Identification of Potential Biomechanical Risk Factors for Low Back Disorders during Repetitive Rebar Lifting

ABSTRACT

Purpose – Work-related low back disorders (LBDs) are prevalent among rebar workers although their causes remain uncertain. This study examines the self-reported discomfort and spinal biomechanics (muscle activity and spinal kinematics) experienced by rebar workers.

Design/methodology/approach – Twenty healthy male participants performed simulated repetitive rebar lifting tasks with three different lifting weights, using either a stoop (n =10) or a squat (n =10) lifting posture, until subjective fatigue was reached. During these tasks, trunk muscle activity and spinal kinematics were recorded using surface electromyography and motion sensors respectively.

Findings – A mixed-model, repeated measures analysis of variance revealed that an increase in lifting weight significantly increased lower back muscle activity at the L3 level but decreased fatigue and time to fatigue (endurance time) ($p < 0.05$). Lifting postures had no significant effect on spinal biomechanics ($p < 0.05$). Test results revealed that lifting different weights causes disproportional loading upon muscles, which shortens the time to reach working endurance and increases the risk of developing LBDs among rebar workers.

Research limitations/implications – Future research is required to: broaden the research scope to include other trades; investigate the effects of using assistive lifting devices to reduce manual handling risks posed; and develop automated human-condition based solutions to monitor trunk muscle activity and spinal kinematics.

Originality/value – This research fulfils an identified need to study laboratory-based simulated task conducted to investigate the risk of developing LBDs among rebar workers primarily caused by repetitive rebar lifting.

Keywords: Lifting weight, low back disorder, rebar worker, spinal biomechanics, squat lifting and stoop lifting.

Article Type: Research paper

INTRODUCTION

Work-related low back disorders (LBDs) involve excruciating pain and discomfort or malfunction of spinal muscles, nerves, bones, discs and/or tendons in the lower back region (McGill, 2015). Epidemiological studies provide causal evidence for associations between LBDs and workplace risk factors including heavy physical load, lifting and forceful movements, bending and twisting (awkward postures) and whole-body vibration (Bernard, 1997). Within the construction industry, LBDs are a prevalent health problem which account for over 37% of all absenteeism, 21.3% of claim costs and 25.5% of disability days among workers (Schneider, 2001; Courtney *et al.,* 2002; Hoogendroom *et al.,* 2002; Holmstrom and Engholm, 2003). The prevailing level of risk is not homogeneous throughout all trade disciplines and rebar workers are particularly susceptible to LBDs (Albers and Hudock, 2007). Indeed, Forde *et al.,* (2005) report that LBD is the most common work-related musculoskeletal disorder affecting rebar workers while Hunting *et al.,* (1999) found that the level of LBDs experienced by rebar workers (11.8%) was higher than other construction workers (8.1%).

Biomechanics provides a pragmatic and applied approach to evaluating the association between work place risk factors and LBDs during repetitive rebar lifting tasks (c.f. de Looze *et al.,* 1994a; van Dieen and Kingma, 1999). It is well known that an increase in height when lifting from the ground, fast lifting pace, and an increase in weight lifted will increase spinal loadings and elevate the risk of developing LBDs (Granata and Marras, 1999; Davis *et al*., 2010; Plamondon *et al.,* 2012; Yoon *et al.*, 2012). As such, it is not surprising to use these risk factors as inputs (usually height or pace) in designing lifting guidelines, especially for a repetitive rebar lifting tasks. In addition, these aforementioned studies predict the associations between risk factors and LBDs, the approach adopted required complex data analytics augmented by video footage (to record joint motions) and electromyography (EMG) muscle activity. Such works are impractical in the workplace. In particular, reducing the incidence of LBDs among rebar workers requires endeavors to assess whether different weights of lift represent a LBD risk factor in the workplace.

Ergonomic safety convention states that a squat lifting posture is preferable to stoop lifting postures because it: reduces compression loading and ligamentous strain within the spine (Anderson and Chaffin, 1986; Davis *et al.,* 2010); has inherently lower strength requirements (Anderson and Chaffin, 1986); and reduces perceived low back exertion (Hagen *et al.,* 1993; Hagen and Harms-Ringdahl, 1994). Other studies contradict this established body of knowledge and report a higher perceived physical exertion for squat lifting (Garg and Moore, 1992; Straker and Duncan, 2000) and a higher rate of perceived discomfort (Straker and Duncan, 2000). Consequently, squat lifting postures engender more rapid development of physical fatigue (Hagen *et al.,* 1993). Even though these contradictory studies have widely advocated lifting postures (e.g., stoop and squat) (Van Dieen et al., 1999; Straker, 2003), the effect of lifting various weights and postures on spinal biomechanics (i.e. spinal motion and trunk muscle activity) during repetitive rebar lifting tasks remains unclear. As such, the effect of different weights and lifting postures could be useful in designing repetitive lifting tasks guidelines, particularly for rebar workers. In addition, the effect of different weights and lifting postures on self-reported discomfort during repetitive rebar lifting remains elusive. To mitigate the risk of developing LBDs in rebar workers, there is a need to better understand the subjective and biomechanical demands incurred during repetitive rebar lifting so that pragmatic interventions and risk control measures can be successfully implemented. Therefore, this research seeks to better understand biomechanical risk factors that instigate the development of LBDs using laboratory controlled lifting trials encompassing quantifiable weights and predetermined body postures. Concomitant research objectives are to identify potential biomechanical risk factors and to provide pragmatic, ergonomic guidance to practitioners on optimizing lifting postures for rebar workers.

REBAR WORK AND ASSOCIATED RISK FACTORS

Rebar work is physically demanding, often requires awkward lifting postures and frequently involves heavy manual lifting of weights (Buchholz *et al.,* 2003). Typical work tasks include: i) preparing rebars (e.g. pulling rebars from the stack, cutting or bending rebars); and ii) assembling rebars (e.g. lifting, placing and tying rebars) (Saari and Wickström, 1978). Chan *et al.*, (2012) report that rebar workers in Hong Kong spend 30% of their work time preparing rebars and 70% assembling them. Both tasks require repetitive rebar lifting, involving heavy weight handling with awkward postures. Saari and Wickström (1978) found that 15% of rebar assembly time was spent lifting and carrying rebars of heavy weight ≥ 30 kg and that a stoop lifting posture was commonly used. These physically demanding lifting tasks expose rebar workers to higher LBD risks and increase the mechanical loadings upon the spine structures (e.g. facet joints and intervertebral discs) (Granata and Marras, 1999; Umer *et al*., 2016; Antwi-Afari *et al.,* 2017). This assertion is validated by Marras *et al.,* (1999d) and Davis *et al.,* (2010) who report upon a similar increase in spinal loadings [~15% of maximum voluntary contraction (MVC)] when trial participants lifted heavy weights (27.3kg and 42.7 kg).

