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Ergonomics and Comfort in Protective and Sport Clothing: A Brief Review

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Abstract

Industrial and sport protective clothing (PC) is governed by protection requirements and sport clothing is generally selected on the basis of performance and comfort. The impact of PC on performance is determined by the nature of the work or sport, the metabolic rate required, the ambient environment, and the characteristics of the PC. The chief ergonomics challenge of PC is when moderate to high work rates must be performed in moderate to hot ambient environments. Comfort is typically subjectively measured and impacts performance. Comfort is multifactorial and dynamic rather than static. Sport clothing design is chiefly concerned with maximizing heat and moisture loss and comfort; however, attempts to use synthetic fabrics to increase comfort and heat dissipation have generally not been successful. Future innovations may include protective and sport clothing that responds to the environment, and that features integrated cooling systems with greater cooling capacity and practicality for mobile workers and sportsmen. A brief review of key challenges in the ergonomics of PC and sport clothing is presented along with potential directions for advancing ergonomics and comfort.

Keywords: Heat Stress; Sportswear; Clothing and Sports Performance; Work Performance; Microclimate; Layer; Moisture; Evaporation; Sweat

Abbreviations: PC: Protective Clothing; WBGT: Wet Bulb Globe Temperature

Introduction

The aim of this review is to provide a brief perspective on comfort and performance challenges in protective and sport clothing. Protective clothing (PC) is needed in work or sport to protect against physical hazards, impact, abrasion, and against toxic hazards. Protective and sport clothing may also be used to enhance performance.

Protective and sport clothing provide vital functions but also add to physiological loads that could contribute to a progressive decline in physical and mental capacity [1-3]. This consequently could lower productivity and performance to variable extents [1,2]. The impact of clothing on comfort and performance of individuals at work or sport are therefore of particular importance. We review the ergonomics of industrial and sport PC and sport clothing with regard to the interactions between humans and clothing, with a view to optimize human comfort, safety well-being and performance.

In this review, protective clothing includes clothing covering over 30% of the body and used in industry, sport, the military and emergency response. Sport clothing includes clothing which provides protection impact and abrasion, or improves performance. The current design of most protective industrial and sport clothing reduces the rate of heat dissipation; therefore, this clothing presents particular challenges to health and performance in hot and high humid environments in both industry and sport. Consequently, this review will cover a variety of applications with emphasis on the challenges in comfort and ergonomics for warm to hot environments.

Why Protective and Sport Clothing?

In industry typically government mandates require the use of PC under specified circumstances. In the United States, for example, the National Institutes for Occupational Safety and Health and the National Fire Protection Association regulate PC requirements [3]. PC is often mandatory to protect from physical, nuclear, pathogenic, and chemical hazards at work. Examples include: the ballistic protective vest which protects against projectiles in law enforcement and military applications; firefighter's PC which serves to protect against heat and flame; and encapsulating coveralls which protect against toxins and pathogens in biomedical, and hazardous materials work sites. Encapsulating PC may also be required to protect from contaminants being released into clean room work environment in modern industry. Likewise, chemical PC is used in manufacturing as well as in remediation of sites with lead or friable asbestos. In addition, radiation protection via clothing may also be required. Chemical and biological, and sometime radiation clothing protection also is commonly needed for emergency first responders, military applications, and medical personnel. PC may be used in cold environments to protect against cold hazards.

In sport, some sport regulating bodies require certain sport PC, but this is generally done only in the most general terms, allowing sportsmen and team's latitude in what is used. Sport PC becomes a mandatory requirement in certain sports such as American football, baseball, lacrosse, and field and ice hockey. In cricket, American football and baseball, and other sports the PC padding is used to protect against impact and abrasion. In sport clothing, clothing may also provide warmth, as for cross-country skiing, open water swimming, sport breath-hold, and scuba diving. Sportswear worn by bicyclists

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often offers a convenient means for storing food and other items of use, as well as providing support and padding.

