mesomorphy – (endomorphy + ectomorphy)

As a brief explanation of what these coordinates are describing, endomorphic body types are associated with having a round physique, typically with short arms and legs and a large amount of mass on their frame. Athletes with an endomorphic body type are often limited in agility and speed but excel in sports of strength such as power lifting. Mesomorph bodies gain muscle easily and are capable of being strong and athletic. Sporting events of equal weight training and cardio activity are most identifiable to a mesomorphic build due to the body’s ability to quickly adapt and transform to muscle building exercises. Ectomorph body types are characterized by a lean figure and linear physique. A fast metabolism and delicate body build leads to difficulty gaining muscle strength. Those with ectomorphic body types are best in distance sports requiring muscle endurance such as running, basketball, or soccer. Figure 1 shows a somatograph representing the classification of body type. By grouping similar athletic body types to a specific sport, predictions can be made on athletic performance in relationship to body structure (Williams, 2012).

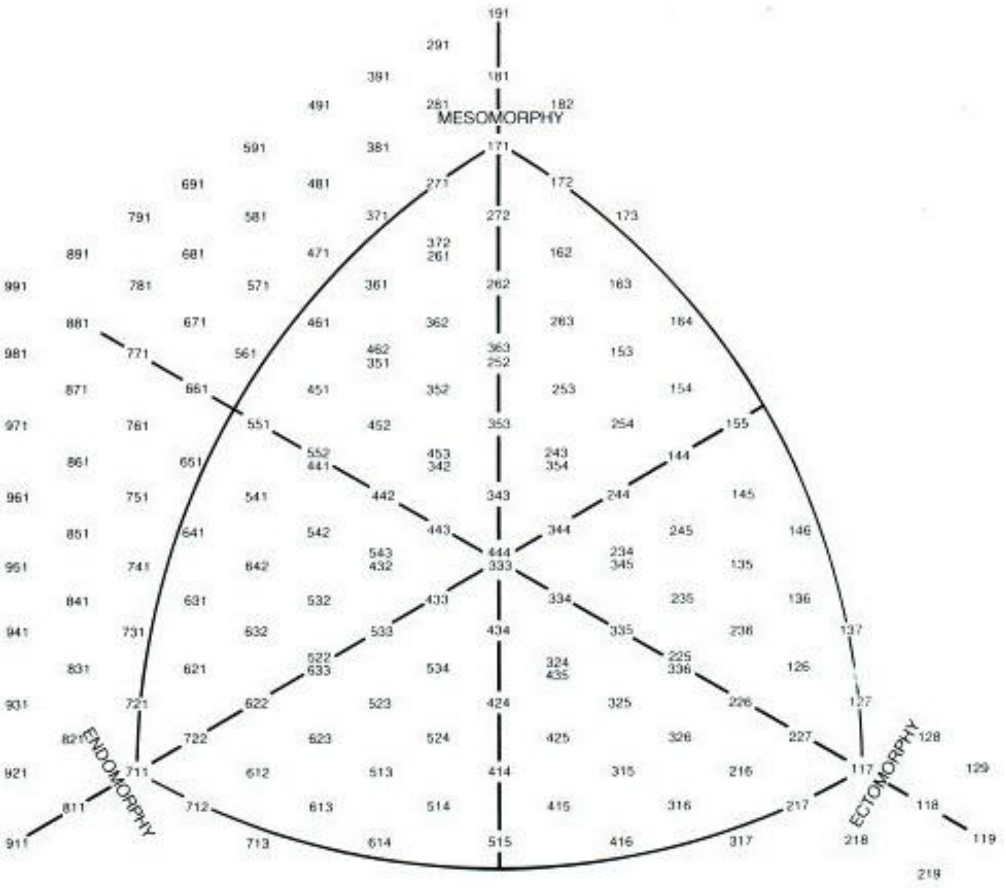

***Figure 1*. Graphical representation of somatotype classification (Carter & Heath, 1990)**

Although different body types may be predisposed to certain sports, altering or enhancing one's body composition is maintained through physical training for exercise and sport. Much like classifying physical build into body type, exercise can be identified as either dynamic or static. Dynamic exercise involves changes in muscle length that creates a small intramuscular force. Continuous movement of the muscles and joints lead to improvements in blood circulation, strength and endurance. Static exercise uses little movement of the joints and creates large intramuscular force brought on by exerting the muscles at high intensities. Improvements of strength are common with static exercise, yet it can rapidly increase blood pressure, becoming problematic for individuals with high blood pressure and poor circulation (Basilico, 1999; Maron & Zipes, 2005; Michelle, 2010) Table 1 describes the classifications of exercise by sport.

Table 1. ***Types of Exercise by Sport*** **(cited in Basilico, 1999)**

	A. Low dynamic	B. Moderate dynamic	C. High dynamic
I. Low static	Billiards Bowling Cricket Golf Riflery	Baseball Softball Table tennis Tennis (doubles) Volleyball	Badminton Cross-country skiing (classic technique) Field hockey* Orienteering Race walking Racquetball Running (long distance) Soccer* Squash Tennis (singles)
II. Moderate static	Archery Auto racing*† Diving*† Equestrian*† Motorcycling*†	Fencing Field events (jumping) Figure skating* Football (American)* Rodeo*† Rugby* Running (sprint) Surfing*† Synchronized swimming†	Basketball* Ice hockey* Cross-country skiing (skating technique) Football (Australian rules)* Lacrosse* Running (middle distance) Swimming Team handball
III. High static	Bobsledding*† Field events (throwing) Gymnastics*† Karate/judo* Luge*† Sailing Rock Climbing*† Waterskiing*† Weight lifting*† Windsurfing*†	Body building*† Downhill skiing*† Wrestling*	Boxing* Canoeing/kayaking Cycling*† Decathlon Rowing Speed skating

*Danger of bodily collision
†Increased risk if syncope (loss of consciousness) occurs

2.2. Physical Demands on Body during Performance

The body is trained to adapt to the physical changes brought on by elevated aerobic exercise. According to the American College of Sports Medicine (2012), aerobic exercise is defined as "any activity that uses large muscle groups, can be maintained continuously and is rhythmic in nature." Aerobic exercise is beneficial in areas of burning fat, muscle strengthening throughout the body, strengthening muscles of the heart and lungs to adapt to increased blood flow and oxygen levels. Elevated activity brought on by aerobic exercise causes an increase of physical demands on the cardiovascular system yet meeting these physical demands is necessary in improving function and strength of muscle. As physical activity is being performed, heart rate is raised to keep up with the demand of oxygen needed for muscle movement. Thus, the heart more rapidly pumps blood throughout the body, increasing circulation to working muscles (Kochan, 2011). The subsequent increase of blood flow through the muscular walls of the arteries leads to increased blood pressure, which can become problematic for athletes with already high blood pressure.