Risk Assessment Methods

Risk assessment methods for lifting tasks are categorized into four thematic groupings, namely: i) self-reports; ii) observational methods; iii) direct measurement techniques; and iv) camera-based techniques. Self-reports are widely used in epidemic and ergonomic studies (David, 2005; Inyang *et al.,* 2012) and prominent exemplars adopted in practice include the: Nordic Musculoskeletal Questionnaire (Reme *et al.,* 2012); Borg Scale (Li and Yu, 2011); and Job Requirements and Physical Demands Survey (JRPDS) (Dane *et al.*, 2002). In a construction context, Riihimaki (1985) uses self-report survey questionnaires to investigate the effect of heavy physical work upon the backs of rebar workers and house painters. However, self-report assessment methods are subjective and prone to introducing recall bias (that is, a systematic error caused by differences in a participant's reporting accuracy or incompleteness of their recollections) (Spielholz *et al*., 2001; Jones and Kumar, 2010).

Observational methods developed are myriad and include the: *Assessment of Repetitive Task (ART)* (The Health and Safety Executive, 2009); *Manual Handling Assessment (MAC)* (The Health and Safety Executive 2002); *Ovako Working Analysis System (OWAS)* (Karhu *et al.*, 1977; and Kivi and Mattila, 1991); *Posture, Activity, Tools, and Handling (PATH)* (Forde and Buchholz, 2004); *Rapid Upper Limb Assessment (RULA)* (McAtamney and Corlett, 1993; and McGorry and Lin, 2007); *Rapid Entire Body Assessment (REBA)* (Kim *et al.*, 2011; and Hignett and McAtameny, 2000); *Quick Exposure Check (QEC)* (University of Surrey Health and Safety Executive, 1999); *Washington State's ergonomic rule* (WAC 296-135 62-051) (Washington State Department of Labor and Industries, 2010); *Strain Index* (Drinkaus *et al.*, 2005); and *3D Static Strength Prediction Program (3DSSPP)* (The Center for Ergonomic at the University of Michigan, 2016). Although these observational methods are an improvement upon self-reports, they are subjective, lack precision and are less reproducible in work situations (Coenen *et al.*, 2011).

Conventional direct measurement techniques include surface Electromyography (sEMG) recording of muscle action, video-based motion, inertial measurement unit (IMU) and lumbar motion monitor (LMM) (Merletti and Parker, 1999; Umer *et al.*, 2016; Antwi-Afari *et al.*, 2017). sEMG recordings are ubiquitous within extant literature and typically report upon muscle exertions by attaching a group of sensors to the skin over the muscles being sampled (Ning *et al.*, 2014; Umer *et al.*, 2016; Antwi-Afari *et al.*, 2017). Recordings of muscle tension and computerized analysis of myoelectric signals evaluate spinal biomechanics (Nimbarte *et al.*, 2014). sEMG sensors accurately measure physical exposure detection of manual handling activities (e.g. repetitive lifting tasks) and are applicable to both indoor and outdoor settings (Kim and Nussbaum, 2013).

Equipment cost and data analysis time preclude their use on a large number of participants or for long-term data collection (Wang *et al.*, 2015a).

Camera-based techniques utilise video/image sensors to capture human movements from indirect measurements (Han and Lee, 2013; Seo *et al.*, 2014). Consequently, they allow remote analysis of work tasks without disturbing the work process. Accuracy however, relies upon the manual input of posture and joint angles and a direct line of sight (Han and Lee, 2013). Furthermore, this approach cannot: differentiate whether a person is stationary and stable or struggling to regain balance; or detect body postures under bright light conditions (Chen *et al.*, 2014).

Although these four methods have been used in both field and laboratory-based studies, direct measurement methods under strict laboratory controlled conditions (using a combination of sEMG and IMU sensors) provide an affordable and detailed solution to assessing LBDs risk factors during simulated repetitive rebar lifting tasks (Moeslund *et al.*, 2006). Consequently, this research study examines and compares the effect of different lifting weights and lifting postures on spinal motion and trunk muscle activity during simulated repetitive rebar lifting tasks.

RESEARCH METHODS

A convenient sample of twenty (20 no.) healthy participants (all males) was recruited from the student population of the Hong Kong Polytechnic University to participate in this study (Table 1). Sample exclusion criteria included 'high risk' participants with a history of: low back pain (using the 10-item Oswestry Disability Index (ODI) > 20%) (c.f. Fairbank and Pynsent, 2000; Wong *et al.*, 2016); and/or cardiac or other health problems (e.g. dizziness, chest pain, and heart pain) (using a 7-item Physical Activity Readiness Questionnaire (PAR-Q)) (c.f. Baecke *et al.*, 1982). Participants provided their informed consent as approved by the Human Subject Ethics Subcommittee of The Hong Kong Polytechnic University (reference number:

HSEARS20160719002). No significant between-group difference in demographic data and ODI scores was observed.

<Insert Table 1 about here>

Experimental Design and Procedure

Participants rated the perceived exertion/pain threshold of their body parts on an 11-point (0 to 10) Borg categorical rating scale (Borg CR 10) where 0 indicates '*no pain*' and 10 indicates '*the worst imaginable pain*' (Borg, 1998), before marking the site of their body pain on a body diagram (Rustoen *et al.*, 2004). Within industry, three rebar workers often work as a group to repetitively lift four (4 no.) to ten (10 no.) pieces of reinforcing bar (weighing approximately 7.1kg to 17.8kg) from the floor to the target location (e.g. at waist level) (Figure 1a-b). Pilot study observational research trials conducted (pre-full laboratory testing) reveal that either a stoop or squat lifting posture is used in repetitive movements with an average of 10 lifting cycles per minute. One-third of the weight of four (4 no.) and ten (10 no.) pieces of rebars were comparable to approximately 5% and 15% of an individual's maximum lifting strength (MLS) as measured using an isometric strength testing device (Chattecx Corporation, USA). Thus, to simulate lifting loads of rebar, participants were instructed to repetitively lift and lower three different weights that corresponded to 5%, 10% and 15% of their MLS. Each participant was instructed to start in either a stoop or a squat position and then visualize the handle (of the isometric strength testing device) as a bundle of rebars and gradually pull the handle upward until the subjective perceived MLS was achieved. This procedure was repeated after a 2-minute break. The highest value generated on the digital force monitor (Piezotronics, New York Inc., USA) during the two trials was assumed to be the participant's MLS.

<Insert Figures 1a-b about here>

Participants were then randomly assigned using the Latin Square (an *n* x *n* array) to perform the trial. The lifting sequence of the weights was randomized to counterbalance the accumulative effect of different weights. For safety purposes, instead of lifting a bundle of rebars in a laboratory, the target lifting load was placed in a wooden box (measuring 30 × 30 × 25 cm) with hole handles at either side. Using both hands, participants lifted the box from floor level to a bench at waist level, waited for three (3 no.) seconds (without losing contact with the box) and then lowered the box back to the floor and waited another three (3 no.) seconds before resuming the next cycle. Each participant was instructed to lift each of the three weights repetitively until subjective fatigue was reached (i.e. the participant could not complete a cycle of lifting after strong verbal encouragement). A metronome provided a beat to guide the task (approximately 10 cycles/minute). Prior to data collection, participants were allowed to practice once with each of the target weights using the assigned lifting posture (Straker, 2003). A twenty-minute rest was interspersed between the lifting of different weights.

