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Designing a Test Battery for Ergonomics of Personal Cooling Garments

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Abstract
Personal cooling garments (PCGs) are effective in helping wearers combat heat stress. However, ergonomics problems of PCGs have received little research attention so far. Along with the increasing application of personal protective devices in the construction industry, the interaction and their suitability between human and these devices have been emphasized by manufacturers and end-users. Hence, a key comprehensive ergonomic assessment of PCGs should be launched before wider application in industrial settings can be realized. As there is lacking of standard ergonomic test practice on PCGs, this study proposes a test battery for the ergonomic evaluation on PCGs. The proposed experimental design includes two major procedures: 1) identifying wearing conditions of construction workers with PCGs, and 2) executing both subjective and objective measurements on human factors. This protocol will provide solid guidelines to researchers and practitioners for the comprehensive evaluation of the ergonomic design of PCGs.

Keywords
Ergonomics, Personal cooling garment, Wearing condition, Subjective and objective assessment

1. Introduction

Along with the promotion of personal protective devices in the construction industry, there has been an increased emphasis on their ergonomic design (Lin and Harvey, 1997). Ergonomics is the discipline that seeks to improve the safety and well-being of humans by concentrating on the harmonious cooperation between human and the designs of jobs, tools, machines and the environment (Licaros-Velasco, 1998; Slabbert *et al.*, 2014). Concerning the high risk of heat-related illness in the construction industry, personal cooling garments (PCGs) are considered useful alternatives to protect construction workers from a stressful environment. Their effectiveness in alleviating physiological and psychological strain has been well documented in numerous studies (e.g., Hadid *et al.*, 2008; Kim *et al.*, 2011).

Nevertheless, potential drawbacks of PCGs, such as bulkiness, heaviness, and power supply restrictions, have been already reported (Hadid *et al.*, 2008; Chan *et al.*, 2013). Inappropriately designed PCGs may further adversely affect, mobility, comfort, and work performance (Chan *et al.*, 2013). Ergonomic problems of PCGs, such as additional weight and body movement restriction, may result in excessive metabolic production, thereby augmenting body heat strain (Larsen *et al.*, 2011) and inducing musculoskeletal pain (Akbar-Khanzadeh *et al.*, 1995). Comfort and usability are important facets related to workers' preference and acceptance of PCGs (Chan *et al.*, 2013); thus, these factors must be considered in the overall evaluation of PCGs. In view of this, there is a pressing need to evaluate the ergonomic design of PCGs before promoting their widespread use in industrial settings.

The effects of typical ergonomic issues related to PCGs, such as clothing sizing and fit, as well as their compatibility with other personal equipment, have been received little concern so far. A few studies have conducted ergonomic evaluation on PCGs (e.g., Kim *et al.*, 2011; Chan *et al.*, 2013), but these studies lack of holistic evaluation in terms of test methodologies. For instance, Kim *et al.* (2011) only examined a limited number of subjective attributes of a liquid-cooled garment in a controlled laboratory test. Although Chan *et al.* (2013) administered a relatively comprehensive subjective assessment on the acceptability of PCGs in field studies, objective measurements were not included. Such assessment might not be able to provide explicit guidelines for improving the ergonomic design of PCGs.

Standard test practices in ergonomic evaluations exist; however, these are mostly for personal protective clothing (PPC) rather than for PCGs. There is a need to have a set of guidelines with which to evaluate the ergonomic impact of PCGs. This study initially proposed an experiment protocol for an ergonomic evaluation of PCGs, which comprises a series of tests involving both subjective and objective assessments. The proposed protocol was based on the extensive ergonomic evaluation of PPCs and the ergonomic considerations of construction works. The protocol proposes that the principles of testing may be successfully applied to ergonomic evaluations of various types of PCGs in future research works.

2. Framework of the proposed protocol

ISO 26800 (2011) defines the four principles of ergonomics: thermal interaction, anthropometric characteristics, biomechanical characteristics, and human sensory. A thermal interaction between wearers and PCGs is beyond the scope of this study. The ergonomic evaluation of PCGs depended on wearing scenarios in actual use. The ideal situation of the ergonomic evaluation is to ask construction workers to wear specific PCGs while performing their daily work in actual industrial settings. An alternative approach is to conduct a laboratory experiment, which is designed to produce accurate and reproducible results under a certain test condition, when it is unfeasible to test in all possible conditions due to limited time and costs (Havenith and Heus, 2004). The body movements and the overall level of metabolic energy expenditure of the human subjects should be simulated as close as possible to those of actual wearers (ISO 26800, 2011). The key step of such an experiment is to identify a typical wearing condition that can accurately simulate actual use conditions. The typical circumstances of wearing PCGs may involve "who," "when," "where," "duration," "what task should be done," and "what else should be noted," as shown in Figure 1. These may differ depending on the type of trade; hence, a specific trade by trade study should be performed.