Aerobic capacity is measured by endurance level and determines the amount of oxygen to be transported to exercising muscles. As fitness duration and intensity increase, aerobic capacity increases. The blood flow to working muscles is rich in oxygen. For muscles to maintain performance and receive oxygen-rich blood, a continual exchange is required of the carbon dioxide and oxygen within the lungs. This exchange elevates respiration and increases the breathing rate (Kochan, 2011) As the breathing rate occurs more rapidly, lung capacity increases and more carbon dioxide is being exhaled; allowing the athlete to work longer at a higher intensity before feeling winded (Kochan, 2011; Michelle, 2010). Ultimately, functions of the cardiovascular system work in response to one another to meet the physical demands of the body during performance.

2.3. Athletes with Physical Disabilities

The Americans with Disabilities Act defines a person with a “disability” as having a “physical or mental impairment that substantially limits one or more major life activities of the individual” (Americans with Disabilities Act, 1990). The body of someone with a physical disability may have significant differences from someone who is able-bodied, both in shape and mobility. However, training for both disabled and able-bodied athletes can be similar and athletes with a disability put the same continuous effort into training their bodies to adapt to physical demands and avoid injuries. Training and injury prevention programs may be modified for the serious athlete with disabilities.

The Paralympic Games are the Olympic equivalent competitions for athletes with disabilities. The Paralympics (Paralympics, 2012) classifies disabled athletes into 1 of 6 categories: wheelchair athletes, amputees, athletes with cerebral palsy, visual impairment, intellectual impairment and “les autres”. Les Autres is the French term for “the others” and denotes other locomotor disabilities. Such disabilities may include: dwarfism, multiple sclerosis, and arthritis of major joints, among others (Huckstep & Sherry, 1997)

Injuries sustained through participation in athletic events may differ from those of able-bodied athletes. Injuries to athletes with disabilities tend to be clustered by classification. For example, wheelchair athletes are likely to sustain upper body extremity injuries; blind athletes may suffer more from injuries to lower body extremities and cerebral palsy athletes may experience both upper and lower body injuries (Klenck & Gebke, 2007). Wheelchair athletes often have complaints of upper body injuries including rotator cuff impingement, rotator cuff tendonitis, bicep tendonitis, and tear of the long head of biceps tendon (Klenck & Gebke, 2007; Patel & Greydanus, 2009). When compared to able-bodied athletes, wheelchair athletes have a significantly higher ratio of shoulder abduction to adduction strength leading to muscle imbalance due to incessant overuse (Halpern & Cardone, 1998). Additional sustained injuries of wheelchair athletes include peripheral entrapment neuropathies, carpal tunnel syndrome and progressive neuromuscular scoliosis, limiting cardiorespiratory capacity (Patel & Greydanus, 2009).

Blind athletes are limited in physical activity due to sensory impairment. Many blind athletes experience bodily injuries of the lower extremity related to falls. In such cases, there may be fractures and soft tissue injuries caused by overuse of extremities or lack of environmental awareness. Fractures and soft tissue injuries could similarly occur in able-bodied athletes from different causes (Huckstep & Sherry, 1997; Klenck & Gebke, 2007).

Amputee athletes require additional adaptive and prosthetic devices, so limitations may arise during training and competition regarding proper fit and adjustments made to the device. The prostheses are prone to add a level of discomfort to the athlete and may lead to an increase in skin pressure, abrasions, blisters, or skin rash that may not have otherwise been present (Patel & Greydanus, 2009). With consideration to the location of amputation, muscle and tissue may experience limitations in movement. Lower limb amputees compensate by increasing lateral flexion and extension of the lumbar spine causing back pain (Patel & Greydanus, 2009). Table 2 shows some of the patterns of injuries to disabled athletes by athletic group.

Table 2. ***Examples of Patterns of Injuries to Disabled Athletes*** **(Ferrara et al., 1992)**

Disabled Athlete Group	**injury (% of total)**
NWAA athletes (wheelchair)	shoulder, arm, elbow (57%)
USABA athletes (blind)	ankle, lower extremities (55%)
USCPAA athletes (cerebral palsy)	knee (21%), then shoulder, forearm/wrist, and leg/ankle

NWAA, National Wheelchair Athletic Association; USABA, United States Association for Blind Athletes; USCPAA, United States Cerebral Palsy Athletic Association

Pressure sores can be a significant physical limitation for wheelchair athletes and the most common complication in spinal cord injury. Athletes with pressure sores experience elevated skin pressures over the sacrum and ischial tuberosities for extended periods leading to discomfort during training and competition (Halpern & Cardone, 1998). Pressure sores are classified into grades between 1-4 (David, Chapman, & Chapman, 1983; Klenck & Gebke 2007):

Grade 1: Skin unbroken but discoloration: blister or persistent redness
Grade 2: Superficial skin loss
Grade 3: Destruction of the skin without cavity (full thickness of skin), possibility with black discoloration or slough.
Grade 4: Destruction of the skin with cavity (involving underlying tissue/structures).

In addition to injury, there are other issues that athletes with disability may experience to a greater extent than their able-bodied counterparts, which would benefit from some type of monitoring system. One such challenge is thermoregulation, defined as the body's ability to regulate internal temperature by balancing heat gain and heat loss. Heat exchange from the body can be done through processes of conduction, convection, radiation, and evaporation (Howe & Boden, 2007).

Conduction – a direct transfer of heat through physical contact with another object.
Convection – cooling of the body through movement of air or water molecules over exposed skin (e.g. cycling).
Radiation – the direct release of heat from the body to the environment by infrared rays.
Evaporation – occurs via perspiration of the skin and the most effective way to release heat.

Athletes with a disability may have impaired temperature-regulating mechanisms or lack of sensation causing a greater susceptibility to problems such as hypothermia. Likewise, lack of control of peripheral blood flow and impairment of sweating causes risk for hyperthermia (White, 2002).