Surface Electromyography Measurements

Two pairs of wireless bipolar Ag/AgCl surface electrodes (Noraxon TeleMyo sEMG System, Noraxon USA Inc., USA) were attached to the bilateral lumbar erector spinae (LES) at the L3 level (Figure 2) (Hermens *et al.*, 1999; Wong *et al.*, 2016). The diameter of the electrode was 15mm and the inter-electrode distance was 20mm. A standardized skin preparation procedure was administered (including skin abrasion with light sandpaper, cleaning with alcohol and shaving of hair if necessary) to ensure the skin impedance was below 10 kΩ (Xie *et al.*, 2015). Raw sEMG signals were sampled at a frequency of 1500Hz with the common mode rejection ratio of 100db and then digitized by a 16-bit analog to digital (A/D) converter.

<Insert Figure 2 about here>

Prior to performing the lifting task, participants were instructed to perform two trials of back extension MVC against manual resistance. The participants maintained the MVC for 5 seconds with a 2-minute rest between trials (Hu *et al.,* 2009; Wong *et al.,* 2016). The maximum root mean square (RMS) of sEMG signal for each LES muscle was identified using a 1000ms moving window passing through the sEMG signals during the two MVCs. The highest RMS sEMG signal of each LES muscle was chosen for normalization. Raw electrocardiography signals were filtered from sEMG channels using an electrocardiography-reduction algorithm (c.f. Konrad, 2005). The resulting sEMG signals were band-pass filtered between 20 Hz and 500 Hz. A notch filter centered at 50 Hz was used to eliminate power-line interference. The rectified and processed sEMG signals with an averaging constant of 1000ms were used to provide the root mean square (RMS) sEMG signals. The RMS sEMG signals from the left and right of the LES muscle were averaged because the paired *t*-test found no significance between-side difference in sEMG signals during the repetitive lifting tasks ($p > 0.05$). The sampled RMS sEMG data were normalized to the highest RMS sEMG during MVC and expressed as a percentage MVC (%MVC) sEMG.

To quantify back muscle fatigue, two major phenomena were measured. First, the median frequency (MF) of raw sEMG signals for each LES muscle (during each lifting period) was partitioned into twenty epochs (without overlap). The MF of the sEMG power spectrum in each epoch was analyzed by a Fast Fourier Transform technique with a smoothing Hamming window digital filter (Smith, 2003; Kellis and Katis, 2008). The MF of sEMG for each of the 20 epochs was normalized with respect to the initial MF obtained prior to lifting. An observed decrease in normalized MF values between the beginning and end of the lifting task (i.e. a negative slope on the normalized MF plot) represented muscle fatigue. Second, the endurance time (time to fatigue) recorded at the end of each lifting weight task were compared as an additional quantitative measure of back muscle fatigue. Decreases in time to fatigue were taken as an indicator of global back muscle fatigue.

Spinal Kinematic Measurements

Three inertial measurement unit motion sensors (Noraxon MyoMotion system, Noraxon USA Inc., USA) were attached to the spinous processes at the T1, T12 and S1 levels (Figure 2) and kinematics data was sampled at 100Hz. Motion sensors estimated the spatial orientation of body segments by integrating the signals of multiple electromechanical sensors (accelerometers, gyroscopes and/or magnetometers using specific sensor fusion algorithms) (Umer *et al.*, 2016). The thoracic and lumbar kinematics were estimated from the relative differences in 3-dimensional movements namely: i) flexion/extension; ii) lateral bending; and iii) axial rotation) between the sensors attached to the T1 and T12 levels and the T12 and S1 levels respectively (Figure 2).

Analysis of sEMG and Kinematic Data during Lifting

Signals from sEMG electrodes and motion sensors were synchronized using the Noraxon MR 3.8 software (Noraxon USA Inc., USA). Standard Amplitude Analysis (SAA) normalized the sEMG signals of LES and spinal kinematic signals during the repetitive lifting task. Specifically, SAA divided the lifting task period into three equal time phases (initial, middle and final) so that temporal changes in kinetics and kinematics during lifting with different weights or postures could be estimated. The mean kinetics and kinematics in the middle lift phase of SAA were used to represent the average spinal biomechanics during lifting, thus allowing comparisons between different lifting weights or postures to be made.

Statistical Analysis

Demographic characteristics and the self-reported pain/perceived exertion measures (using Borg scale) between the two lifting posture groups were compared by separate independent *t*-tests. Since the Shapiro-Wilk tests revealed that sEMG and kinematic data were normally distributed, a separated (2×3) mixed-model repeated measures analysis of variance (ANOVA) was used to evaluate the effect of lifting postures (*between-group factor*) and lifting weights (*within-subject* *factor*) on the corresponding sEMG and spinal kinematics (thoracic or lumbar range of motion). A separated one-way repeated measures ANOVA then evaluated the difference between the normalized MF of sEMG and time to fatigue data whilst post hoc pairwise comparisons were conducted with the Bonferroni adjustment. The Statistical Package for the Social Science version 20.0 (IBM, USA) was used for statistical analysis and significance was $p < 0.05$.

EFFECT OF LIFTING WEIGHTS ON sEMG ACTIVITY AND TRUNK KINEMATICS

The middle SAA results illustrate that sEMG activity of LES muscles significantly increased as the lifting weights of the repetitive task increased (Table 2). Post hoc pairwise comparisons revealed that heavier lifting weights led to significantly higher LES activity (Figure 3). The lifting weight corresponding to 15% MLS caused the highest LES muscle activity (approximately 55% MVC sEMG), regardless of lifting postures.

<Insert Table 2 and Figure 3 about here>

Because the independent *t*-tests displayed no significant difference in the negative slope of normalized sEMG MFs (or time to fatigue between the two lifting posture groups), the sEMG MFs and time to fatigue data from both groups were averaged to analyze the effect of different lifting weights on LES muscle fatigue and time to fatigue. Heavier lifting weights led to significant decreases in the normalized sEMG MF of LES muscles ($p < 0.05$) (Figure 4). The negative slopes of sEMG MFs of back muscles for 5%, 10%, and 15% of MLS were -0.08, -0.12, and -0.18 respectively ($p < 0.05$). Similarly, the time to fatigue significantly decreased as the lifting weights increased ($p < 0.05$). The average lifting durations for 5%, 10%, and 15% of MLS were 205.6 seconds, 131.6 seconds and 87 seconds respectively (Figure 5).