Examples of sport clothing to enhance performance, include special swimming suits, now banned for Olympic competition [4,5] because they were shown to give a performance advantage. Speed skating and down-hill ski suits also provide aerodynamic advantages [6,7]. More often, in both professional and recreational sport, comfort of the wearer is considered an integrated part of performance sport clothing. Some clothing is sold in both sport and industry for its alleged ability to improve comfort and reduce heat stress via "wicking sweat away from the skin" [8]. In adventure sports such as mountain climbing, sport clothing with advanced moisture-wicking and quick-drying properties attracts interest particularly for wet environments or those with large temperature changes. Sport clothing has also been marketed which allegedly liberates heat to warm users. Whereas the principle is based on the heat released when particular fabrics absorb water, the amount of heat released is low. The heat may be liberated before the wearer goes into the cold and some liberated heat will be lost to the ambient environment, so the useful heat effects may be minimal [Bishop, unpublished observations].

Characteristics of Clothing Comfort

Clothing comfort is rated among its most important attributes [9,10]. Bell et al. [11] reported that clothing comfort rating was associated with performance on a cognitive exam. Maintaining accurate cognition and a positive mood is especially important in emergency first responders and law enforcement and military applications in PC.

Clothing comfort is a very complex characteristic of PC and sport clothing. Comfort is comprised of: 1) thermal, 2) non-thermal, 3) and wear conditions [12]; or: 1) physiological, 2) psychological, and 3) physical components [13]. Comfort arises from the integrated visual, thermal, and tactile sensations, the psychological status, body-clothing interactions, and ambient environments [14]. Comfort of the same PC or sport clothing may change over time and initial judgment of clothing comfort or discomfort may change after a period of wear. If clothing becomes damp or wet, in most cases comfort diminishes [15,16].

Thermal comfort is a key issue in PC use and ergonomics as well as in sport clothing. It arises in part from neural thermosensory monitoring of the area between the wearer's skin and the outer-most layer of the clothing, the micro-environment [17-21]. In fact, it should be noted that comfort has little to do with the macro-environment and much more to do with the micro-environment, the only environment with which the body has contact. It is also noteworthy that even the nude body forms a micro-environment that is generally warmer and more humid than the ambient environment except in the hottest ambient environments.

Comfort measurements of clothing must be based on subjective evaluations of human wearers (e.g., see [22,23]) which integrate the combined effects of all relevant variables of clothing systems on comfort [24]. Wong et al. [25] proposed a combination of objective and subjective measures to model comfort, which probably will yield the best validity. Accurately predicting human responses to PC seems unlikely in view of the observed variable nature of humans with respect to comfort [26]. For further information on measuring comfort, see Bishop [27].

Ergonomics Issues

Ergonomics issues in industry

In industry, the key ergonomics issue is minimizing the reduced human performance and productivity that often accompanies PC use. Reduced productivity arises from several issues including the weight and bulk of the clothing, visual and tactile reductions associated with some clothing, and the heat stress that typically accompanies PC use in hot ambient environments. As can be seen in Table 1, the weight of PC directly contributes to the energy costs of a task, and this contribution is most profound for weight supported activities as opposed to seated activities such as driving a forklift or other vehicle. The weight of PC may be most problematic for workers such as firefighters who have to transport themselves, their PC, and equipment up several flights of stairs [28].

The bulk of PC may add to the energy costs of the movement [29].

