

Developing Innovative Functional Clothing That Supports the Safety and Productivity of Construction Workers: A Feasibility Study

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Construction is generally considered a blue collar, hands-on industry, and the attire of those working on construction sites mostly consists of jeans, T-shirt, and steel toe boots. Although specific jobs such as welding may require the use of personal protective equipment and specially designed clothing to protect their eyes and bodies, workers usually wear their own clothing with no consideration of job functionality. Most of the clothing products currently available offer no real benefits to the worker. To cope with excessive physical demands in construction, worker often use non-prescribed medical supplies and equipment such as braces, splints, and supports to deal with work-related illnesses and injuries. However, contemporary clothing functions and features, used in conjunction with non-medical supports, can improve the safety and productivity of construction workers. This study investigated a range of carpenter activities to identify the body parts affected and the consequential injuries typically suffered. A functional clothing prototype to mitigate the physical burden of a worker is then suggested which it is hoped will establish momentum for the introduction of an interdisciplinary approach integrating construction, fashion, medicine, and biomechanics. The introduction of functional clothing for the construction industry that takes into account job functionality is long overdue.

Keywords: Functional clothing, Work-related illness and injuries, Carpenters, Job functionality, Productivity

Introduction

Although one of the main objectives of the Occupational Safety and Health Administration (OSHA) is to significantly reduce work-related illnesses and injuries (WIIs), data from the Bureau of Labor Statistics (BLS) still reports substantial numbers of recordable cases that result in devastating human injuries and loss of life on construction sites, incurring major economic costs. Work-related injuries are a serious occupational health problem in the construction industry, with construction workers suffering 3.9 injuries per 100 full-time equivalent workers, although fatal construction injuries are down nearly 42 percent since 2006 (Bureau of Labor Statistics, 2012). There is a general agreement that published injury rates data undercount the actual injury experience, including injury counts in construction (Grzywacs et al., 2012); data collected by the U.S. Bureau of Labor Statistics underestimates the actual number of nonfatal WIIs according to Dong et al. (2011). Within the construction industry, the burden of injuries is unevenly distributed among the different trades (Grzywacs et al., 2012). For instance, injury rates among roofers are elevated relative to other trades (CPWR, 2008). Construction and extraction occupations are classified into 23 different trades by the U.S. Department of Labor based on their job descriptions, with duties and injuries included as subsections in the classifications utilized. Each trade has distinct physical activity or mobility demands that are directly related to the occurrence of major injuries within that trade. Unlike a worker in a manufacturing plant that works static in place, a construction worker is required to move from place to place, work environments and risk factors are constantly changing as the construction project progresses. Most construction workers equip themselves with the bare minimum of safety gear and tools because of the high level of physical effort required to carry out their duties and the many static and awkward postures involved, as well as the need to constantly move around the construction site. To support construction workers and help them cope with the physical demands of their jobs, clothing designed specifically to address the needs of different trades could significantly reduce work-related illnesses and injuries if used in conjunction with appropriate safety gear. Although some construction trades do wear protective clothing to reduce their exposure to toxic materials during hazardous activities, most construction workers

simply wear jeans and T-shirts that provide the basic function of clothing but fail to consider individual workers' duties and the safety demands of the various trades.
This study investigates the feasibility of developing functional clothing that will not only enhance the occupational safety and health of those working on construction sites but also help construction workers maximize their productivity. This exploratory pilot study looked at the various human factors involved for workers, in this case carpenters, performing a range of different construction activities around a building site, examining how individual body parts are affected by the various activities and identifying any that are linked with consequential injuries. We then move on to suggest possible functional features that could be integrated into a worker's clothing in order to mitigate their physical burdens.