<Insert Figures 4 and 5 about here>

Although there was no significant difference in spinal motion angles (lumbar and thoracic regions) during all phases of lifting at the three different lifting weights (Table 3), a consistent trend of increases in middle SAA lumbar flexion angles was observed as the lifting weight increased, regardless of the lifting posture (Table 3). Heavier lifting weights resulted in significant increases in perceived exertion/pain intensity for both lumbar and quadriceps/calf muscles ($p < 0.05$).

<Insert Table 3 about here>

EFFECT OF LIFTING POSTURES ON sEMG ACTIVITY AND TRUNK KINEMATICS

There was no significant difference in the middle SAA sEMG activity of LES muscles between the two lifting posture groups ($p = 0.34$) nor any group and weight interaction effect ($p = 0.18$). However, the stoop lifting posture displayed a higher absolute LES muscle activity during the middle SAA sEMG activity than squat lifting across all three lifting weights (Figure 3).

Similarly, lifting postures had no significant effect on spinal kinematics regardless of the lifting weight, although the stoop lifting posture demonstrated higher absolute lumbar and thoracic flexion angles than those in the squat lifting posture (Table 3). Interestingly, there was a decreasing trend in thoracic flexion angles as the lifting weights increased during different phases of stoop lifting. However, no such trend was noted in the thoracic regions during squat lifting (Table 3). Participants in the stoop lifting posture group experienced significantly higher discomfort/pain at their lower back, while those in the squat lifting posture group suffered from significantly higher discomfort at quadriceps and calf muscles (Table 4).

<Insert Table 4 about here>

DISCUSSION

The analysis results reveal that an increase in lifting weight significantly increased lumbar muscle activity and decreased fatigue (as measured by sEMG MFs)/ time to fatigue. However, lifting weights had no significant effect on spinal kinematics regardless of lifting posture adopted. Conversely, lifting posture had no statistically significant effect on any of the spinal biomechanical parameters, although stoop lifting posture appeared to elicit higher absolute LES sEMG amplitude, and larger absolute thoracic and lumbar flexion angles. Participants in the stoop lifting group experienced significantly higher pain intensity in the lumbar region when compared to those in the squat lifting group.

Effect of Lifting Weights on Spinal Biomechanics and Pain Perception during Lifting

Heavier lifting weights significantly increased the activity and pain intensity of back muscles. These findings concur with prior studies that found increased back muscle activity during lifting tasks might increase the risk of LBDs (Lavender *et al.,* 2003). Davis *et al.,* (2010) similarly found an increase in muscle activity (~15% MVC) when masonry workers lifted heavy bags (42.7kg) compared to a half-weight bag (21.4kg). While this aforementioned study (*ibid*) evaluated a 50% reduction in weight, the current study evaluated 10% reduction of rebar weight (from 15 to 5% MLS) with similar increases in muscle activity (14.3% MVC). These findings concur with previous studies (c.f. Potvin *et al.,* 1991; Van Dieen *et al.,* 1994) which estimate peak lumbar loads for stoop lifting to be 5% greater than squat lifting posture. Yingling and McGill (1999) proffer that the lifting capacity of an individual is related to the respective internal tolerances, such as the physical and physiological capacity of a body to cope with external loading. Lifting heavy weights also increases the amount of back muscle compressive forces acting upon the lumbar spine (Callaghan and McGill, 2001) and challenges an individual’s internal tolerance (Granata and Marras, 1999). Although spinal motions appeared to be unaffected by lifting weight, the absolute value of lumbar flexion angles increased as lifting weights increased. These results concurred with findings reported by Dolan and Adams (1998) and Wong and Wong (2008). Dolan and Adams (1998) for example, observed an increase in lumbar flexion angles (from 54.9°±8.7° to 55.7°±8.9°) as the lifting weight of a repetitive lifting task increased. Thus heavier lifting weights appear to increase an individual's ability to maintain a neutral/upright body posture. Since increased trunk flexion heightens mechanical loading on the lumbar region, this partly explains the increased lumbar muscle activity and increased risk of LBDs for heavy manual lifting (Granata and Marras, 1999).

Heavier lifting weights led to faster muscle fatigue as evidenced by a temporal decrease in sEMG MF and time to fatigue as corroborated by previous research (Sparto *et al.*, 1999; Mawston *et al.*, 2007; Granata and Gottipati, 2008). Sparto *et al.*, (1999) found a significant reduction in sEMG MF of the back muscles as the repetitive lifting increased from 35% to 70% of the average maximal lifting force. Consequently, the findings presented substantiate that repetitive lifting of heavy weights increases the risk of back muscle fatigue and the possible development of LBDs. To minimize risk therefore, rebar workers should perform alternative tasks with different physical exposures and use frequent breaks to minimize back muscle fatigue (Seo *et al.*, 2016).

Effect of Lifting Postures on Spinal Biomechanics and Pain Perception during Lifting

The insignificant effect of lifting postures upon spinal biomechanics observed concurs with prior research (De Looze *et al.*, 1994a). For example, Hagen and Harms-Ringdahl (1994) found no significant difference in lumbar loading between stoop lifting and squat lifting when participants lifted a 8.5kg or 17kg weight. The negative findings reported upon herein might be attributed to other reasons. First, a redundancy in the recruitment of motor units, within and between lumbar muscles (c.f. Hodges and Tucker, 2011), may mean that participants use heterogeneous back muscle recruitment strategies to perform the same task, which might lead to negative results. Second, the experimental protocol adopted resulted in a fast onset of back muscle fatigue and rapid task termination, hence subtle differences in back muscle activity or trunk kinematics between the two lifting postures might have been missed. Future research may use different lifting parameters (e.g. lifting speed) to detect the potential effect of different lifting postures on spinal biomechanics. Third, because participants were tested in repetitive symmetrical lifting tasks, the results might be different had asymmetrical lifting tasks been performed (e.g. combined lifting and twisting).

Although no statistically significant difference in biomechanical parameters was found between the two lifting postures, the stoop lifting posture demonstrated higher absolute LES activity and lumbar flexion angles. These findings concur with previous research that show higher muscle activity and spinal motion for the stoop lifting posture when compared to the squat lifting posture (Straker and Duncan, 2000; Albers and Hudock, 2007). Importantly, increased lumbar flexion during the stoop lifting posture may cause creep and related laxity of spinal ligaments (Solomonow *et al.,* 2003), and impose greater loading to back muscles and ligaments that increase the risk of back injury (Wang *et al.*, 2000). Therefore, the findings presented support a prior recommendation to adopt the squat lifting posture (Garg and Moore, 1992). Akin to previous research (Hagen and Harms-Ringdahl, 1994), stoop lifting elicited significantly higher back discomfort/pain than squat lifting, where the latter may increase the risk of back injury (Straker, 1997).