Thermoregulation in disabled athletes with spinal cord injury, particularly quadriplegics, can be difficult to control due to the paralysis of skeletal muscle and loss of automatic nervous system control resulting in low tolerability to thermal extremes (Halpern, Boehm, & Cardone, 2001; Klenck & Gebke, 2007).

3. Vital Monitoring During Athletic Performance

Vital monitoring during athletic performance is necessary in evaluating an athlete's response to training and competition and allowing for preventative measures in avoiding overexertion and potential injury. Athletic performance is associated with meeting required levels of maximal exertion; because of this athletes may have different health parameters than non-athletes. Three main vital signs routinely monitored by healthcare professionals during athletic training and performance includes respiration rate, heart rate and body temperature. Measurements of these basic body functions are used to assess the athlete's overall health and are reliable indicators of how the body will react to elevated activity for both able-bodied and disabled athletes.

3.1. Respiration Applications

Respiration is measured by the inflation and deflation of the chest and abdomen during a respiratory cycle and can be monitored by impedance pneumography and inductive plethsmography. Chest impedance pneumography relates the decrease in conductivity and increase of conductance paths to the expansion of the chest by increased gas volume and extracellular fluid volume. Subsequently, electrical impedance increases during inspiration and decreases during expiration (Landon, 2003). Such changes in thoracic electric impedance may be used to monitor (1) respiratory rate; (2) changes in lung gas volume; (3) changes in lung water (congestion and edema); and (4) heart rate and cardiac stroke volume (Grenvik et al., 1972; Gupta, 2011). In measuring respiration, impedance pneumography involves the insertion of low current and high frequency signals (50 to 500 kHz) into the tissue through two or four electrodes located across the chest recording thoracic movements of the rib cage during a respiratory cycle (Gupta, 2011; Landon, 2003). Since respiration monitoring assesses the phase relationship between the rib cage and abdomen, impedance pneumography is limited to this type of measurement.

An additional advantage of respiratory monitoring is the application of inductive plethysmography to measure changes in the amount of air being inhaled or exhaled during a respiration cycle. Inductive plethysmography technology has less signal interference and distortion than impedance pneumography by measuring the phase relationship between two bands placed over the abdomen and the rib cage (Landon, 2003). As electrical currents are passed through the sensors, an oscillating circuit is acquired and different magnetic fields create waveforms to detect changes during respiration.

3.2. Heart Rate Applications

The heart is the major organ of the cardiovascular system and functions by circulating blood flow to organs of the body. Heart rate measurements are taken at a resting rate (awake, but rested and recovered) or exercise rate (to measure intensity of aerobic exercise). Heart rate is measured by finding a pulse on the point of the body where blood is being pulsated through the artery and will vary in measurement due to the levels of exchange between oxygen absorption and excretion of carbon dioxide.

An athlete's heart can be reshaped to adapt to regular, high-intensity training. It is this reshaping that allows the heart to more effectively pump blood throughout the body (Riddington, 2012). Athletes Heart is a common condition causing an enlargement of the heart resulting from intense prolonged exercise and training. The increase in growth of the heart chamber is necessary in order to keep up with the required blood flow and oxygen levels needed throughout performance (Lohr, 1999). Structural changes brought on as a result of Athletes Heart include thickening of the muscular walls, restriction of blood flow, lower resting heart rate and irregular heartbeat.

Current heart rate monitoring devices or ECG/EEG (electrocardiogram) are more effective than manual methods in accurately assessing an athlete's heart condition over short periods of time and detecting abnormalities through irregular heart beat. ECG monitoring devices transmit electromagnetic activity obtained via a signal transmitter located in a chest strap worn across the body to detect contractions of the heart muscle and transmit a signal to a receiver, likely worn on the wrist as a watch or armband, displaying the heart rate measurement.

3.3. Body Temperature Regulation Applications

Heat related illnesses are caused by the body's inability to regulate its temperature and are brought on by both internal and external factors. Internal factors are those related to the athlete (medical condition, dehydration, sunburn, etc). External factors are those related to the environment (temperature, humidity, excessive clothing). The internal and external factors can prompt cases of mild heat illness (heat edema, heat rash, heat syncope, heat cramps) or more severe cases such as heat exhaustion and ultimately heat stroke (Howe & Boden, 2007). Risk factors related to heat illness are illustrated in Table 3.

Table 3. ***Summary of Risk Factors for Heat Illness*** **(Howe & Boden, 2007)**

Internal Factors	External (Environmental) Factors
Comorbid medical conditions - respiratory, cardiovascular, hematologic Dehydration History of heat-related illness Medications or supplements Overmotivation Poor acclimatization Poor cardiovascular fitness Skin condition – eczema, psoriasis, burns, etc.	Activity Level Excessive and/or unsuitable clothing Lack of water or sufficient shade Temperature (ambient) Humidity Sunburn

In any competitive environment where maximal exertion is required, particularly in high endurance events, it is possible for an athlete to experience a loss of consciousness from heat stroke. The occurrence is expected to increase when there is an increase of race distance, temperature and/or humidity (Sallis, 2004). Methods of heat transfer occur through conduction, convection, radiation or evaporation. Athletic performance can be compromised when the body needs to regulate its temperature due to the energy required to affect this function. Energy is expended to cool the body as levels of physical activity are increased, limiting its use in other areas of the body.

Body temperature varies at different locations on the body. Areas of the core (abdominal, chest and central nervous system) often have a cooler temperature range than the arms and legs (Sessler, 2008). The core body temperature is highly regulated and monitored as it can give significant indication to the thermoregulatory effects brought on by elevated physical activity. Regulation of core body temperature is controlled by "behavioral and autonomic mechanisms that actively balance heat production and heat loss" (Insler & Sessler, 2006, p. 825).

Body temperature monitoring is used as a means to assess thermal status; however, various methods are used to obtain temperature readings according to convenience and type of transducer used (Insler & Sessler, 2006). A transducer is a device used to convert energy from one form to another. Energy converted by means of a transducer is done so either through direct contact from a patch or by embedding the transducer into the garment structure used for monitoring. The use of a transducer has advantages over traditional health monitoring methods in terms of minimized size, higher bandwidth, active sensing, and quicker response time. The two most commonly used transducers for body temperature monitoring are thermistors and thermocouples (Sessler, 2008). Sessler notes, "thermistors are temperature-sensitive semi-conductors, whereas thermocouples depend on the tiny current generated when dissimilar metals are joined" (p. 2). More advanced monitoring systems involving infared sensors eliminate direct contact by measuring infared energy emitted from the skin surface. Skin-surface temperatures are significantly lower than core body temperatures; therefore a more accurate assessment of temperature is achieved through the combination of non-core and core body temperatures.