Functional Clothing

Throughout history, human clothing has adapted to reflect a wide range of physical, social, geographical, and functional considerations. However, although clothing now has the potential to integrate advanced functions that improves comfort and enhances occupational safety and health, the clothing worn by construction workers has hardly changed in decades, even though it could now incorporate features that reduce WIIs due to repetitive physical activities and static and awkward postures. Functional clothing is a broad concept and items of clothing can now be designed to protect the wearer from hazards in the environment such as fire, extreme heat and cold, water, chemicals, particulates in the air, blood-borne pathogens and other biological agents, electrical current, ultra-violet light and radioactive materials, as well as physical forces or impacts due to bullets, vehicles, sports equipment, work equipment, or falling debris. This works both ways: clothing can also help protect the environment from bodily contaminants, for example the clean room apparel used in the production of micro-electric components and in other sensitive environments (McCullough, 2001). The design process for such garments focuses on specific user activities carried out under extreme environmental conditions from sportswear to spacesuits, taking into account the functional needs of the wearer, the nature of the potential risk and the anticipated duration of the user's exposure to hazards. Functional clothing design starts with understanding wearer needs and applying evidence-based methods, after which engineering principles interact with the creative, intuitive processes of art and fashion (Watkins & Dunne, 2015). Thus, functional clothing design is inherently interdisciplinary in nature, involving multiple research domains such as medicine, biotechnology, physics, and computing, among others, to meet the many and varied requirements of the users (Gupta, 2011). The most important factor in designing functional clothing, however, is to understand the human user and how they will wear the clothes. To solve problems related to specific users' needs in extreme environments, designers must consider comfort, durability, protection and dimensional stability, but as yet little research has looked at the needs of construction workers (Chan et al., 2016). The general context of clothing for workers in various industries has been developed passively, as protective clothing, rather than actively considering job functionality. It is also important to note that protective clothing must distinguish between two extremes, the first being where the user voluntarily exposes themselves to potential harm, and the other where the exposure is involuntary (Scheurell, 2001). Much of the earlier research into functional apparel design has focused on specific areas such as people with disabilities (Carroll & Kincade, 2007; Jung et al., 2010), protective clothing for pesticide application (Boorady et al., 2009), and clothing for farmers (Choi & Ashdown, 2002), but as yet there has been only minimal research into functional clothing for construction workers and gardening industry workers.

Research Approach

The research reported here sought to understand and recognize the necessity of functional clothing for those working in the construction industry. It is hoped that this will establish the momentum needed to launch an interdisciplinary effort that will harness the talents of scholars in construction management, fashion design, industrial medicine, biomechanics, and textiles to improve safety and productivity for construction workers and others working in hazardous environments. There is no widely utilized functional clothing that takes into account the job functionality required in the construction industry, hence it is not immediately obvious how best to apply and integrate functional clothing for construction workers. The first step must therefore be to suggest a prototype for functional clothing for a specific trade in order to develop an understanding of the linkage between general field activities and WIIs. In order to assess the risks faced by construction worker that are associated with the general field activities and obtain an idea of how functional clothing could support safety and productivity, for this study we began by identifying worker activities in terms of burden factors link to specific anatomical body regions.

In general, pilot studies represent the initial phase of the research process, where researchers propose an approach that will later be used in a larger scale study and examine its feasibility (Leon et al., 2012). The pilot study reported here is based on an extensive literature review, current market research on the currently available functional wear for construction workers and a brainstorming session, culminating in the development of a functional clothing prototype for a carpenter. The following primary tasks are involved:

1. Identification
    a. Conduct a literature review to establish momentum for functional clothing development
    b. Understand individual job responsibilities and duties in general field activities
    c. Identify common work-related illnesses and injuries
2. Categorization
    a. Identify burden activities in terms of general field activities that cause WIIs
    b. Analyze the burden activities by breaking them down into specific routine activities
3. Linkage
    a. Determine which relationships and interactions among burden activities affect individual anatomical body regions
    b. Determine any linkages between routine activities that adversely affect specific body regions and the WIIs caused
4. Convergence
    a. Analyze problems and the needs to improve safety and productivity in job functionality
    b. Conduct market research on the functional clothing currently available for construction workers
    c. Identify design requirement, (i.e., mobility, tactile sensitivity, tool capacity, etc.)
    d. Develop a prototype design

This pilot study is expected to identify the comprehensive knowledge elements needed for effective functional clothing that will support job functionality among construction workers.