IMPLICATIONS AND LIMITATIONS

The research findings obtained from trunk kinematics suggest that rebar workers should lift a small number of rebars (i.e. 4 pieces of rebars) to minimize the muscle activity and fatigue of back muscles. Several other factors were identified and further exacerbate the risk posed (i.e., lifting weights, muscle fatigue, awkward posture and repetitive motions) and provide new insights into understanding the assessment/analysis methods during repetitive lifting tasks. Training workers in health and safety issues provides a basis for consistent awareness, identification, analysis, and control of musculoskeletal disorders. Therefore, construction/safety managers on site should consider these identified risk factors and provide suitable training programs for rebar workers and other 'at risk' construction trades (e.g. masons and carpenters) (Albers and Estill, 2007). The results obtained from biomechanical and psychological criteria (e.g. muscle activity, trunk kinematics and muscle fatigue) and subjective pain intensities (using Borg's scale) also suggest that squat postures should be adopted during repetitive rebar lifting tasks. Furthermore, non-stop lifting and lowering of rebar can rapidly cause lumbar muscle fatigue and pain. Consequently, rebar workers are recommended to lift rebar using assistive devices where possible (e.g. exoskeletons or back belts) (Kraus *et al.*, 1996) to mitigate risks posed and to take frequent rest (20mins break) before the onset of subjective fatigue. The recommended lift weight is 7.1 kg (5% MLS) at a rate of 10 cycles/min when working in a confined space with feet stationary.

Although the current research study provides valuable spinal biomechanical information regarding various lifting weights and postures on a relatively small sample of novice male individuals, the findings might not be generalized to experienced rebar workers or other construction trades due to potential differences in terms of the physical and physiological capacity of their bodies, internal tolerance etc. However, the same research protocol can be adopted to investigate the impacts of lifting weights and postures on spinal biomechanics among older rebar workers. The findings not only can improve our understanding of aging in modifying the relation between lifting posture and spinal biomechanics but also can help develop age-specific preventive strategies in future. Furthermore, because the current study was conducted in a laboratory controlled setting, the impact of the external environment (e.g. high temperature) on the lifting capacity of rebar workers remains unknown. Future research is therefore needed to: i) investigate the impact of various lifting weights and postures on the spinal biomechanics so as to develop appropriate lifting guidelines for workers with different working experiences; ii) determine actual lifting capacity/endurance of rebar workers working on site (vis-à-vis laboratory controlled conditions); and iii) adjust the confounding effects of psychosocial factors, gender, and age group in order to quantify the relationship between different lifting parameters (e.g. lifting speed/duration, lifting weights, height, and lifting postures) and LBDs in rebar workers.

CONCLUSIONS

This is the first study to examine the effect of different lifting weights and lifting postures on the spinal biomechanics of individuals during simulated repetitive rebar lifting tasks. The results reveal that heavier lifting weights significantly: i) increase sEMG activity of lumbar muscles and low back pain intensity; and ii) decrease sEMG MFs of lumbar muscles and time to fatigue regardless of lifting postures. The increase in sEMG activity of lumbar muscles and low back pain intensity indicate that heavier lifting weights increase the amount of back muscle compressive forces acting upon the lumbar spine which can increase the risk of LBDs. The current study also estimates the normative time to fatigue for asymptomatic individuals during repetitive lifting of weights similar to the actual rebar work. These preliminary normative data may help develop practical guidelines for repetitive rebar lifting. In addition, rebar workers should consider the normative time to fatigue associated with lifting weights when designing guidelines for lifting activities, especially for a repetitive rebar lifting tasks. Although the stoop and squat lifting postures appeared to elicit similar effects on spinal biomechanics of our participants, stoop lifting significantly increased low back pain compared to squat lifting. This observation substantiates the adoption of squat lifting for minimizing LBDs for workers during repetitive rebar lifting. Future studies should investigate the cost effectiveness of using various potential ergonomic interventions and assistive devices in enhancing the productivity of rebar workers and reducing their risk of developing LBDs.

ACKNOWLEDGEMENTS

The authors acknowledge the Department of Building and Real Estate of The Hong Kong Polytechnic University for funding this research. The authors thank Mr. Man Cheung and Mr.

Kelvin Lam for their technical support and all the participants involved in this study. Special thanks are given to Mr. Yang Xintao for assisting the experimental set-up.

DEDICATION

To June Edwards [3/12/47 – 13/5/17] - a lady of great distinction, grace and elegance personified; loved by all and remembered forever.

REFERENCES

Albers, J. T. and Estill, C. F. (2007) Simple Solution: Ergonomics for Construction Workers, U.S. Department of Health and Human Services–National Institute for Occupational Safety and Health. Available via: https://www.cdc.gov/niosh/awards/hamilton/aliceabs08.html [Accessed: May, 2017].

Albers, J. T. and Hudock, S. D. (2007) Biomechanical Assessment of Three Rebar Tying Techniques, International Journal of Occupational Safety And Ergonomics, Vol. 13, No. 3, pp. 279-289. DOI: 10.1080/10803548.2007.11076728.

Anderson, C. K. and Chaffin, D. B. (1986) A Biomechanical Evaluation of Five Lifting Techniques, Applied Ergonomics, Vol. 17, No. 1, pp. 2 – 8.

Antwi-Afari, M. F., Li, H., Edwards, D. J., Parn, E. A., Seo, J. and Wong, A. Y. L. (2017) Biomechanical Analysis of Risk Factors for Work-Related Musculoskeletal Disorders During Repetitive Lifting Task in Construction Workers, Automation in Construction, Vol. 83, pp. 41-47. DOI: 10.1016/j.autcon.2017.07.007.

Baecke, J. A., Burema, J. and Frijters, J. E. (1982) A Short Questionnaire for the Measurement of Habitual Physical Activity in Epidemiological Studies, American Journal of Clinical Nutrician, Vol. 36, No. 5, pp. 936–942.

Bernard, B. P. (1997) Musculoskeletal Disorders and Workplace Factors: A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of The Neck, Upper

Extremity, and Low Back, US DHHS, National Institute For Occupational Safety And Health, Cincinnati. Available via: http://ergonomics.uq.edu.au/public/pdf/97-141.pdf [Accessed: May, 2017].

Borg, G. (1998) Borg's Perceived Exertion and Pain Scales, Human Kinetics: Champaign, IL. IBSN: 978-0880116237.

Buchholz, B., Paquet, V., Punnett, L., Lee, D. and Moir, S. (1996) Path: A Work Sampling Based Approach to Ergonomic Job Analysis for Construction and Other Non-Repetitive Work, Applied Ergonomics, Vol. 27, No. 3, pp. 177–187. DOI: http://dx.doi.org/10.1016/0003-6870 (95)00078-X.

Buchholz, B., Paquet, V., Wellman, H. and Forde, M. (2003) Quantification of Ergonomic Hazards for Ironworkers Performing Concrete Reinforcement Tasks During Heavy Highway Construction, American Industrial Hygiene Association Journal, Vol. 64, No. 2, pp. 243-250. DOI: http://dx.doi.org/10.1080/15428110308984814.