3.4. Challenges Faced in Disability Monitoring

The classification of disability varies by individual sport but is critical when implementing appropriate physiological testing procedures (Goosey-Tolfrey, 2006). Challenges may arise when inaccurate evaluations of body measurements and physical ability become cause of faulty readings in vital sign detection. Therefore, an acknowledgement and understanding of individual disability testing procedures and expected state of physiological status is vital in the monitoring process.

The physiological state of able-bodied athletes typically follows standardized baseline measurements, such as age-predicted maximal heart rate. However, certain procedural limitations may occur when monitoring athletes with a disability. Due to the individual nature of the disability, increased complexity may be involved in monitoring athletes with a disability regarding both cognition and placement of device. In addition, levels of sensitivity to monitoring systems may be present that are not a factor with the able-bodied athlete. Athletes with a disability often lack the ability to control peripheral blood flow (White, 2002), which can be problematic in monitoring thermoregulation as well as respiratory fatigue. Proper blood flow to the muscles is essential in preventing respiratory muscle fatigue. In monitoring athletes with a disability, limited peripheral blood flow to the respiratory muscles can also lead to inaccurate assessments of circulatory regulation. An athlete whose physical limitation affects the accuracy of health monitoring, whether by sensitivity of the monitoring system or placement of device will require adjustments be made to able-bodied guidelines.

As an example of how these challenges impact the ability to accurately monitor athletes with disabilities, the wheelchair athlete presents a variety of limitations. Responses of the physiological state may vary in upper limb exercises caused by insufficient blood circulation of the lower extremities and nerve fiber dysfunction (cited in Goosey-Tolfrey, 2006). Subsequently, heart rate will remain lower than the predicted response from an able-bodied athlete due to the minimal use of the lower body extremities. Vital sign measurements may also be affected if the area being monitored is prone to lesions (i.e. pressure sores). Pressure sores arise from prolonged pressure to the skin and can increase the sensitivity and integrity of the skin (Klenck & Gebke, 2007). If the area to be monitored coincides with the site of the pressure sore, the monitoring device may require alternative placement, which may interfere with the accuracy of the testing procedures.

4. Performance Apparel in Athletics

Specialized apparel can be designed to perform two important tasks for athletes: monitoring and enhancement. Compression apparel is traditionally used to enhance athletic performance by providing muscle support and stability throughout training and competition; however, the benefits of compression apparel can be further enhanced to include monitoring of an athlete's physiological status by integrating biomedical sensors directly into the garment. Most current technologies on the market allow for vital sign monitoring to occur externally on the body. Such devices include: a heart rate monitor watch; a wireless accelerometer for respiration monitoring, and in-shoe pressure distribution devices. The complexity of adding independent monitoring into a garment eliminates the need for wired attachments and additional devices giving way to increased intensity and endurance of performance.

4.1. Benefits of Compression Apparel in Athletics

Compression apparel was originally designed for therapeutic medicine but it was discovered that the therapeutic benefits were applicable in environments of highly elevated aerobic activity to enhance exercise performance (Rebel, 2010). As physical activity is elevated in a competitive sporting environment, physiological performance and comfort significantly benefit through the use of compression apparel by providing gentle pressure to the body. Experimental research shows compression apparel to be effective in the following ways (Liu & Little, 2009).

- Reduced post-exercise trauma and lactic acid buildup
- Reduced perceived muscle soreness and oscillation
- Promoted recovery of force production
- Enhanced repetitive jump power
- Improved pro-prioception and core stability
- Increased oxygen delivery and minimize delayed-onset muscle soreness
- Regulated core temperature and keep user dry
- Enhanced circulation by promoting venous return

Physical interactions between compression apparel and the body activate sensory perception responses. Subjective and objective physical responses generate senses of comfort or discomfort to the user. Performance benefits of compression apparel are brought on by mechanisms of change in kinematics, change in blood flow and dampening of soft tissue (Coza, 2008). The use of compression apparel during performance minimizes muscle activity and amount of energy exerted (Coza, 2008).

Clothing with gradient compression is engineered to give the body varied levels of surface pressure at different parts of the body by applying the "highest degree of compression on the parts of the body that are furthest from the heart" (Cole, 2008, p. 60) to increase circulation of blood flow and oxygen to the heart and other core organs, providing increased levels of strength and endurance.

5. Textile Based Monitoring

Electrocardiogram (ECG) monitoring is a recording procedure used in measuring the electrical activity of the heart. The measurements are recorded via electrodes placed externally on the body across the chest to aid in detecting irregularity of heartbeat, position of heart chambers, the effect of increased physical activity, and additional illnesses related to the heart muscle. An interconnection between electrode and textile is possible when the "electrodes are embedded into textile substrates to fulfill pre-determined function" (Lymberis & De Rossi, 2004, p. 334). The effectiveness of directly embedding the sensors into textile substrates stems from advancements in technology and the elimination of wired attachments. Textile-embedded biomedical sensors can be integrated into textile substrates in a seamless manner providing increased levels of comfort and strength against noise and motion detection in long-term ECG and respiration monitoring (Kang, 2006). The seamlessness of the textile electrodes enables monitoring capabilities to provide more efficient long-term readings than in previous applications.

By directly or indirectly monitoring the vital signs of an athlete through electrode sensors, data showing changes in physiological status can be readily available for medical personnel. The interconnected technology utilized by sensors monitors specific vital signs and transmits the data from one signal point to the other via a predetermined data path (Park, Mackenzie, & Jayaraman, 2002). Communications between paths are converted into readable data that is transmitted to a monitoring system for real-time information of the individual's health parameters, which can be reacted to by a trainer, coach or medical staff.

Conductive Fibers and Yarns

Conductive and functional materials used as sensors and connectors are being integrated into garments by means of fibers and yarns (Paradiso, Loriga, & Taccini, 2004). Electronically conductive fibers are either naturally conductive or specially treated to create conductivity (Meoli, 2002). Conductive fibers electronically produce high conductivity because they are developed using metallic fibers such as silver, aluminum, copper, steel etc. The conductive fibers are bundled together through a bundle-drawing process and integrated with the base material to maintain washing capabilities and appearance and hand of a normal fabric (Meoli, 2002; Meoli & May-Plumlee, 2002; Merritt, 2008).