Characteristics of the Work or Sport	
Metabolic Rate	The higher the metabolic rate, the more heat the worker/sportsman must dissipate - good in cold environments, challenging in the heat.
Economy/Efficiency	The more economical the worker/sportsman, the less energy liberated as heat.
Weight-Supported	If the worker/sportsman must support his/her own body weight plus the weight of protective clothing (PC) and other equipment, the total weight will impact the required metabolic rate.
Characteristics of the Protective and Sport Clothing	
Weight	Impacts the energy costs of transporting the additional weight of PC.
Resistance to Movement	Raises the energy costs. The greater the interference and the greater the movement required, the greater the increase in energy costs.
Clothing Insulation	Impacts the micro-environment under clothing. High insulation reduces the heat transfer rate.
Clothing Permeability	Impacts the micro-environment under clothing. Low permeability reduces the sweat evaporation rate.
Clothing Reflectivity	Impacts the heat gain of clothing.
Percent of Surface Area of Body Covered	Fully encapsulating PC generally presents more ergonomics issues for work in warm/hot environments.
Degree of Isolation	Fully encapsulating PC totally isolates the worker from the environment; some PC has many openings for movement of air in and out. Greater the air exchange may be advantageous or disadvantageous depending on the environment and other factors listed above.
Fit	May impact clothing pumping effects, depending on the clothing and movements.
Fabric	Industrial PC fabrics must exhibit protective characteristics, but in sport clothing, moisture transfer, style, and comfort are important for marketing. Some fabrics may release a small amount of heat.
Characteristics of the Ambient Environment	
Temperature	Impacts dry heat transfer between the worker/sportsman and the ambient environment.
Water Vapor Pressure	Impacts evaporation rate and cooling.
Radiant Load	Radiation from any source will increase the heat that must be dissipated by the worker/sportsman.

Table 1: Key variables Affecting the Ergonomics of Protective and Sport Clothing.

This is due to both the weight and the energy costs of bending the layers of PC. Again this may be illustrated most readily in firefighter PC, where multiple layers of fabric are required to protect the worker. We have measured firefighter PC at 19.1 kg [30,31], so just carrying this weight adds to the metabolic costs. Added burden of PC also displays changes in the wearer's gait variability and influences the balance, muscular capabilities and fatigue, which increase the likelihood of slips and falls during prolonged work [32-35].

Any increase in energy costs due to PC [29] will raise the metabolic rate therefore raising the heat produced by the worker. In cold environments, this will keep the person warmer. In warm/hot environments, this further raises the heat dissipation requirements. The American Conference of Government Industrial Hygienists guidelines for work in PC [36] use the ambient wet bulb globe temperature (WBGT) and the anticipated metabolic rate, which does not account for any additional metabolic costs of any PC use [29] to specify work-rest ratios for workers. Use of the ambient WBGT is appropriate for "light summer clothing" for which it was originally intended [37], but must be adjusted in some manner for PC use. This has been done using "adjustment factors" [38,39]; however, this approach does not account for the differences in adjustment factor between very cold ambient conditions where the appropriate adjustment is large, and very hot environments (such as on the fire field) where the appropriate adjustment might be negative. This and other issues have been discussed extensively elsewhere [40].

The most problematic aspect of PC use is when work or sport occurs in hot ambient environments (Table 1). The nature of PC reduces the rate of heat loss in both industry and sport. Humans working or exercising at moderate or higher metabolic rates remove the metabolic heat via sweat evaporation from the skin. PC of all types typically reduces sweat evaporation from the skin, consequently reducing the rate of heat loss. When the rate of heat loss falls below the rate of production, heat storage occurs raising the risk of heat injury. Less recognized is the potential diminution of cognitive capabilities [31,41,42], which may be particularly important in emergency first responders. Sweat rates have been as high as 1.0 L/hr during industrial simulations [43] and hypohydration is also exacerbated by inadequate opportunities to drink during respiratory protective mask use in industry. Dehydration of 2% of body mass has been associated with reduced performance and increased risk of heat injury [44,45].

In cold ambient environments, the insulative value of some PC is advantageous because heat dissipation is reduced. However, in some industrial situations, the metabolic rate variations may result in workers being cold sometimes and too hot others, within the same ambient environment. PC use in cold environments adds no marked difference in heat loads when performing moderate work load [46]. For some industrial PC situations, such as working in toxic environments, the ability to adjust clothing insulation may be restricted which can result in workers being alternatively too hot or too cold.

Ergonomics issues in sport

In sport, unlike PC in industry, clothing is much less regulated. For example, the National Collegiate Athletic Association regulates when American football clothing should not be worn (to protect against heat stress in pre-season practices which occur in hot weather), rather than specifying specific sport PC requirements [47]. Most of the major sports organizations and governing bodies, such as the International Olympic Committee [48], do not regulate sport clothing for training and competition in environmental extremes. Sport clothing is regulated, however, in swimming [4,5].