Callaghan, J. and McGill, S. M. (2001) Intervertebral L Disc Herniation: Studies on a Porcine Model Exposed to Highly Repetitive Flexion/Extension Motion with Compressive Force, Clinical Biomechanics, Vol. 16, No. 1, pp. 28–37. DOI: https://doi.org/10.1016/S0268-0033(00)00063-2.

Chaffin, D. B., Andersson, G. B. J. and Martin, B. (1999) Occupational Biomechanics, Third Ed. Wiley: New York.

Chan, A. P. C., Yam, M. C. H., Chung, J. W. Y. and Yi, W. (2012) Developing a Heat Stress Model For Construction Workers, Journal of Facilities Management, Vol. 10, No. 1, pp. 59–74. DOI: 10.1108/14725961211200405.

Chen, J., Ahn, C. R. and Han, S. (2014) Detecting the Hazards of Lifting and Carrying in Construction Through a Coupled 3D Sensing and Imus Sensing System, Computing in Civil and Building Engineering, pp. 1110–1117. DOI: 10.1061/9780784413616.138.

Coenen, P., Kingma, I., Boot, C. R.L., Faber, G. S., Xu, X., Bongers, P. M. and Van Dieen, J. H. (2011) Estimation of Low Back Moments from Video Analysis: A Validation Study, Journal of Biomechanics, Vol. 44, No. 13, pp. 2369–2375. DOI: https://doi.org/10.1016/j.jbiomech.2011.07.005.

Courtney, T. K., Matz, S. and Webster, B. S. (2002) Disabling Occupational Injury in the U.S. Construction Industry, 1996, Journal of Occupational And Environmental Medicine, Vol. 44, No. 12, pp. 1161–1168.

Dane, D., Feuerstein, M., Huang, G. D., Dimberg, L., Ali, D. and Lincoln, A. (2002) Measurement Properties of a Self-Report Index of Ergonomic Exposures for use in an Office Work Environment, Journal of Occupational and Environmental Medicine, Vol 44, No. 1, pp. 73–81. DOI: 10.1097/00043764-200201000-00012.

David, G. C. (2005) Ergonomic Methods for Assessing Exposure to Risk Factors for Work-Related Musculoskeletal Disorders, Occupational Medicine, Vol. 55, No. 3, pp. 190–199. DOI: 10.1093/occmed/kqi082.

Davis, K. G., Kotowski, S. E., Albers, J. and Marras, W. (2010) Investigating Reduced Bag Weight as an Effective Risk Mediator for Mason Tenders, Applied Ergonomics, Vol. 41, No. 6, pp. 822–831. DOI: 10.1016/j.apergo.2010.02.001.

De Looze, M. P., Kingma, I., Thunnissen, W., Van Wijk, M. J. and Toussaint, H. M. (1994) The Evaluation of a Practical Biomechanical Model Estimating Lumbar Moments in Occupational Activities, Ergonomics, Vol. 37, No. 9, pp. 1495–1502. DOI: http://dx.doi.org/10.1080/00140139408964929.

Dolan, P. and Adams, M. (1998) Repetitive Lifting Tasks Fatigue the Back Muscles and Increase the Bending Moment Acting on the Lumbar Spine, Journal of Biomechanics, Vol. 31, No. 8, pp. 713–721. DOI: https://doi.org/10.1016/S0021-9290 (98)00086-4.

Drinkaus, P., Bloswick, D.S., Sesek, R., Mann, C. and Bernard, T. (2005) Job Level Risk Assessment Using Task Level Strain Index Scores: A Pilot Study, International Journal of

Occupational Safety and Ergonomics, Vol. 11, No. 2, pp. 141–152. DOI: http://Dx.Doi.Org/10.1080/10803548.2005.11076643.

Fairbank, J. C. and Pynsent, P. B. (2000) The Oswestry Disability Index 5, Spine, Vol. 25, No.22, pp. 2940–2952.

Forde, M. S. and Buchholz, B. (2004) Task Content and Physical Ergonomic Risk Factorsi n Construction Ironwork, International Journal of Industrial Ergonomics, Vol. 34, No. 4, pp. 319-333. DOI: https://doi.org/10.1016/j.ergon.2004.04.011.

Forde, M. S., Punnett, L. and Wegman, D. H. (2005) Prevalence of Musculoskeletal Disorders in Union Ironworkers, Journal of Occupational and Environmental Hygiene, Vol. 2, No. 2, pp. 203–212. DOI: http://dx.doi.org/10.1080/15459620590929635.

Garg, A. and Moore, J. S. (1992) Prevention Strategies and the Low Back in Industry, Occupational Medicine (Philadelphia, Pa.), Vol. 7, No. 4, pp. 629–640.

Granata, K. P. and Marras, W. S. (1999) Relation Between Spinal Load Factors and the High-Risk Probability of Occupational Low-Back Disorders, Ergonomics, Vol. 42, No. 9, pp. 1187–1199. DOI: 10.1080/001401399185072.

Granata, K. P. and Gottipati, P. (2008) Fatigue Influences Dynamic Stability of the Torso, Ergonomics, Vol. 51, No. 8, pp. 1258–1271. DOI: http://dx.doi.org/10.1080/00140130802030722.

Hagen, K. B. and Harms-Ringdahl, K. (1994) Ratings of Perceived Thigh and Back Exertion in Forest Workers During Repetitive Lifting Using Squat and Stoop Techniques, Spine, Vol. 19, No. 22, pp. 2511–2517.

Hagen, K. B., Hallen, J. and Harms-Ringdahl, K. (1993) Physiological and Subjective Responses to Maximal Repetitive Lifting Employing Stoop and Squat Technique, European Journal of Applied Physiology and Occupational Physiology, Vol. 67, No. 4, pp. 291 – 297. DOI: 10.1007/BF00357625.

Han, S. and Lee, S. (2013) A Vision Based Motion Capture and Recognition Framework for Behaviour-Based Safety Management, Automation in Construction, Vol. 35, pp. 131-141. DOI: https://doi.org/10.1016/j.autcon.2013.05.001.

Hermens, H. L., Freriks, B. F., Merletti, R., Stegeman, D., Blok, J., Rau, G., Disselhorst-Klug, C. and Ha¨Gg, G. (1999) Seniam-European Recommendations for Surface Electromyography, Roessingh Research and Development, Enschede. Available via: http://www.seniam.org/pdf/contents8.PDF [Accessed: May, 2017]

Hignett, S. and McAtamney, L. (2000) Rapid Entire Body Assessment (REBA), Applied Ergonomics, Vol. 31, No. 2, pp. 201–2015. DOI: 10.1016/S0003-6870(99)00039-3.

Hodges, P.W. and Tucker, K. (2011) Moving Differently in Pain: A New Theory to Explain The Adaptation to Pain, Pain, Vol. 152, No. 3, pp. S90-S98. DOI: https://doi.org/10.1016/j.pain.2010.10.020.

Holmstrom, E. and Engholm, G. (2003) Musculoskeletal Disorders in Relation to Age and Occupation in Swedish Construction Workers, American Journal of Industrial Medicine, Vol. 44, No. 4, pp. 377–384. DOI: 10.1002/ajim.10281.

