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An integrated biomechanical modeling approach to the ergonomic evaluation of drywall installation

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ABSTRACT

Three different methodologies: work sampling, computer simulation and biomechanical modeling, were integrated to study the physical demands of drywall installation. PATH (Posture, Activity, Tools, and Handling), a work-sampling based method, was used to quantify the percent of time that the drywall installers were conducting different activities with different body segment (trunk, arm, and leg) postures. Utilizing Monte-Carlo simulation to convert the categorical PATH data into continuous variables as inputs for the biomechanical models, the required muscle contraction forces and joint reaction forces at the low back (L4/L5) and shoulder (glenohumeral and sternoclavicular joints) were estimated for a typical eight-hour workday. To demonstrate the robustness of this modeling approach, a sensitivity analysis was conducted to examine the impact of some quantitative assumptions that have been made to facilitate the modeling approach. The results indicated that the modeling approach seemed to be the most sensitive to both the distribution of work cycles for a typical eight-hour workday and the distribution and values of Euler angles that are used to determine the "shoulder rhythm." Other assumptions including the distribution of trunk postures did not appear to have a significant impact on the model outputs. It was concluded that the integrated approach might provide an applicable examination of physical loads during the non-routine construction work, especially for those operations/tasks that have certain patterns/sequences for the workers to follow.

1. Introduction

It is widely accepted that there are three types of external ergonomic exposure assessment strategies: subjective judgment, systematic observation, and direct measurement. These three methods are listed in general order of increasing precision (David, 2005; Li and Buckle, 1999; Van der Beek and Frings-Dresen, 1998). Subjective judgment comes from reviews of experts or self reports of workers. It usually provides only limited information on workplace exposure to physical and psychosocial risk factors for musculoskeletal disorders. When a certain occupational task involves movements of different body parts such as manual material handling during construction work, it is imperative to evaluate the required posture, muscle exertion forces, and joint moments through workplace observations, or direct measurements, or a combination of both. It has been reported that video observation and direct measurement could provide similar levels of accuracy and reliability (Leinonen and Ma, 1996). Although direct measurements are generally considered as the most accurate method to assess exerted forces, it is often problematic to conduct direct measurements in field studies, especially within the construction industry due to potential interference with the work.

The internal exposure of the musculoskeletal system can be best evaluated through biomechanical models, varying from two-dimensional static linked segment models to three-dimensional dynamic models (Van der Beek and Frings-Dresen, 1998). In order to more accurately assess the magnitude of physical loads during construction, biomechanical modeling requires proper estimation of input variables including anthropometric data, joint angles, external forces, and internal muscle parameters (Winkel and Mathiassen, 1994). The difficulty of application of direct measurements may suggest that a combination of other methods of measurement be chosen, with an ultimate goal of a representative

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sample of work and actual variation of exposure being captured (Tak et al., 2007).

Drywall installation is a typical type of strenuous construction work, which exposes workers to various ergonomic hazards, including handling of heavy and bulky materials, repetitive screwdriving motions, and awkward postures. The body parts most commonly injured are the axial skeleton and shoulder, where back sprains, simultaneous sprains to the back and neck, and shoulder strains occur frequently (Chiou et al., 2000; Hsiao and Stanevich, 1996; Lemasters et al., 1998; Lipscomb et al., 1997, 2000). Previous biomechanical analyses of drywall installation examined the physical stress and postural stability during lifting of the drywall panels (Pan and Chiou, 1999; Pan et al., 2002/2003). The authors realized many practical limitations to conducting accurate, non-invasive and reasonably priced ergonomic assessments at the worksite due to the dynamic nature of construction activities. Therefore, future study was needed to identify the most reliable exposure assessment methods, evaluate possible ergonomic solutions, and recommend the safest, biomechanically sound handling methods for construction workers and other related laborers (Pan and Chiou, 1999).

With the development and application of PATH (Posture, Activity, Tools, and Handling), an observational work sampling-based approach to direct observation (Buchholz et al., 1996), it has become practical to quantify the percent of time that construction workers are exposed to awkward postures, various tasks and activities, and manual handling (Buchholz et al., 2003; Forde and Buchholz, 2004; Fulmer et al., 2004; Paquet et al., 1999, 2001, 2005; Rosenberg et al., 2006). PATH has also been used in other industrial sectors that involve non-repetitive job activities including retail, agriculture, and healthcare industries (Earle-Richardson et al., 2005; Kurowski et al., 2012; Pan et al., 1999; Park et al., 2009).