Identification of Hazardous Working Conditions

This study explores the normal physical demands of the job and the incidents that often cause injuries and illnesses among construction workers in order to determine how recent advances in clothing design and materials can be utilized to create customized apparel that supports occupational safety and health on construction sites. To understand the feasibility of designing functional clothing that enhances both work activities, and job functionality, we focus on the specific needs of single trade, namely carpenters. This trade was selected because carpenters make up the largest proportion of building trade occupations. They work both indoors and outdoors and are involved in a wide range construction types, from building highways and bridges to installing kitchen cabinets (Choi et al., 2016). Carpenters are involved in all phases of commercial and residential building construction, as well as in the construction of roads, bridges, and tunnels, representing numerous exposures to both chemical and physical hazards (Lemasters et al., 1998). As a result, carpenters also have a higher rate of injury and illness than the national average for workers, with the most common injuries being strains/sprains due to manually lifting heavy materials (Bureau of Labor Statistics, 2015).

According to the National Institute for Occupational Safety and Health (NIOSH), epidemiological studies have found evidence of a causal relationship between physical exertion at work and work-related musculoskeletal disorders (WMSD) (Bernard, 1997). Several factors are known to be associated with WMSD, including repetitive motion, excessive force, awkward and/or sustained postures, and prolonged sitting or standing (da Costa & Vieira, 2010). In order to understand the physical burdens or stresses that directly or indirectly result in WIIs, the general field activities of carpenters can be analyzed by breaking down individual activities into burden factors such as force & muscle effort, awkward body postures, repetitive work & movement, or vibration from tools, as shown in Figure 1. These can then be linked to the anatomical body regions most likely to be affected and the resulting WIIs. A carpenter's overhead work, for instance, directly affects his or her neck, shoulder, back, and hand, so the roadmap identifies tendonitis in the shoulder as likely resulting from an excessively prolonged overhead working position. Breaking down individual activities in this way, especially burden activities, can also help determine feasible ways to utilize functional clothing to support burden activities and avoid the related WIIs.