Hoogendoorn, W. E., Bongers, P. M., De Vet, H. C. W., Ariens, G. A. M., Van Mechelen, W. and Bouter, L. M. (2002) High Physical Work Load and Low Job Satisfaction Increase the Risk of Sickness Absence Due to Low Back Pain: Results of a Prospective Cohort Study, Occupational Environmental Medicine, Vol. 59, No. 5, pp. 323–328. DOI: http://dx.doi.org/10.1136/oem.59.5.323.

Hu, Y., Wong, Y. L., Lu, W. W. and Kawchuk, G.N. (2009) Creation of an Asymmetrical Gradient of Back Muscle Activity and Spinal Stiffness During Asymmetrical Hip Extension, Clinical Biomechanics, Vol. 24, No. 10, pp. 799–806. DOI: https://doi.org/10.1016/j.clinbiomech.2009.07.013.

Hunting, K. L., Welch, L. S., Nessel-Stephens, L., Anderson, J. and Mawudeku, A. (1999) Surveillance of Construction Worker Injuries: The Utility of Trade-Specific Analysis, Applied Occupational Environmental Hygiene, Vol. 14, No. 7, pp. 459–470. DOI: 10.1080/104732299302666.

Inyang, N., Al-Hussein, M., El-Rich, M. and Al-Jibouri, S. (2012) Ergonomic Analysis and the Need for its Integration for Planning And Assessing Construction Tasks, Journal of Construction Engineering and Management, Vol. 138, No. 12, pp. 1370-1376. DOI: 10.1061/(ASCE)CO.1943-7862.0000556.

Jones, T. and Kumar, S. (2010) Comparison of Ergonomic Risk Assessment Output in Four Sawmill Jobs, International Journal of Occupational Safety and Ergonomics, Vol. 16, No. 1, pp. 105–111. DOI: 10.1080/10803548.2010.11076834.

Karhu, O., Kansi, P. and Kuorinka, I. (1977) Correcting Working Postures in Industry: A Practical Method for Analysis, Applied Ergonomics, Vol. 8, No. 4, pp. 199–201. DOI: https://doi.org/10.1016/0003-6870(77)90164-8.

Kellis, E. and Katis, A. (2008) Reliability of EMG Power-Spectrum and Amplitude of the Semitendinosus and Biceps Femoris Muscles During Ramp Isometric Contractions, Journal of Electromyography and Kinesiology, Vol. 18, No. 3, pp. 351–358. DOI: https://doi.org/10.1016/j.jelekin.2006.12.001.

Kim, S. and Nussbaum, M. A. (2013) Performance Evaluation of a Wearable Inertial Motion Capture System For Capturing Physical Exposures During Manual Material Handling Tasks, Ergonomics, Vol. 56, No. 2, pp. 314–326. DOI: http://dx.doi.org/10.1080/00140139.2012.742932.

Kim, S., Nussbaum, M.A. and Jia, B. (2011) Low Back Injury Risks During Construction with Prefabricated (Panelised) Walls: Effects of Task and Design Factors, Ergonomics, Vol. 54, No. 1, pp. 60–71. DOI: http://dx.doi.org/10.1080/00140139.2010.535024.

Kivi, P. and Mattila, M. (1991) Analysis and Improvement of Work Postures in the Building Industry: Application of the Computerised OWAS Method, Applied Ergonomics, Vol. 22, No. 1, pp. 43–48. DOI: https://doi.org/10.1016/0003-6870(91)90009-7.

Konrad, P. (2005) The ABC of EMG: A Practical Introduction to Kinesiological Electromyography, Noraxon, Inc.: Scottsdale, AZ, USA. ISBN: 0-9771622-1-4.

Kraus, J. F., Brown, K. A., Mcarthur, D. L., Peek-Asa, C., Samaniego, L., Kraus, C. and Zhou, L. (1996) Reduction of Acute Low Back Injuries by Use of Back Supports, International Journal of Occupational and Environmental Health, Vol. 2, No. 4, pp. 264-273. DOI: 10.1179/oeh.1996.2.4.264.

Lavender, S. A., Andersson, G. B. J., Schipplein, O. D. and Fuentes, H. J. (2003) The Effects of Initial Lifting Height, Load Magnitude, and Lifting Speed on the Peak Dynamic L5/S1 Moments, International Journal of Industrial Ergonomics, Vol. 31, No. 1, pp. 51 – 59. DOI: https://doi.org/10.1016/S0169-8141 (02)00174-9.

Li, K. W. and Yu, R. (2011) Assessment of Grip Force and Subjective Hand Force Exertion Under Handedness and Postural Conditions, Applied Ergonomics, Vol. 42, No. 6, pp. 929–933. DOI: https://doi.org/10.1016/j.apergo.2011.03.001.

Marras, W. S., Granata, K. P., Davis, K. G., Allread, W. G. and Jorgensen, M. J. (1999) Effects of Box Features on Spine Loading During Warehouse Order Selecting, Ergonomics, Vol. 42, No. 7, pp. 980-996. DOI: 10.1080/001401399185252.

Mawston, G. A., Mcnair, P. J. and Boocock, M. G. (2007) The Effects of Prior Warning and Lifting-Induced Fatigue on Trunk Muscle and Postural Responses to Sudden Loading During Manual Handling, Ergonomics, Vol. 50, No. 12, pp. 2157–2170. DOI: http://dx.doi.org/10.1080/00140130701510139.

Mcatamney, L. and Corlett, N. E. (1993) RULA: A Survey Method for the Investigation of Work-Related Upper Limb Disorders, Applied Ergonomics, Vol. 24, No. 2, pp. 91–99. DOI: http://dx.doi. org/10.1016/0003-6870 (93)90080-S.

McGill, S. M. (2015) Low Back Disorders, 3rd Ed., Human Kinetics: Amsterdam, Netherlands. ISBN: 13: 9781450472913.

Mcgorry, R. W. and Lin, J. H. (2007) Power Grip Strength as a Function of Tool Handle Orientation and Location, Ergonomics, Vol. 50, No. 9, pp. 1392–1403. DOI: http://dx.doi.org/10.1080/00140130701340115.

Merletti, R. and Parker, P. (1999) Electromyography. Wiley Encyclopaedia of Electrical And Electronics Engineering, Vol. 6, pp. 523– 540. DOI: 10.1002/047134608X.W1413.

Moeslund, T. B., Hilton, A. and Krüger, V. (2006) A Survey of Advances in Vision-Based Human Motion Capture and Analysis, Computer Vision Image Understanding, Vol. 104, No. 2, pp. 90–126. DOI: https://doi.org/10.1016/j.cviu.2006.08.002.

Nimbarte, A. D., Zreiqat, M. and Ning, X. (2014) Impact of Fatigue and Shoulder Position on the Flexion-Relaxation Response in Cervical Spine, Clinical Biomechanics, Vol. 29, No. 3, pp. 277–282. DOI: https://doi.org/10.1016/j.clinbiomech.2013.12.003.