In sport, as in industry, the energy costs of the sport PC contribute more to those players moving their body a lot (e.g., a running or defensive back) than those who move less (e.g., offensive lineman). In sport it is well known that the sport PC of American football slows the player, so running times are reported with and without the football PC.

The increased heat strain of sport PC and the high metabolic rates during many sports may lead to hypohydration. Hypohydration is also exacerbated by inadequate opportunities to drink during sport competitions. Hypohydration contributes to the risk of heat illness [49]. Hypohydration also negatively affects performance during soccer [50] and has been proposed to play a role in fatigue [51,52]. Sweat rates have been as high as 2.9 L/h during sport competition [53]. Hypohydration during PC use also causes deterioration in mood and increase in perception of exertion [31], which could be critical in work place practice or during game competition that requires sustained attention and highly controlled mood state.

Heat stroke is the third leading cause of death in the United States for sportsmen, exceeded only by cardiac abnormalities and neck and cervical injuries [54]. For high-school sports for 100 schools over a 2-year span, almost 19% of all injuries were related to dehydration and heat illness [54]. Sport clothing could exaggerate the risk of heat illness. Evidence has shown sport PC (i.e., helmet, shoulder pads) that is worn during American football game resulted in higher physiological strain [55], which is consistent with data reporting that risks of heat illness among American football players were 10 times higher than other athletes [56]. Future research is warranted with sport PC in impact sports.

It is obvious that impermeable clothing will retard sweat evaporation, but even permeable clothing tends to raise the water vapor pressure under the PC, slowing the rate of evaporation and heat dissipation. Likewise, impermeable and semi-permeable parts of PC in sport, such as the protective pads in cricket, American football, and baseball restrict evaporation to varying extents depending on the characteristics and area of the coverage.

Davis et al. [57] examined the impact of almost-encapsulating Islamic athletic clothing on female sportswomen exercising in a hot environment. Surprisingly the extra clothing did not significantly increase the heat strain under the conditions of the study. Islamic athletic clothing did significantly decrease clothing comfort and increased skin wetness due to increased skin contact compared to a traditional soccer uniform.

Other sport clothing retards sweat evaporation, but generally to a lesser extent than sport PC. In some sports such as running, cycling, and soccer, the high metabolic rates require high rates of heat dissipation [51,58]. In most cases in the heat, the less clothing covering the skin, the better the thermoregulation.

Manufacturers have touted many novel fabrics as having superior sweat removal properties. Most research has not supported this concept [59]. For example, Ha et al. [60] compared 100% polyester to 100% cotton with 5 females completing 4 bouts of 10 min of exercise of 30% VO_{2max} in 24°C. In polyester compared to cotton, rectal temperature increased significantly faster and the overall temperature was higher throughout the trial. Mean heart rate was higher in polyester; and cotton exhibited a higher surface temperature suggesting that dry heat loss could occur more easily [60]. The same results were seen in a 37°C environment with polyester compared to cotton and a cotton and wool blend [60,61]. Enhanced moisture absorption by the fabric liberated more heat [60,62-64], which may help wearers feel more comfortable and dry with cotton compared to polyester. Four of five subjects felt wetter with polyester compared to cotton [60] attributed to decreased skin wetness with cotton because it held more moisture than polyester, which had been previously shown [16,65] in polyester compared to cotton [66] and wool [67]. However, if the polyester material is hygroscopically treated, skin wetness can be reduced [67]. For further comparisons of fabrics in sport clothing applications see the following references [59,61,64,68-73].

It appears that 100% polyester fabric or other synthetic fabrics offer no thermoregulatory or comfort advantages with some studies showing a worse thermoregulation and clothing comfort than natural fabrics [59]. Most studies have not replicated typical intermittent exercise but have been more work-related [60,61,64,73]. Even when studies have incorporated protocols similar to most athletic or recreational endeavors, no thermoregulatory advantage has been gained with synthetic fabrics [71,74,75].