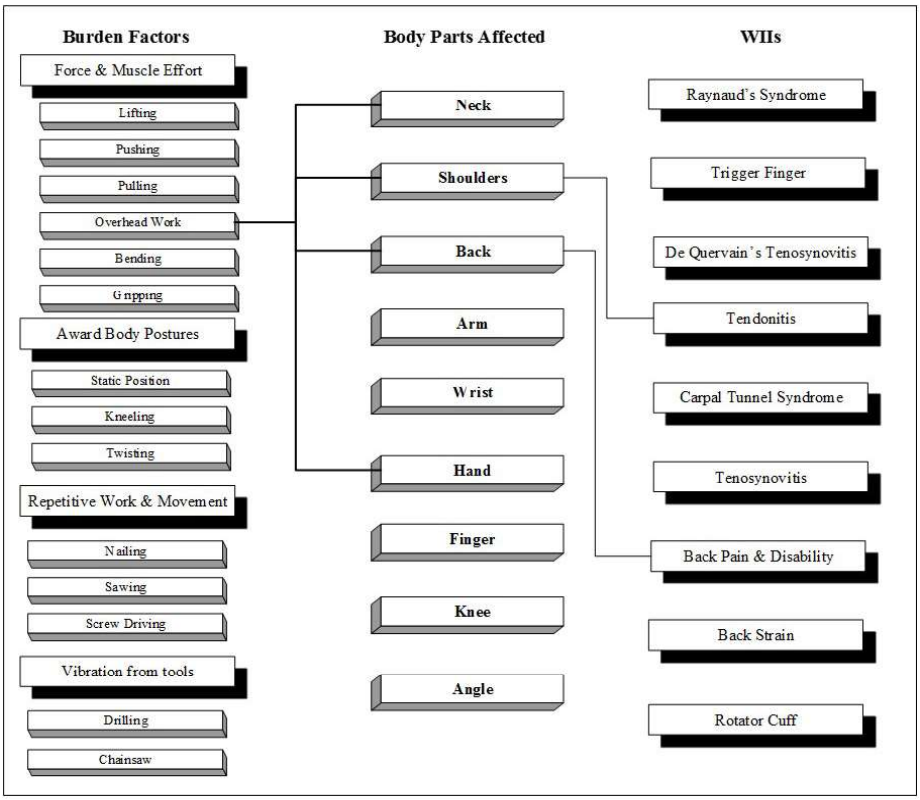

Figure 1: A Roadmap from Carpenters' Routine Activities to Their Work-related Illnesses and Injuries

Implementation of Functional Clothing

To develop a design prototype for carpenters' functional clothing, understanding wearer needs is essential if we are to develop appropriate clothing that satisfies the needs of the different individuals who will wear it (Neves et al., 2015). Construction consists of the aggregation of special tasks, with each construction crew performing distinct tasks that are associated with different risk factors. Each construction crew uses a specific part of the body and utilizes static and awkward postures repetitively as they perform their assigned task. Many construction workers use medical supplies and equipment that they have purchased themselves, including back braces, finger splints, calf sleeves, knee supports, and so on because these supplies are readily available without prescription (Figure 2).

Figure 2: Prescribed (upper images) and Non-Prescribed (lower images) Medical Supplies and Equipment

Generally, the use of braces and splints is to manage musculoskeletal disorders and address acute injuries and chronic conditions, as well as for the prevention of injury. We therefore posed the following research question:

RQ1. Can the use of body (e.g. ankle, knee, back, neck, etc.) supports integrated into their clothing help alleviate burden factors and prevent injuries?

Effective functional clothing for carpenters should not only enhance their occupational safety and health but also help them maximize their productivity. Breaking down activities into burden factors, as shown in Figure 1 identifies their specific needs and the context of each, as shown in Table 1. This development process is useful for designers seeking to analyze the human factors of specific design processes through brainstorming and other creativity-based techniques and come up with a prototype. Further, the process enables designer researchers to translate ideal concepts from visual frameworks and problem definitions into specific details explaining what the design should achieve (Watkins & Dunne, 2015). Many researchers working on functional clothing design have focused on individual design factors such as fabric, pattern construction, or details (Chan et al., 2016; Neves et al., 2015). Functional apparel and medical supplies for construction workers must also take into account the need to protect workers from multiple hazards. This suggested design prototype, however, utilizes a versatile approach that seeks to break the vicious cycle between WIIs and burden factors to improve carpenters' safety and productivity while still taking into account anthropometric biomedical and ergonomic design aspects.

Table 1: Design requirements for improving the safety and productivity of carpenters

Variable	Sub-variable	Requirement
Mobility	Shoulder mobility	Allows unimpeded shoulder flexion to 180°
Mobility	Spinal mobility	Allows unimpeded spinal flexion
Mobility	Crotch mobility	Allows unimpeded crotch flexion to 180°
Tactile sensitivity	Pressure sensitivity	Prevents localized pressure of greater than 100 kPa
Tactile sensitivity	Vibration sensitivity	Reduce vibration through support
Tactile sensitivity	Skin sensitivity	Protects skin from particles
Body temperature	Surface temperature	Maintains body temperature within the range of 32-37°C
Interaction with harness	Tools capacity	Allows hands to reach tools easily

To support as complete an understanding as possible of the context in which carpenter's functions are used in various activities, the following design requirements and solutions are suggested when developing a design prototype.