Yarn-based sensors fabricated using piezoresistive fibers allow for more efficient measurements of extension (Huang, Shen, Tang, & Chang, 2008; Paradiso, Loriga, & Taccini, 2004). Elevated physical activity increases the expansion of the chest cavity and extension of abdominal muscles during respiration. Pieroresistive fibers are sensitive to the changes in thoracic and abdominal circumference caused by the mechanical deformation (Pacelli, Loriga, Taccini, & Paradiso, 2006). Piezoresisitive fibers are highly conductive and are able to provide sensing capabilities due to fiber swelling caused by the separation of conductive (nano) particles, which generates the current (Van Langenhove & Hertleer, 2006; Poon & Liu 2011). The resistance change of piezoresistive fibers in response to applied strain and deformation can be used to evaluate biomedical variables of respiration, movement, posture etc. (Poon & Liu, 2011). Possible shortcomings of the pieroresistive yarns may include: low dynamic range, poor repeatability, performance deterioration after washing/repeated folding and complicated manufacturing process (Huang et al., 2008).

Optical fibers are useful in the application of health monitoring systems for their ability to respond to different wavelengths across sensing locations (Dhawan, 2007). Optical fibers are typically 120 micrometers in diameter and function by transmitting pulses of light as communication signals without necessary repetition (Meoli, 2002; Meoli & May-Plumlee, 2002). Two variations of optical fibers can produce sensory output; silica and plastic based. Silica based optical fibers are comprised of a chemical and sand composition that is melted into a molten glass liquid which is then drawn out in order to produce the filament optic fiber (Dhawan, 2007; Meoli, 2002; Meoli & May-Plumlee, 2002). Silica based fibers have a high tenacity and are not easily affected by high temperatures. However, since they are glass-based, the fibers are subject to end breaks or breakage resulting from applied tension (Dhawan, 2007). Comparably, plastic optical fibers offer advantages in minimal breakage but may lack the optical strength produced by the silica based (Dhawan, 2007; Meoli, 2002; Meoli & May-Plumlee, 2002).

5.2. Conductive Rubbers (Coatings)

Carbon rubbers or conductive rubbers have similar qualities to that of embedded fabric sensors in obtaining respiration and ECG measurements. Conductive rubbers typically are used in electrode application by means of combining a silicon rubber and a conductive material such as glass, silver, or carbon and are integrated into textile substrates through coating technologies (Merritt, 2008; Poon & Liu, 2011). Several advantages and disadvantages arise with the application of conductive rubbers: (1) conductive rubber electrodes have significant durability and washable properties, (2) carbon and silicon are biodegradable and are able to withstand the external environment for long periods of time, (3) the silicon coating of the electrode allows for a smooth surface area for skin contact more so than stainless steel electrodes aiding in comfort to the individual, (4) the silicon coating reduces the chance of motion and noise impedance during monitoring by trapping sweat exerted from the individual (Merritt, 2008), (5) conductive rubbers are thin and flexible which make them applicable for several electronic textile end uses (Meoli, 2002; Meoli & May-Plumlee, 2002; Merritt, 2008). Electrodes coated with conductive rubbers possess apparent disadvantages as well: (1) corrosion of the metal fibers and conductive rubbers is likely to occur as salt from the sweat released from the individual causes erosion of the rubbers, (2) the different types of metal used in the electrode (i.e. nickel) may cause skin allergies to develop (Merritt, 2008).

5.3. Printing and Finishing

Screen Print technology is a method of using conductive inks for electrical interaction and allows for monitor implementation by printing directly onto the fabric. Metals such as carbon, silver, nickel, copper and gold are coated with a type of substrate that acts as a protective layer to reduce losing electrical conductivity (Meoli, 2002; Suh, Carroll, & Oxenham, 2011). Protective coatings of the substrate vary in physical and chemical properties so selection of use is determined by application (Suh, Carroll, & Oxenham, 2011). Once the conductive inks are printed, they are coupled with an electronic component creating a wireless current circuit that aids the sensor in touch and voice activation (Meoli, 2002). Printable circuit technology has increased in popularity in applications requiring material flexibility and the ability to withstand abrasion and laundering without loss of conductivity. In addition, the printed wearable technology promotes comfort by eliminating wired attachments on the body. Table 4 provides a summary of the sensing components of e-textiles used for health monitoring and their relationship to specific applications.

Table 4. ***E-textile Sensors in Health Monitoring*** **(Poon & Liu, 2011)**

Devices	Sensing components	Signals	Applications
Woven or knitted with conductive yarn/rubber/ink	Fabric sensors	Electrocardiogram	Cardiopulmonary
Woven or knitted with conductive yarn/rubber electrodes	Fabric sensors	Electromyography	Neutral rehabilitation
Woven or knitted with conductive yarn/rubber electrodes	Impedance pneumographic sensors	Respiration	Cardiopulmonary
Textile fibers small-sized strips based on conductive yarn	Inductive plethysmographic sensors	Respiration	Cardiopulmonary
Textile fibers or small-sized strips based on conductive yarn/carbon filled rubber/electro active polymer	Piezoresistive sensors	Respiration	Cardiopulmonary
EAP based textile fibers or small-sized strips	Piezoresistive sensors	Movement and posture	Neutral rehabilitation
EAP based textile fibers or small-sized	Piezoresistive sensors	Carotid pulse, radial artery pulse, heart apex pulse, and sound	Cardiopulmonary
Optical Fibers	Optical Fibers	Pulse oxygen	Cardiopulmonary
EAP based textile fibers or small-sized strips	Thermoelectric sensors	Skin temperature	Neutral rehabilitation
Woven or knitted conductive yarn/rubber/&optical fibers	Fabric sensors	Cuffless blood pressure	Cardiopulmonary

5.4. Problems with Measuring Impedance Performance of Electrodes in Athletics

The structure of the fabric and the design of a garment considerably impact the impedance performance of electrodes. The textile is a platform for the electrode sensors and the sensors are only as beneficial as the placement in the fabric in which they are embedded. It is critical for sensors to be positioned accurately on or within the garment to avoid impedance and noise interruption, since athletes in high performance and technical activities will exhibit significant fluctuations in respiratory and ECG monitoring.