Davis and Bishop [47] recently reported that most studies examining synthetic compared to natural fabrics have used a modest environmental (19-27°C) temperature with only a few studies employing a hot environment (≥30°C). Fabrics showing superior properties in a low-intensity exercise in cool or moderate conditions may be overwhelmed in hotter and more humid environments or during higher metabolic rates.

Another innovation in sport clothing is so-called "compression garments". Previously, compression garments have been used in clinical settings for patients with circulatory problems [76,77], with the intent of increasing venous blood flow and reducing venous stasis [78]. Recently, compression garments have been introduced to sport and their use has since spread.

Compression garment manufacturers claim [79] that compression garments "stabilize" the muscle which allegedly increases blood flow to the working muscles, thereby leading to improved performance. Possible performance and recovery benefits from wearing compression garment have been reported [80,81]. However, other researchers did not find any physiological, thermoregulatory, or performance benefits from wearing compression garments [82] [Balilionis, unpublished]. Higher mean skin temperatures were reported after 30-min intermittent exercise protocol with full-body compression garment [83], during five minute warm-up [80] and 4×15 minute repeated bout exercises [82] with compression garment compared to control. Collectively the studies suggest that it is not likely that improved performance effects will be found [80-83].

There is little research concerning the impact of channeled-fabric synthetic compression garment on thermoregulation and performance. One manufacturer [79] stated that compression garments with inner and outer channels in the fabric cool the body and aid sweat evaporation from the clothing by moving the moisture and warmth away from the skin and thus improve performance. Study participants reported feeling more comfortable and that they felt that they sweated less with a channeled synthetic compression t-shirt compared to regular synthetic t-shirt during 3-hour "industrial protocol" [Balilionis, unpublished] and 30-km bike time trial [Balilionis, unpublished] in a hot environment. In addition, changes in rectal and chest skin temperature were smaller with channeled synthetic compression t-shirt compared to regular synthetic t-shirt [Balilionis, unpublished].

In winter sports and some recreational sports during cool weather such as sport hunting, camping, and rock climbing, sport clothing to keep sportsmen warm is highly valued. In contrast to the difficulties in developing new fabrics to keep sportsmen cool, advances have been made in warmth [84-86] using advanced insulated fiber and fabric structures. Recent innovation includes battery-powered heated trousers designed for boosting Olympic athletes' performance. Passive heating of the thighs following the warm-up completion using pants incorporating electrically heated pads slowed the decline in muscle temperature and enhanced the subsequent sprint cycling performance [87].

Sport clothing is often marketed based on the ideas of improving performance, reducing thermal stress, keeping the sportsman drier, and often on the basis of improved comfort. Taken the above available evidence together, claims about superior sport clothing fabrics should be tested.

Improving Comfort and Ergonomics

From our research, the best hope of improving the comfort and ergonomics of protective and sport clothing lies in the development of new materials and new approaches. Materials improving upon the well-known triple-layer moisture transmitting material (Gore-Tex, Gore Inc., Elkton, MD, USA) may improve vapor transmission rate and increase sweat evaporation in industrial and sport PC. Other materials may provide better protection with less bulk and weight, such as some modern fabrics have done for ballistic vest protection (e.g., Kevlar, E.I. DuPont, Wilmington, DE, USA). Novel fabric technology in the laboratory includes shape memory material and phase change material which contains automatic environmental acclimatizing properties [88], potentially having wide applications in protective and sport clothing. Innovative three-dimensional fabric structure could also reduce the expense and weight with improved protection [89].

Other than future development of advanced materials, we suggest clothing cut should be studied. Clothing affects thermoregulation to varying degrees, with evaporative resistance being the major determinant in maintaining the thermal balance [59]. Vapor and moisture permeability characteristics of the clothing play a critical role in influencing the micro-environment and therefore the wearer comfort. In this regard, increasing ventilation through smart clothing cut or combining different fabric panels (e.g., employing highly vapor permeable fabric) at critical points could yield better performance and comfort. This has been supported in a recent study [90], in which placing clothing vents at torso, arm, and legs in combat uniforms promoted heat transfer and reduced physiological strain. This aspect of clothing ergonomics is easily achievable. More research is needed to determine locations of critical points within the micro-environment of protective and sport clothing and thus will enable manufactures to incorporate smart vents at critical points.

