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An evaluation of wearable sensors and their placements for analyzing construction worker's trunk posture in laboratory conditions

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A B S T R A C T

This study investigates the effect of sensor placement on the analysis of trunk posture for construction activities using two off-the-shelf systems. Experiments were performed using a single-parameter monitoring wearable sensor (SPMWS), the ActiGraph GT9X Link, which was worn at six locations on the body, and a multi-parameter monitoring wearable sensor (MPMWS), the Zephyr BioHarness™3, which was worn at two body positions. One healthy male was recruited and conducted 10 experiment sessions to repeat measurements of trunk posture within our study. Measurements of upper-body thoracic bending posture during the lifting and lowering of raised deck materials in a laboratory setting were compared against video-captured observations of posture. The measurements from the two sensors were found to be in agreement during slow-motion symmetric bending activities with a target bending of ≤45°. However, for asymmetric bending tasks, when the SPMWS was placed on the chest, its readings were substantially different from those of the MPMWS worn on the chest or under the armpit.

1. Introduction

1.1. Work-related musculoskeletal disorders in construction

Construction workers are exposed to physically demanding tasks that require repetitive lifting, carrying, and installing of materials with non-neutral postures (Spielholz et al., 2006). These activities result in lower-back pain and injury (Frymoyer et al., 1980). For instance, rodmen have been found to be 3.9 times more likely to suffer from lower-back injuries compared to non-construction workers. Their full-flexion posture was found to contribute to their high injury rate (Rose et al., 2001). Tak et al. (2011) observed various levels of ergonomic hazards for workers in several construction trades and found that tilers, carpenters, and plasterers were exposed to back flexion for 40% of the observed time. Repetitive lifting tasks intensify muscular tension and are the cause of most work-related musculoskeletal disorders (WMSDs) among construction workers particularly in the lower back (Holmström et al., 1992). Lower back disorders are reported as the major cause of early retirement and turnover owing to disability and absenteeism (Burdorf and Sorock, 1997). These issues strongly affect the construction industry and are exacerbated by a post-recession workforce migration to other industries that amounted to about 20% of pre-recession workers (Barker, 2011).

1.2. Traditional ergonomic risk exposure assessment tools

Observation-based methods, such as the rapid upper limb assessment (RULA), Ovaco working postures assessment system (OWAS), posture, activity, tools, and handling (PATH), and rapid entire body assessment (REBA), have been traditionally used to assess the working posture. These methods rely upon direct observation and rating onsite or video recording and rating offsite (Valero et al., 2016; Vieira and Kumar, 2004). However, these methods are time-consuming and are potentially biased due to the subjective judgment of the raters (Vieira and Kumar, 2004). Therefore, the methods are recommended to be used by certified professional ergonomists or raters who are trained in ergonomics and industrial hygiene. But the practitioners experienced difficulties when using them in real-work conditions (Diego-Mas et al., 2015). Furthermore, the adoption of these methods is restricted by the nature of the construction industry. Video recording of construction activities is difficult due to the dynamic nature of construction activities, which involve multiple moving workers who

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are not limited to a stationary area. Workers, heavy equipment, and materials also share the same space, creating interferences and occlusions for human raters and video recording. Moreover, there are safety concerns that limit access to onsite raters.

1.3. Technology-based systems for occupational health and safety research

New wearable sensor technologies are emerging for occupational health and safety (OHS) research and can be classified into two main categories: (a) simple systems that are based on signal sensor/single-body location designs that only monitor body motion, and (b) complex systems involving multiple sensors that collect motion and physiologic measures. The first category of wearable sensors can be exemplified by current accelerometry-based monitors, which we refer to as “single-parameter monitoring wearable sensor” (SPMWS) systems. One of the examples is the accelerometer which is used to track a human's physical activity and motion by measuring the person's three-axis acceleration parameters at a single body location and estimating the person's physical activity, vibration, and inclination based on the measured acceleration data. Another example of the SPMWS systems for the collection of a body motion parameter is the inertial measurement unit (IMU) sensor which collects acceleration, gyroscope, and magnetometer data. IMU sensors can be worn on the wrist, waist, back, hip, thigh, or ankle by using wrist bands, waist loops, sticker patches, or belt pouches. Most SPMWS systems can log data to an internal memory as well as transmit real-time data to a personal computer through a gateway.