Allowing mobility

The first consideration is to ensure mobility at the shoulder, spine and crotch in order to improve productivity based on the axes of motion of the body (longitudinal axis, transverse axis, and medial axis). Movement is crucial for every activity carpenters perform. In particular, functional clothing that incorporates ways to transport various items of equipment on the body should allow users to move quickly and to avoid danger easily, even when working in extreme environments. Thus, providing easy mobility with segment design requirements can affect user's productivity and performance (Watkins & Dunne, 2015).

Solution:

a. Stretchable fabric with a slightly loose fit pattern construction
b. Partial ease (the difference between the garment and the body in each garment area), cut or contour (the shape of pattern pieces and the relationship of garment segments to one another), especially in the underarm and crotch areas
c. Elastic bend

Tactile sensitivity

The second consideration is tactile sensitivity. Since clothing is effectively a second skin covering the body, it is important for carpenters to experience good tactile sensitivity for both safety and productivity. The sub-variables of tactile sensitivity are categorized into pressure sensitivity related to transporting burdens and overhead work, vibration sensitivity related to tool use, and skin sensitivity due to contact with particles of various materials. As a result, the design requirements should emphasize preventing localized pressure, reducing vibration, and protecting skin from particles, all of which are related to user safety and performance. Through reducing impacts during construction, work-related injuries of carpenters should decrease.

Solution:
a. Embossed and flexible pads on shoulders, elbows, and knees
b. Protection in the form of elastic bands and light pads from elbow to wrist
c. Adjustable fastenable belts from chest to back that interconnect with the shoulder pads
d. High waistbands to alleviate pressure and back pain with adjustable fastenable belts

Body temperature

The third consideration is to maintain a comfortable body temperature. Since carpenters are often performing hard physical labor under hot and humid weather conditions, maintaining a comfortable body temperature will support productivity, convenience, and safety (Chan et al., 2016).

Solution:
a. Dri-fit, cooling, and breathable fabric over whole body
b. Mesh fabric on details
c. Minimize protectable equipment

Tool capacity

Lastly, carpenters need to carry various tools during construction in order to perform activities such as nailing, driving screws, or climbing. The option to carry tools on their person enables carpenters to reduce movement and gives them easy access to their equipment. However, excessive tool capacity can introduce extra pressure on the body and decrease movement, so this design detail should be minimized (Watkins & Dunne, 2015).

Solution:
a. Pocket details
b. Loop on adjustable fastenable belt on chest and waist

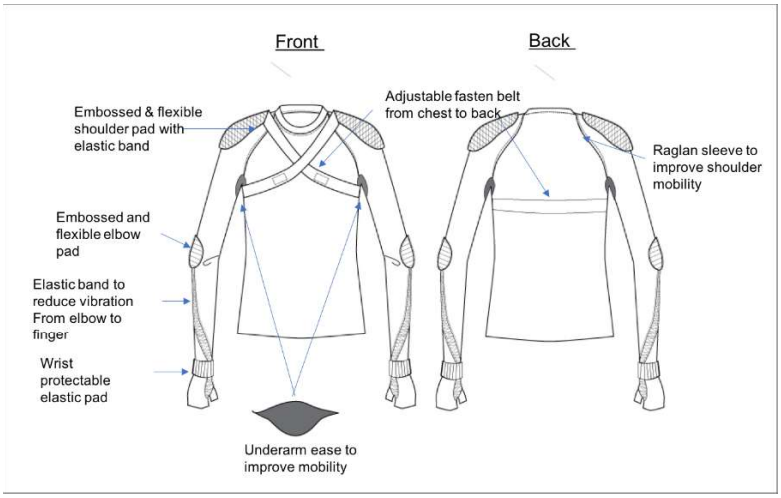

Figure 3 Functional clothing design for carpenter's upper garment

Based on these design requirements, the design researcher working on this project has suggested the prototype design for a carpenter's uniform shown in Figures 3 and 4. The design is inspired by the active wear used in extreme