Fabric electrode sensors knitted into a garment often experience a significant amount of stretch, which can lead to technical limitations. Stretch associated with knitted sensors may adversely impact the quality of signal detected throughout monitoring. This is in part due to extension levels of the individual in places on the body where strain is applied (Kang, 2006). In these cases, measurements of the inductance and resistance of the knitted structure could prove to be non-linear and irregular. Adjustments in sensor length in the direction of the strain or altering the position of the sensors across the stretchable portion can help to minimize the stretch (Kang, 2006). However, since compression fabric is comparable to that used in swimwear, stretch is also required of the electrode under compression. Stretch will vary in the extension of the knitted structure and can adversely affect the signal quality of the electrodes (Kang, 2006; Silva et al., 2009).

As thermoregulation needs to occur in the body throughout athletic performance, perspiration or sweat is exerted from the individual and is likely to impact monitoring by increasing motion and noise impedance. The pH level in perspiration varies in each individual, thus high levels of chemical activity can lead to erosion of fibers and/or electrodes causing impedance in monitoring and inaccurate read of data. Impedance performance of electrodes can also be affected by environmental factors such as changes in climate or weather conditions (Kang, 2006). Elements such as rain or snow can limit performance in that water holds similar properties to that of electrolyte gel as it wets the electrode and therefore reduces the skin electrode resistance (Silva et al., 2009).

6. Product Development of Athletic Apparel

Product development of functional apparel has a somewhat linear process that stems from assessing the need of the customer and the function of the garment. This is particularly critical in the design of performance apparel for athletes with disabilities. Product developers of athletic apparel need to take into account the physical demands of an individual sport and how it will translate to movements of the body. Proper fit of the apparel to meet the demands of individual sports is especially important in the product development process. Table 5 illustrates the types of fit of athletic gear that most accurately approaches these demands.

Table 5. ***Olympic Sports, Athletes, and Athletic Wear*** **(Liu & Little, 2009)**

Olympic Sport	***Athletic Category***	***Physical Demands***	***Athletic Gear***
Athletics (Track and Field)	Running, Jumping, Field Events	Speed, endurance, power	Form Fitted/Loose
Badminton	Racquet Sport	Aerobic stamina, agility, strength, speed and precision	Semi-form fitted
Baseball	Bat-and-ball	Strength, speed, precision/power	Form-fitted
Basketball	Team sport, indoor or outdoor	Agility, speed, precision	Loose
Boxing	Combat sport	Strength, speed, defense	Loose
Canoeing	Kayak, straight racing	Endurance, speed	Form fitted
Cycling	Bicycle riding	Endurance, power, speed	Form fitted
Equestrian	A horseback rider	Precision, skill	Semi-form fitted
Fencing	Competitive swordsmanship	Speed, precision, skill	Semi-form fitted
Football (Soccer)	Team sport	Speed, stamina, skill, precision	Semi-form fitted
Gymnastics	Competitive physical exercise	Agility, coordination, stabilization	Form fitted
Judo	Martial art and combat sport	Skill, strength, power	Loose

Rowing	Competitive water sport	Endurance, skill	Form-fitted
Table Tennis	Racquet sport	Skill, speed, precision	Semi-form fitted
Tennis	Racquet sport	Endurance, skill, speed	Semi-form fitted
Wrestling	Martial arts	Strength, stabilization, skill	Loose
Triathlon	Multi-sport endurance event	Endurance, power, speed	Form-fitted
Weight Lifting	Weight training	A combination of power (strength and speed), technique, flexibility and consistency	Form-fitted

Physiological performance benefits to the wearer are attributed to contact pressure in the garment. Thus, fit and fabrication of the garment play a critical role in enhancing these benefits. Increased activity subjected by the individual sport influences variable movements of the body. As the garment is stretched, strain is applied, causing deformation of the fabric. Points of strain will vary according to athletic body type and participation of sport, but awareness of where these points are located will assist product developers in knowing where more or less fabric is needed in the garment and how to combine the pressure with the specific needs of the disabled athlete (Tarrier, Harland, Jones, Lucas, & Price, 2010).

From a design perspective, style details such as type of neckline and placement of closures is of the utmost importance in athletic apparel. Athletes with a disability can experience loss of dexterity or poorly functioning joints and muscles, therefore product development of garments for individuals with special needs must be mindful of the position of closures and seams; the ease with which the garment can be removed as well as the comfort and selection of fabrics used to adhere to specific body types. Reich and Shannon (1980) attempted to simplify the design process by combining categorization of common physical limitation groups and then identifying clothing needs and limitations of each group. Table 6 illustrates suggested clothing styles related to each physical limitation. The xx and oo’s relate to the level of appropriateness for these limitations (ranging from xx being very difficult to wear, to oo being very easy). The influences of physical limitation of an individual were obtained through a questionnaire regarding: (1) physical handicap, (2) clothing and dressing needs, (3) special devices, and (4) demographic factors. Of the responses gathered, 296 useable responses were used to divide the common physical limitations into groups to assess clothing style features and the physical difficulty experienced by each group. The common physical limitations are classified into six groups: Lower leg (problems associated with the feet, ankle, knee and lower leg); Lower torso (problems associated below the waist, hips, upper leg and lower back); Upper torso (shoulder, upper back, upper arm and above the waist); Hand (dexterity of fingers); Arm (elbow, lower arm and waist) and the Neck.

Table 6. ***Style Related to Common Physical Limitation*** **(Reich & Shannon, 1980)**

Style features	Lower Body		Upper Body			
	Lower leg	Lower torso	Hand	Upper torso	Arm	Neck
Necklines						
Turtle	xx	xx	xx	xx	xx	xx
Jewel	o	o	o	oo	o	o
Shirtwaist	o	o	o	o	o	o
V-neck	o	o	oo	o	o	o
U-neck	-	o	oo	o	oo	o
Sleeves						
Long	x	xx	xx	-	xx	xx
¾ Length	o	oo	xx	xx	xx	xx
Short	-	-	oo	oo	oo	oo
Cuffs						
Button	xx	xx	xx	xx	xx	xx
Rib	o	o	xx	xx	xx	xx
Elastic	o	o	xx	xx	xx	xx
Fasteners						
½ buttons	xx	xx	xx	xx	xx	xx
Large buttons	oo	oo	xx	xx	xx	xx
Snaps	xx	xx	xx	xx	xx	xx
Hooks and eyes	xx	xx	xx	xx	xx	xx
Ties or lacing	xx	xx	xx	xx	xx	xx
Hook and loop tape	-	o	oo	oo	oo	-
Belts and loops	xx	xx	xx	xx	xx	xx

xx = very difficult ($p < .001$)
x = difficult ($p < .05$)
o = not difficult (p < .05)
oo = easy (p <.001)
- = not significant

Thus, an athlete with a disability affecting the arms might be best served by a garment with a U-neck, shorter sleeves and fastenings using hook-and-loop (Velcro®) tape. Athletes with upper body injuries will have easiest accessibility in short sleeve garments without cuffs. Fasteners and closures are likely to be of difficulty for all athletes with physical limitation.