The joint angle and load ranges that are represented by the PATH data are categorical rather than continuous. However, the Monte-Carlo simulation method, which is used to generate random numbers from a defined distribution, can be utilized to extract discrete values from the categorical PATH data for biomechanical analysis of the low back and shoulder (Tak et al., 2007). The Monte-Carlo method has also been successfully used both to capture the trunk muscle activity during torso bending (Mirka and Marras, 1993) and to simulate variability in muscle moment arms and physiological cross-sectional areas for prediction of shoulder muscle force (Chang et al., 2000; Hughes and An, 1997).

The objectives of this study were to first describe a hybrid model integrating work sampling, computer simulation, and biomechanical modeling to conduct the ergonomic analysis of drywall installation (Yuan, 2006, 2013a, 2013b; Yuan et al., 2007). The required muscle contraction forces and joint reaction forces at the low back and shoulder during a typical eight-hour drywall installation workday were estimated utilizing Monte-Carlo simulation to convert PATH categorical data into continuous variables as inputs for three-dimensional static biomechanical models. Then, a sensitivity analysis (See appendix) was conducted to examine the impact of some quantitative assumptions that have been made to facilitate the modeling approach, so that the robustness of this modeling approach could be demonstrated and the impact of drywall storage position and size on the physical demands for drywall installers could be evaluated later (Yuan and Buchholz, 2014).

2. Methods

2.1. Overview of methods

The study describes an integrated model through which the muscle contraction forces and joint reaction forces at the low back and shoulder during drywall installation were estimated (Fig. 1). The PATH methodology provided the basic characterization of drywall installation work by quantifying the percent of time that the drywall installers were conducting different activities with different body segment (trunk, arm, and leg) postures. The relative frequencies of key activities, recorded over two hours, were used to construct eight-hour-workday activity series using Monte-Carlo simulation (Step A in Fig. 1). The biomechanical model input variables, including anthropometric data, joint angles, external load force and position vectors, and internal muscle parameters including coordinates of muscle origins and insertions and physiological cross-sectional areas, were then generated for the analyses of the low back and shoulder (Steps B1 and B2 respectively in Fig. 1). Utilizing different optimization programs in MATLAB (The MathWorks, Natick, MA, USA), the three-dimensional static equilibrium equations were solved and the biomechanical model outputs of muscle contraction forces and joint reaction forces at the low back and shoulder were computed and summarized (Steps C1 and C2 respectively in Fig. 1). In order to demonstrate the robustness of this modeling approach, the sensitivity analysis (See appendix) was conducted at the end of the present study.

2.2. Observational work sampling – PATH

A total of 126 PATH data points were collected on a crew of eight drywall workers by two well-trained researchers from the Construction Occupational Health Program (COHP) at the University of Massachusetts Lowell. The observations were made from October 2003 to January 2004 at a condominium construction site in Boston, MA, USA. The researchers used handheld computers (Compaq Aero 1500 and Casio E-200) to record the PATH observations at sixty-second intervals, and the PATH template was programmed onto those PDAs using InspectWrite (Penfact Inc., Boston, MA, USA).

Seven main activities which represent a typical drywall installation task were examined in this study, including: 1. cut/measure; 2. lift; 3. carry; 4. hold/place; 5. screw; 6. in between; and 7. other. As determined by Pan and Chiou (1999), the drywall lifting method in which the worker used one hand to support the horizontal drywall sheet at its bottom and the other hand to grasp the sheet at its top produced the highest L4/L5 disc compression forces and therefore appeared to be the most stressful. It was assumed that the drywall installers in this study exclusively used such a lifting method as a demonstration of the worst case scenario. Activity 6 (in between) denoted exclusively loading/adjusting the screw guns and it always followed activity 5 (screw). Activity 7 (other) included climb/descend, communicate, mark/draw, and other miscellaneous job activities.

2.3. Generation of eight-hour-workday activity series

2.3.1. Basic drywall installation work cycles

Two different drywall installation work cycles were identified based on field observations, involving: 1) a whole sheet of drywall (Sheetrock® Brand Gypsum Panel from CGC Inc., typically 1.22-m (4-ft) wide, 2.44-m (8-ft) long and 15.9-mm (5/8-in) thick, with bulk density of 881 kg/m^3 (55 lb/ft^3)), and 2) a partial piece. The two installation processes were observed to entail a different series of activities.

For the whole sheet of drywall, the worker first lifts it from storage, where the drywall sheets are piled flat on the ground (Step A in Fig. 2). The worker then carries it to the hanging location with the postures shown in Step B (Fig. 2). The third step is to rotate the drywall sheet and to place it at the destination (Step C in Fig. 2). Last, the worker drives screws into the drywall sheet to fasten it to