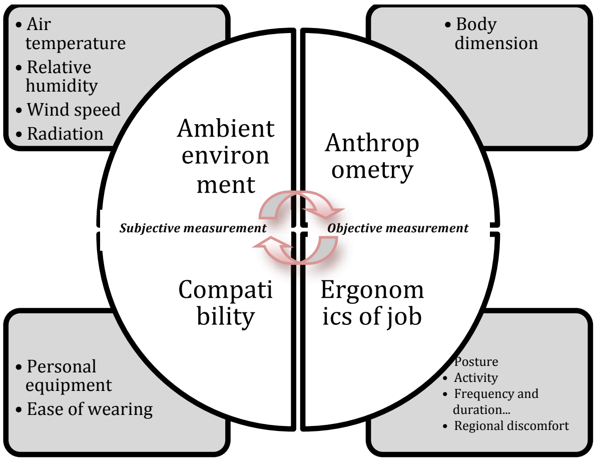
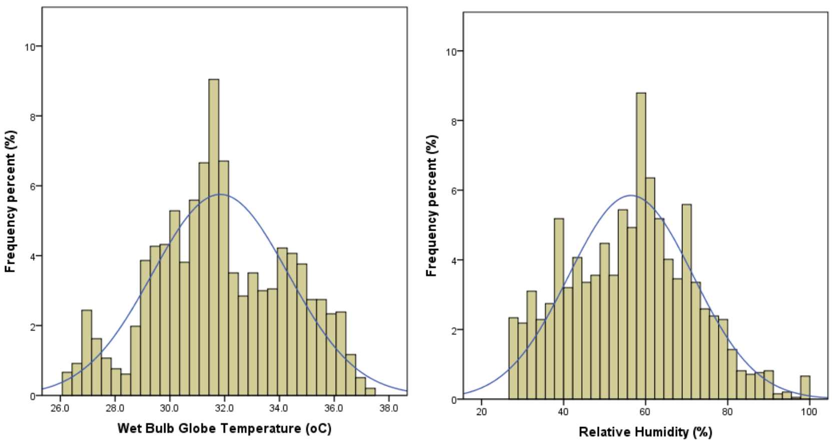


Figure 1 Design of wearing conditions

2.1 Wearing conditions

2.1.1 Ambient environment

Ambient environment has considerable impact on human factors (ISO 26800, 2011). The mean and standard deviation of wet bulb globe temperature and relative humidity collected on construction sites in summer of 2012 and 2014 were 31.8 (2.5) °C and 56.4 (15.2)%, respectively (Figure 2). A hot and humid working environment should be chosen for an ergonomic assessment on PCGs.



a b

Figure 2 Environmental data collected on construction sites in 2012 and 2014 summer: a) WBGT, b) relative humidity. Blue line presents as normal distribution curve.

Data source: Chan, A.P.C., Yang, Y., Wong, D.P., Lam, E.W.M., and Li, Y. (2013). "Factors affecting horticultural and cleaning workers' preference on cooling vests." *Building and Environment*, 66, 181-189. Chan, A.P.C., Yang, Y., Wong, F.K.W., Chan, D.W.M., Lam, E.W.M. (2014). "Predicting the wearing comfort of summer work uniforms for construction workers." Working paper.

2.1.2 Anthropometric characteristics

Anthropometric characteristics comprise the main factors affecting the load bearing of the body, e.g., increase in body weight may result in increased load-bearing (Van den Bogert *et al.*, 1999). Fitness level and heat acclimation can also influence the performance of physical activities in hot environments (Sawka *et al.*, 1984). Such key evidences imply that the bias of anthropometric factors may have considerable impact on the experimental results arising from participants' biophysical maladjustments. When it is impossible to invite local rebar workers to participate in an ergonomic assessment, a group of local, physically active students may be an alternative.