Accelerometer-based systems have been found to be useful and more practically applicable for assessing workers' exposures in terms of the degree and intensity of flexion during working hours. These systems have been used to assess the level and frequency of WMSDs exposure for various occupations by measuring inclinations of body parts. Estill et al. (2000) measured the arm acceleration of workers in assembly lines by using a single-axis accelerometer worn on the wrist to assess the WMSD exposure levels of upper limb motions. Paquet et al. (2001) used accelerometers to assess the trunk, shoulder, and leg postures of simulated construction job tasks including carrying wood beams and moving bricks and concrete blocks. Bernmark et al. (2011) evaluated a triaxial accelerometer as a tool to analyze the head movement inclination in computer work tasks. Thamsuwan and Johnson (2015) used tri-axial accelerometers for evaluating non-neutral work postures of the upper arms and back required by orchard workers' apple harvesting activities. Dahlqvist et al. (2016) validated a low-cost tri-axial accelerometer for measuring the inclination angles and velocities of the head, upper back, and upper arm movements with painting, computer work, furniture polishing, and elevated arm activities.

The second major category of wearable sensors consists of composite motion and physiological status monitors collecting multiple streams of data, which we refer to as “multi-parameter monitoring wearable sensor” (MPMWS) systems. Environmental and occupational exposures are often multifactorial and require multiple measures. Composite sensors provide a rich and holistic dataset compared with SPMWSs. For instance, MPMWS systems, besides tracking an activity, can also perform electrocardiogram (ECG) monitoring and respiratory rate measurement. Despite offering advantages of collecting various types of data, few validation studies have been conducted for MPMWS systems. Moreover, there are limitations when using the systems, as their designs often assume that they are worn in specific body locations specified by the sensor manufacturers. However, securing the systems with affixation aids, such as chest belts or compression shirts, is often not an option, despite the fact that they may improve wearer comfort, reduce interferences, and ensure data quality, because construction activities often involve vigorous movements.

MPMWS and SPMWS systems also differ based on the number of pivotal parameters they cover (Zhu et al., 2015). Generally for OHS research in construction, MPMWS systems are more desirable if the research objective is to investigate the construction worker's biomechanics in an integrated manner. SPMWS systems may be used in more integrated research studies, but would require separate physiological monitoring devices, such as a HR monitor, which introduces additional complexity and cost during data collection and analysis.

1.4. Purpose of the research

MPMWS systems have been used in several OHS research studies (Cheng et al., 2013; Dolezal et al., 2014; Lee and Migliaccio, 2016; Smith et al., 2014). The reliability and validity of the MPMWS for physiological measurements including the HR and BR have been studied (Gatti et al., 2014; Johnstone et al., 2012; Villar et al., 2015). However, previous studies have not validated the MPMWS system for analyzing the ergonomic postures of construction workers even though some models such as the Zephyr BioHarness™3 (ZB) (Medtronic, Dublin, Ireland) collect 3-axis acceleration data and estimate torso inclination. This study compares the accelerometer measurements from the ZB against a reference SPMWS system, the AG accelerometer (ActiGraph, LLC, Pensacola, FL), as well as against posture assessments from video recordings to determine the quality of thoracic bending measurements from exemplary MPMWS and SPMWS systems.

Specifically, in this study, we focus on measurements of upper body thoracic bending posture during material lifting and lowering. The results from past studies have shown that accelerometer locations are critical to the validity and reliability of the physical activity and sleep measurements (Gatti et al., 2016; Schall et al., 2016; Slater et al., 2015). The placement of sensors for ergonomic trunk posture has not yet been fully evaluated, although Faber et al. (2009) studied the optimal locations in the placement of a single inertial sensor on the posterior back for trunk inclination measurements. Our comparison among the selected MPMWS and SPMWS systems is therefore based on different sensor placements for analyzing non-neutral posture of the trunk body. Furthermore, the current study examines the error in bending angle measurements associated with different body placements for repetitive bending activities.

2. Method

2.1. Instruments

SPMWS accelerometer systems have been used widely for public health and occupational health research. For instance, the AG accelerometer described in Table 1, has been used to assess human activity levels and sedentary behavior (Matthews et al., 2008), energy expenditure (Plasqui and Westerterp, 2007), and sleep quality (Ancoli-Israel et al., 2003). The AG was originally developed to monitor physical activity and sleep for adults and children, generally. For instance, Donaire-Gonzalez et al. (2013) used the AG accelerometer (GT3X model) as a gold-standard for energy expenditure measurement for comparison smartphone-based energy expenditure measurement. Validation studies for ergonomic posture analysis have been conducted using the AG as well. The AG measurements were found to be correlated with a gold-standard motion analysis reference system for arm and trunk inclination in slow- and medium-speed simulated working tasks