sports such as football and rock climbing. Since many of the design requirements, including mobility and tactile sensitivity, for carpenters closely resemble those also required by sports players, the design researcher applied the design factors commonly used for sportswear to the carpenter's functional uniform design. As a result, the upper and lower garments are both designed with a slightly looser fit. Stretchable, dry-fit, cooling, and breathable fabric is used to support mobility and maintain the wearer's body temperature. Partial ease, cut or contour are incorporated in the design as part of the fit of the garment. In particular, the underarm and crotch areas are designed to include gussets to provide extra mobility. For the tactile sensitivity, embossed, flexible, and breathable pads are used with adjustable elastic bands at the shoulder, elbow, back waist, and knee similar to those used in orthopedic medical equipment. Tight long sleeve tops and long pants are designed to protect skin from particles. Since all the fabric used will be stretchable, with dry-fit, cooling, and breathable functionality, the length of the sleeve and pants design should be suitable for carpenters. Lastly, additional pockets on the pants, and loops on the adjustable fastenable belt across the chest and waist are designed to carry frequently used tools.

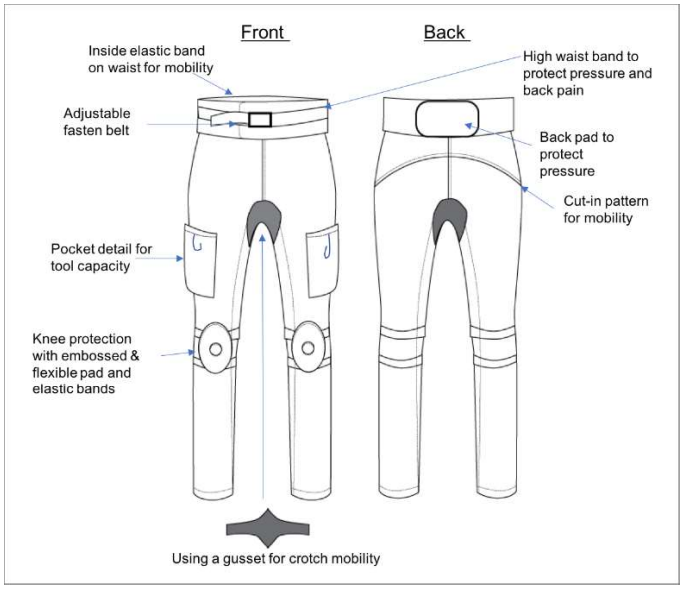

Figure 4: Functional clothing design for carpenter's lower garment

Discussion and Conclusion

Functional clothing is an emerging area in the construction industry, although it is already widely used in areas such as sport to improve performance. This is a rapidly evolving segment of the technical textiles market, representing an area where clothing crosses conventional boundaries and integrates research from domains such as medicine, biotechnology, nanotechnology, physics and computing, among others, to meet the multifaceted and complex requirements of the user (Gupta, 2011). As this study indicates, the use of functional clothing in construction has immense potential as a new approach to improving the safety and productivity of construction workers.

Linking routine activities to their consequential WIIs provides a useful understanding of the burden factors afflicting various workers and highlights potential intervention points and opportunities for functional clothing development. The case based study presented here examines the factors that affect a specific trade and then goes on to suggest a design prototype that addresses the burden factors that adversely affect worker safety and productivity, as well as the consequential WIIs. The main objective of this research was to develop a process that facilitates the implementation of functional clothing within the construction industry and identifies gaps between the status quo to find more effective ways of utilizing job functionality, providing workers with a better work environment and at the same time improving safety and productivity.

This research has established a foundation for a new conceptual approach towards functional clothing for construction workers, culminating with a design prototype for a carpenter's work outfit. However, at present this research is in its infancy and a great deal of work is needed to develop the functional clothing into a useable form and facilitate its implementation.

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