2.1.3 Ergonomics of construction work—rebar work as an example

In order to assess PCGs from an ergonomic point of view, it is important to gain information about the actual manual work of construction workers. This way, the biomechanical interaction between the PCGs and the human body can be determined. For the purpose of examining the ergonomic assessment of PCGs in relation to their effects on task performance and comfort, participants need to perform task-related activities in consideration of the nature of the actual construction work and regional body discomfort.

Apart from requiring the lengthiest work cycle, rebar work, by its very nature, is one of the most physically demanding and highly dynamic tasks in the construction industry (Jarkas, 2010). It is challenging to accurately quantify the ergonomic profiles of rebar work (Buchholz *et al.*, 1996; Paquet, 1998). Hence, a work-sampling based approach called PATH (posture, activity, tool, handling) has been widely employed for assessing ergonomics of work (Buchholz *et al.*, 1996; Spielholz *et al.*, 2006; Mathiassen *et al.*, 2013). This strategy is feasible in accurately and conveniently capturing valid estimates of ergonomic hazards associated with construction work (Forde and Buchholz, 2004). A full description of the PATH protocol can be found in previous studies (e.g., Buchholz *et al.*, 1996; Takala *et al.*, 2010). The target dimensions of the ergonomic assessment of work generally include posture, duration, frequency of actions, and movement (Takala *et al.*, 2010). Posture is usually coded as the orientation of body segments (e.g., trunk, legs, arms, shoulder, neck, and waist). An activity can be categorized into several groups, including (1) manual material handling activities, (2) back/waist postures, (3) arm/shoulder movements, and (4) leg movements, etc. Heavy lifting, forceful pulling, continuous back bending, and tying rods are typical activities and tasks performed by rebar workers (Wickstrom *et al.*, 1978; Saari and Wickstrom, 1978; Dababneh and Waters, 2000). The type of tool should be listed for each operation prior to the PATH assessment. Traditional tying tools, such as pliers and a pigtail, require a worker to bend over to reach the ground and carry out the tying (Dababneh and Waters, 2000). Handling is recorded as a load of the actual weight of a tool, which can be found in a standard construction material database when it is impossible to take direct measurements. These four facets are always accompanied by measurements of their frequencies and duration (Buchholz *et al.*, 1996). Plenty of studies have been performed to assess the ergonomics of rebar work. By conducting the PATH assessment, Forde and Buchholz (2004) found that the rebar workers who spent their work time in non-neutral trunk postures, one or both arms at or above shoulder level, and stood on uneven/unstable work surfaces included 13% to 48%, 6% to 21% and 3% to 53%, of the respondents, respectively. Buchholz *et al.* (2003) reported that non-neutral trunk postures were observed frequently (exceeding 30%), although manual material handling was the most commonly observed activity (exceeding 20%) of all job tasks surveyed. Spielholz *et al.* (2006) reported that rebar workers were commonly in high right-hand force with awkward posture and repetition, back bent >45°, and even lifting >31.8 kg (70 lb) from the ground. Based on the ergonomic assessment of work, a set of the PATH assessment performed by rebar workers can be outlined (e.g., Figure 3), which can provide solid evidence for designing a construction-specific experiment protocol.

a b c

Figure 3 Examples of typical PATH performed by rebar workers: a) non-neutral trunk postures, b) manual material handling, c) lifting iron bar.

In addition to the nature of rebar work, regional body discomfort, and musculoskeletal disorders caused by excessive physical workload cannot be neglected in assessing the ergonomics of PCGs. Wickstrom *et al.* (1978) and Saari and Wickstrom (1978) identified rebar work as a hazardous job that results in a high rate of back injuries. By investigating the prevalence of self-reported musculoskeletal disorder symptoms among 1996 rebar workers, Forde *et al.* (2005) found that the most frequently reported symptoms were pain in the lower back (56%), wrist/hands/fingers (40%), knees (39%), and shoulders (36%). These body regions are most susceptible to injury, and should thus be considered cautiously whether wearing PCGs would increase the risk of such disorders.

As regards the inevitable nature of an ergonomic hazard in construction daily work, there is an urgent demand to avoid the negative ergonomic impacts of PCGs. Prior to the ergonomic assessment of PCGs, a trade-by-trade specific study is necessary to refine the ergonomics of work.

2.1.4 Compatibility

Considering compatibility of PCGs, such as accessibility of pockets while the PCG is worn, the types of zips, buttons, and fasteners used, and the usage with other personal equipment, is also necessary in determining proper wearing conditions.

2.2 Measurements

An overview of parameter measurements on ergonomics of PCG is shown in Figure 4.