Athletes with a disability require garments of specific functional and comfort specifications that are unlikely to be developed in mass-market production (Rosenblad-Wallin, 1985). Traditional product development methods are often directed at target groups with a wide reach to make them profitable for apparel companies. There are significant variations in the core stages of the product development process between conventional and functional clothing. Rosenblad-Wallin (1985) notes, "User-oriented product development results in products with functional values more satisfactory than those of corresponding former products." (p. 286). User-oriented product development is a recommended method of addressing the needs of athletes with a disability by designing garments based on physiological and ergonomic demands, providing better ease of movement and fit for specific body shape (Rosenblad-Wallin, 1985). Differences between traditional product development and user-oriented product development are illustrated in Table 7.

Table 7. ***Development Differences*** **(Rosenblad-Wallin, 1985)**

	Traditional product development	**User-oriented product development**
The starting-point	Textile properties of new materials	The user
The formulation of demands	Based on the clothing manufacturer’s internal knowledge of its target user	Based on subjective and objective demands of the groups use-situation
The development work	Concentrated on the the material, to reach intended protective properties	Total solutions of protection and comfort, researched by a co-ordination between material and model design
Method of evaluation	Limited wear trials to accept or reject a final solution	Repeated small scale wear trials and product modification

While significant importance is placed in the functional value of special needs clothing, design aesthetics play an equally critical role. Through user-oriented product development, athletes with a disability have functional need to satisfy and also wish to promote positive self body image through design aesthetics of mainstream fashion. Furthermore, functional needs of disabled and able-bodied athletes are dependent upon type of sport and coincide by allowing for adjustments in fitting, ease of openings and workable closures. The mainstream consumer market is likely to benefit from technology solutions developed for athletes with physical disabilities (Cassim 2007; Reich & Shannon, 1980).

6.1. Comfort and Performance Testing

Comfort and performance remain a prerequisite in all facets of clothing (Cassim, 2007). Product innovation of smart textiles in athletic apparel will not shift mainstream if comfort and performance do not play a significant role. Furthermore, the importance of comfort and performance is even more critical in product design for athletes with physical limitations. Establishing guidelines to meet comfort and performance specifications for higher-level athletic apparel is an important part of athletic performance for both able-bodied and disabled athletes.

Rosenblad-Wallin (1985) notes “the difference between textile or garment properties and corresponding functional values is that measurements of properties only rank the materials…while the functional values make clear the influence of the product on a human being” (p. 280). The Textile Protection and Comfort Center (T-PACC) at North Carolina State University utilizes testing methods and conducts fundamental research to assess protection and comfort performance of clothing in all stages of development. In addition to the standardized testing procedures of the American Association of Textile Chemists and Colorists (AATCC), the American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO), the T-PACC employs specific measurement techniques to evaluate "interactions between fabric and garment design, climate, physiological, and psychological variables" (T-PACC, 2012), further assisting in the product development stage. One area of focus of the T-PACC includes Comfort Performance. Comfort Performance in athletic apparel is a significant and influential quality required of the end user. Measurement techniques and resources available in assessing subjective and objective comfort performance of high performance athletic apparel include (but are not limited to):

- *Kawabata Evaluation System* – The Kawabata Evaluation System measures the mechanical properties relating to the aesthetic quality of the fabric hand and how comfort is perceived by the human touch. Measurements evaluated by the Kawabata system include: tensile strength, shear stiffness (drape), bending rigidity (flexing), compression (thickness, softness), and surface friction and roughness (next to skin) on tactile sensations. In measuring comfort performance of athletic apparel, evaluations of thickness and softness of compression is a particularly key component. Comfort in clothing denotes the absence of discomfort, thus thicker fabric can interfere with the athlete's ability to perform. The Kawabata System aims to compare measurements of the initial thickness of the fabric to that of the maximum force being applied. The higher the value, the greater the compressibility. Likewise, compressional resilience relates to how much recovery occurs when the force is removed. A higher value indicates greater recovery of the fabric from being compressed.

- *Qmax Warm/Cool Touch Test* – Qmax Warm/Cool Touch Test uses the qmax value (watts/m2°C) to measure the thermal properties of the garment fabric upon contact between garment and skin. This measurement assesses the cool/warm sensation felt by the wearer, which is dependent on the contact area between the skin and fabric surface. The higher the qmax value, the more rapidly heat is moving from the body to the fabric surface, giving way to a cooler feeling fabric. Measurement results from the qmax warm/cool Touch Test can be used to evaluate thermoregulation properties in athletes and relates to heat exchange leading to fluctuations in body temperature. Since athletes with a disability may lack temperature-sensing mechanisms necessary for thermoregulation, the Qmax Warm/Cool Touch Test can be used to compare the rate of heat exchange and comfort needs between athletes with a disability and their able-bodied counterparts.

- *Comfort Wear Test* – The Comfort Wear Test is a subjective evaluation of the garment by participants as they engage in alternative physical activity and rest. The participants perform a routine exercise activity in moderate and warm climatic conditions in order to reach a sweat-wetted-skin condition. Several activities within the test are derived from ASTM F 1154 Standard Practices for Qualitatively Evaluating the Comfort, Fit, Function and Durability of Protective Ensembles and Ensemble Components. The participants of the wear test are randomly assigned to evaluate various garment types to achieve independent ratings based on overall comfort, warm-cool feeling, softness, and/or moistness of the garment. The Comfort Wear Test can be related to Rosenblad-

Wallin's (1985) comparison of traditional and user-oriented product development test methods. By conducting subjective wear tests on both able-bodied athletes and athletes with disability, product development methods can adhere to the specific functional and comfort needs required of the end user.