With regard to the challenges of heat dissipation for PC in warm or hot environments, the best short-term solution is probably micro-environmental cooling [91-93]. This issue has been discussed in a recent publication [40]. In brief, cooling is supplied via either cooled liquid [94], cooled gases [43], or phase-change materials [95]. Typically the cooling garment is a vest but a cooling cap is also available [96]. Often when worn under PC, the cooling capacity may be limited. With phase-change cooling under PC, replacing or removing the cooling system may be problematic under conditions where PC cannot be removed. Supplying large volumes of cooling to mobile workers and sportsmen can be challenging particularly at locations without an electrical supply.

A recently developed cooling system attempts to cool sportsmen or workers by cooling the palmar surface of hands [30]. The battery-powered hand-held cooling device circulates chilled water to cool the palm and fingers, which is suitable for highly mobile and fully encumbered emergency first responders. Sports such as American football and a few others have employed hand cooling in conjunction with fans to provide area cooling. For more information on personal microclimate cooling in occupational settings and sport, see reviews [94,97-100].

While heating is generally less challenging than cooling, self-heated insulated sport clothing remains a need for many winter sports and in military applications during cold weather. The common method to keep one warm in the cold is through the use of multiple insulated layers of clothing, adding extra weight and bulk to the wearer and trapping humidity between layers. A novel approach is now available, involving embedded metallic heating elements (conductive metal materials) into clothing [101,102]. The battery-powered heated trousers used in the past summer Olympics [87] is the most recent technology advancement in this regard. More work is needed to address this technology's field applications during prolonged military operations and wearer discomfort arisen from the rigid nature of metallic elements and its logistic maintenance and durability.

Future Directions

In industrial PC, the need to increase safety and productivity should drive the development of new technology and clothing. In sport clothing, marketing competition will likely provide most of the incentive for further improvements in both comfort and ergonomics.

Development of active fabrics and clothing that responds to activity and the ambient environment should improve comfort as well as performance. Clothing systems that can automatically or easily manually adjust water vapor transmission capacity and the rate of heat dissipation both through the fabric and at openings would be of great value in both industry and sport, and in some PC applications.

Innovation of an integrated cooling clothing system could also allow protective and sport clothing better coping with rapid environmental variations. Portable circulated liquid and gas cooling with ultrathin, flexible tubes in the clothing textile structure have shown some promise for mobile applications. However, it remains challenging to design and manufacture integrated cooling clothing that takes full consideration of usability (e.g., performance, weight of system), durability (e.g., dimensional stability during repeated use, flexural endurance, abrasion resistance, mechanical strength), maintainability (e.g., ease of care, launderability), and affordability (e.g., material cost, maintenance cost).

Future PC and sport clothing is expected to feature smart responses with artificial intelligence that interacts with humans, the environment, and clothing itself. Smart protective and sport clothing systems incorporating noninvasive sensors and monitors into clothing for assessing and diagnosing the wearer's real-time physiological status (e.g., heart rate, electrocardiography, respiration, core temperature, metabolic rate, and blood pressure) and environment (e.g., humidity, heat flux, chemicals) would be of great utility in improving safety. Future smart clothing would allow early detection of medical problems and enable advanced action to ensure safety of the wearer, which is of great value for athletes, emergency first responders, and in military applications. Trans-disciplinary research and development of smart medical systems and technology are currently underway in industry and research laboratories and future technology transfers are foreseeable.

In summary, industrial and sport PC and sport clothing can compromise performance and comfort. With continued research and innovation, it is expected that PC and sport clothing will steadily improve in comfort, health and safety of the wearer.

Conflict of Interest

The authors declare no funding was received for completing this work. Author ZY is a coach of the Chinese Badminton Association, Jiaxing branch. The views herein are the private opinions of author ZY and are not reflecting the views of the Chinese Badminton Association.

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