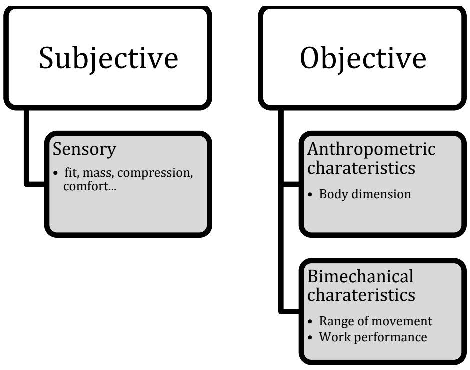


Figure 4 Subjective and objective measurements on ergonomics of PCGs

2.2.1 Subjective measurement

A subjective investigation is one of the most traditional methods of evaluating human sensory reactions toward clothing and textile (Li, 2001). It is generally carried out by analyzing the subjective attributes involved in the questionnaire survey on the basis of wearing experiences. Sensory perceptions are powerful tools for judging individual descriptors on perceived sensations of clothing (Li, 2001). Apart from the studies on thermal-related sensations of PCGs, other facets of ergonomic problems have received little research attention. A comprehensive survey of the subjective perception on PCGs will provide essential information on their ergonomic properties. The ergonomic properties of PCGs can be evaluated using a series of subjective attributes, including freedom of movement, mass, fit, tactile sensation, comfort, pain, operation, compatibility with other personal equipment, and so on. A singular-point bipolar scale is useful in helping wearers judge the levels of their perception. In addition, a semi-structured interview is considered a robust method to gather wearers' new ideas and a detailed set of replies. A set of examples for subjective assessment can be referred to in previous studies (Chan *et al.*, 2013; Havenith and Heus, 2004). Based on these subjective perceptions, the researchers and manufacturers will obtain a comprehensive view of the merits and drawbacks of the ergonomic designs of PCGs. However, a subjective measurement is not optimal enough to provide an explicit guideline with which to ameliorate clothing ergonomic design.

2.2.2 Objective measurement

Many different approaches are available to objectively measure human factors. The literature can be mainly summarized as studies that measure anthropometry, static and dynamic range of movement (ROM), and task performance (Li *et al.*, 2013; Coca *et al.*, 2010). Standard instruments are required for an objective measurement. Anthropometric measurements generally include subject height, body mass (including or excluding PCGs), and body fat composition. The instruments for such measurement may include a flexible tape measure, circumference tape, scale with certified precision, and body fat monitor.

Previous studies have shown that PCGs may restrict human mobility (Chan *et al.*, 2013; Kopias and Bogdan, 2010). A decrease in range of motion (ROM) usually results in restriction of movement (Coca *et al.*, 2010). A static ROM refers to a maximum angular change of a particular joint (Adams and Keyserling, 1993; Coca *et al.*, 2010). It consists of tests that measure the active flexion/extension/abduction of the main body joints (i.e., elbow, shoulder, neck, hip, knee, ankle and wrist) reaching as far as possible from sitting and standing positions (Coca *et al.*, 2010). Dynamic ROM is typically measured when performing various specific tasks that are determined in Section 2.1.3. Static and dynamic ROM can be assessed using a goniometric, torso bend device (e.g., Acuflex I, Novel Products, Inc., Rockton, IL). The objective performance trials (time and number of strides to complete a specific task) are widely conducted to manipulate performance when wearing PPC. However, the results of the performance trails should be the confounding impacts of cooling capacity and the ergonomic problems of PCGs. To standardize each measurement, three repeated values are commonly taken, and an average of the measured values is then reported for each subject. All measurements should be taken by the same researcher to avoid inconsistencies in methodology (Coca *et al.*, 2010).

3. Concluding Remarks

PCGs can limit the wearer's movement, and this may negatively affect workers' enthusiasm and performance. In turn, this leads to an increasing conflict between its cooling function and practical application. There is a pressing need to develop more comfortable PCGs without affecting mobility and work performance. Previously, the evaluation of ergonomic performance while wearing PCGs has not utilized a consistent methodology. This is possibly due to the lack of a standard protocols or published guidelines. The present study, therefore, tries to bridge this research gap by providing solid guidelines for the ergonomic evaluation of PCGs. The recommendation is to have a comprehensive understanding of wearing conditions and sophisticated experimental execution of dominating facets in designing a test battery to evaluate the ergonomics of PCGs.

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