- *Physiological Wear Test* – The Physiological Wear Test is a subjective test used to evaluate the entire garment and its ability to accurately receive physiological data from the wearer. The collected data includes heart rate, skin temperature, and core temperature. The transmission of data occurs via wireless sensor technologies and is used to indicate bodily stress of the wearer. The wireless technologies also allow for an easier read of data, less distractions to the test subject and reduce the possibility of re-testing due to instrument failure caused by slippage. The physiological Wear Test indicates how embedding electrode sensors into compression apparel can aid in vital sign monitoring of athletes throughout competition, without being disruptive in comfort and performance.

Standards and specifications exist to maintain levels of quality and performance in apparel. ASTM, AATCC and ISO have implemented standardized testing procedures that can be used to determine physical and mechanical properties required of performance apparel used in athletics. It is possible that manufacturers of such apparel have also developed rigorous testing procedures for their brands. For example, physical-mechanical properties required of compression apparel for optimum performance directly relate to the raw material used, fiber cross-section, fiber size, yarns, fabric weight and thickness, fit and fabrication of the product and chemical and mechanical finish treatment (Liu & Little, 2009).

Most testing procedures used for performance apparel are dedicated to the materials used to make up the garment. Beyond this, standards and specs could be written for additional testing of finished garments and other products. Based on recommendations from T-PACC personnel and author analysis of existing tests, Table 8 describes some potential testing procedures that would likely be successful in evaluating end-product performance apparel with monitoring capabilities.

Table 8. ***Standardized Testing Methods For Performance Apparel Embedded with Electrode Sensors*** **(G. Liston, personal communication, July 17, 2012)**

Test Methods Applicable to Tactile Comfort of Compression Apparel

- AATCC Test Method #187 Dimensional Changes of Fabrics: Accelerated
- AATCC Test Method #93 Abrasion Resistance to Fabrics: Accelerator Method
- ASTM D7507-10 Standard Specification for Woven High Stretch Fabrics Used in Apparel
- ASTM F2808-10 Standard Test Method for Performing Behind-the-Knee (BTK) Test for Evaluating Skin Irritation Response to Products and Materials that Come into Repeated or Extended Contact with Skin

Test Methods Applicable to Thermal Properties of Compression Apparel

- AATCC Test Method #22 Water Repellency: Spray Test
- AATCC Test Method #195 Liquid Moisture Management Properties of Textile Fabrics
- ASTM F2371-10 Standard Test Method for Measuring the Heat Removal Rate of Personal Cooling System Using a Sweating Heated Manikin
- ASTM D7024-04 Standard Test Method for Steady State and Dynamic Thermal Performance of Textile Materials
- ASTM F1868 Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials
- ASTM E96 Standard Test Method for Water Vapor Transmission of Materials
- ASTM F1291 Standard Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin
- ASTM F2370 Standard Test Method for Measuring the Resistance of Clothing Using a Sweating Manikin
- ISO 11092 Textiles—Physiological Effects—Measurement of Thermal and Water-Vapor Resistance Under Steady-State Conditions

Test Methods Applicable to Embedded Electrode Performance

- AATCC Test Method #76 Electrical Surface Resistivity of Fabrics
- AATCC Test Method #84 Electrical Resistance of Yarns
- AATCC Test Method #115 Electrostatic Clinging to Fabrics: Fabric to Metal

7. Conclusions and Future Work

Interactive electronic technologies that are integrated in textile applications provide numerous opportunities to serve a functional purpose. In areas where functional need requires assessing the physiological state of an individual, certain textile applications may be advantageous. The integration of biomedical sensors into athletic apparel could assist with disease detection and diagnosis during training and performance, as well as potential injury prevention. The focus on the functional needs of smart textiles requires a multidisciplinary approach in research and product development and mutual efforts from scientists and engineers in the fields of wireless telecommunications, textile and clothing, biomedical engineering, and health and medicine (Lymberis & Olsson, 2003).

Approaching product development for athletic apparel from public health and medical perspectives can provide unique advantages in promoting the quality of life for the athlete, particularly those limited by disability or injury. However, there remains a gap in research for inclusion of smart textiles for individuals with physical limitations. Inclusive design is a term used to emphasize structural needs and capabilities to satisfy the requirements of a wide variety of individuals. Currently, inclusive design in clothing is limited due to mass customization approaches in patternmaking. A new product development system based on inclusion of body types according to physical limitation can lead to apparel production involving increased accessibility using original patterns.

As an example of how this might work, wheelchair athletes have limited mobility of their lower extremities and may experience pressure sores in areas where there is tension between skin and seat. To account for the extra padding needed to alleviate the pain from pressure sores, conventional patterns can be manipulated to include the padding as part of the garment rather than be added on as an afterthought. Additional concerns of comfort could also be addressed when determining the location of traditional seams to avoid buildup of tension in certain areas of the body. Knowing that wheelchair athletes suffer the greatest amount of injuries to their shoulders, arms and elbows (Klenck & Gebke, 2007; Patel & Greydanus, 2009) gives designers the information to proactively provide protection in the garments. Using a matrix such as that developed by Reich and Shannon (1980) gives designers options to customize garments according to body area affected by disability. In addition, monitoring systems which will assist in capturing core body temperature, heart rate and respiration rate can be embedded at a number of levels within a garment provided a thoughtful awareness of placement and level of cognition are afforded in the design process.

Little research has also been performed relating athletes with a disability and sports injuries. Physical limitation as a result of disability can be specific to the individual and therefore it is difficult to distinguish injury pattern amongst athletes. A recommendation for further research to compare injury patterns amongst able-bodied athletes and injuries in athletes with a disability would be beneficial in the product development of textile and clothing applications for health monitoring and proper placement of the monitoring device for injury prevention. Functional form of the monitoring device must not be limited by aesthetic preference; likewise the individual wearing the monitoring device should continually experience full mobility and both physical and psychological comfort, including ease of use. Mobility within clothing is challenged when there is an increase of technological function (Suh, Carroll, & Cassill, 2010). Further research in minimizing the bulk and size of portable health monitoring systems and the adaptation of wireless technologies within clothing will aid in promoting both the design aesthetic and functional purpose.

Standards and specifications exist to assess the physical-mechanical properties of newly developed garments and relate to performance attributes. Although performed in a standardized manner, not all testing procedures are a “consensus method, but contribute significantly to understanding comfort perception across many end user scenarios” (G. Liston, personal communication, July 17, 2012). Additional subjective and physiological wear tests amongst different segments of the population such as individuals with physical limitations and the elderly would promote a user-oriented product development approach in areas of clothing-related applications where technological advances in health monitoring would be viable.

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