Ning, X., Zhou, J., Dai, B. and Jaridi, M. (2014) The Assessment of Material Handling Strategies in Dealing with Sudden Loading: The Effects of Load Handling Position on Trunk Biomechanics, Applied Ergonomics, Vol. 45, No. 6, pp. 1399–1405. DOI: https://doi.org/10.1016/j.apergo.2014.03.008.

Plamondon, A., Lariviere, C., Delisle, A., Denis, D. and Gagnon, D. (2012) Relative Importance of Expertise, Lifting Height and Weight Lifting on Posture and Lumbar External Loading During A Transfer Task in Manual Material Handling, Ergonomics, Vol. 55, No. 1, pp. 87–102. DOI: http://dx.doi.org/10.1080/00140139.2011.634031.

Potvin, J. R., Mcgill, S. M. and Norman, R. W. (1991) Trunk Muscle and Lumbar Ligament Contributions to Dynamic Lifts with Varying Degrees of Trunk Flexion, Spine (Philadelphia, Pa.), Vol. 16, No. 9, pp. 1099–1107.

Reme, S. E., Dennerlein, J. T., Hashimoto, D. and Sorensen, G. (2012) Musculoskeletal Pain and Psychological Distress in Hospital Patient Care Workers, Journal of Occupational Rehabilitation, Vol. 22, No. 4, pp. 503–510. DOI: http://dx.doi.org/10.1007/s10926-012-9361-5.

Riihimaki, H. (1985) Back Pain and Heavy Physical Work: A Comparative Study of Concrete Reinforcement Workers and Maintenance House Painter, British Journal of Industrial Medicine, Vol. 42, No. 4, pp. 226–232. DOI: http://www.jstor.org/stable/27723935.

Rustoen, T., Wahl, A. K., Hanestad, B. R., Lerdal, A., Paul, S. and Miaskowski, C. (2004) Prevalence and Characteristics of Chronic Pain in the General Norwegian Population, European Journal of Pain, Vol. 8, No. 6, pp. 555–565. DOI: 10.1016/j.ejpain.2004.02.002.

Saari, J. and Wickstrom, G. (1978) Load on Back in Concrete Reinforcement Work, Scandinavian Journal of Work, Environment and Health, Vol. 4, No. 1, pp. 13–19. DOI: http://www.jstor.org/stable/40964640.

Schneider, S. P. (2001) Musculoskeletal Injuries in Construction: A Review of the Literature, Applied Occupational and Environmental Hygiene, Vol. 16, No. 11, pp. 1056–64. DOI: http://dx.doi.org/10.1080/104732201753214161

Seo, J., Lee, S. and Seo, J. (2016) Simulation-Based Assessment of Workers' Muscle Fatigue and its Impact on Construction Operation, Journal of Construction Engineering and Management, DOI: 10.1061/ (ASCE) CO. 1943-7862.0001182, 04016063.

Seo, J., Starbuck, R., Han, S., Lee, S. and Armstrong, T. J. (2014) Motion Data-Driven Biomechanical Analysis During Construction Tasks on Sites, Journal of Computing in Civil Engineering, Vol. 29, No. 4, pp. B4014005. DOI: 10.1061/(ASCE)CP.1943-5487.0000400.

Smith, S.W. (2003) Digital Signal Processing: A Practical Guide for Engineers and Scientists, Newnes: Boston. ISBN: 0-750674-44-X.

Solomonow, M., Baratta, R.V., Zhou, B.H., Burger, E., Zieske, A. and Gedalia, A. (2003) Muscular Dysfunction Elicited by Creep of Lumbar Viscoelastic Tissue, Journal of Electromyography and Kinesiology, Vol. 13, No. 4, pp. 381–396. DOI: https://doi.org/10.1016/S1050-6411(03)00045-2.

Sparto, P. J., Parnianpour, M., Barria, E. A. and Jagadeesh, J. M. (1999) Wavelet Analysis of Electromyography for Back Muscle Fatigue Detection During Isokinetic Constant Torque Exertions, Spine (Philadelphia, Pa.), Vol. 24, No. 17, pp. 1791– 1798.

Spielholz, P., Silverstein, B., Morgan, M., Checkoway, H. and Kaufman, J. (2001) Comparison of Self-report, Video Observation and Direct Measurement Methods for Upper Extremity Musculoskeletal Disorder Physical Risk Factors, Ergonomics, Vol. 44, No. 6, pp. 588–613. DOI: http://dx.doi.org/10.1080/00140130118050.

Straker, L. (2003) Evidence to Support Using Squat, Semi-Squat and Stoop Techniques to Lift Low-Lying Objects, International Journal of Industrial Ergonomics, Vol. 31, No. 3, pp. 149–160. DOI: https://doi.org/10.1016/S0169-8141 (02)00191-9.

Straker, L. M. (1997) A Critical Appraisal of Manual Handling Risk Assessment Literature, International Ergonomics Association Press: Curtin University, Perth.

Straker, L. and Duncan, P. (2000) Psychophysical and Psychological Comparison of Squat and Stoop Lifting by Young Females, Australian Journal of Physiotherapy, Vol. 46, No. 1, pp. 27–32. DOI: https://doi.org/10.1016/S0004-9514(14)60311-1.

The Center for Ergonomics at the University Of Michigan (2016) 3D Static Strength Prediction Program (3DSSPP V7.0). Available via: Http://C4e.Engin.Umich.Edu/Tools-Services/3dssppsoftware [Accessed: May, 2017].

The Health and Safety Executive (2009) Assessment of Repetitive Tasks (ART) Tool, HSE: London. Available via: Http://Www.Hse.Gov.Uk/Msd/Uld/Art/ [Accessed: May, 2017].

The Health and Safety Executive (2002) Manual Handling Assessment Chart (The MAC Tool), HSE: London. Available via: http://Www.Hse.Gov.Uk/Msd/Mac/ [Accessed: May, 2017].

Umer, W., Li, H., Szeto, G. and Wong, A. (2016) Identification of Biomechanical Risk Factors for the Development of Lower-Back Disorders During Manual Rebar Tying, Journal of Construction Engineering and Management, Vol. 143, No. 1, pp. 04016080. DOI: http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0001208

University of Surrey Health and Safety Executive (HSE) (1999) Quick Exposure Check (QEC) Reference Guide, HSE: London. Available via: http://Www.Ergonomistswithoutborders.Org/Resources/Downloads/QEC_Tool.Pdf [Accessed: May, 2017].

Van Dieen, J. H. and Kingma, I. (1999) Total Trunk Muscle Force and Spinal Compression are Lower in Asymmetric Moments as Compared to Pure Extension Moments, Journal of Biomechanics, Vol. 32, No. 7, pp. 681–687. DOI: https://doi.org/10.1016/S0021-586 9290(99)00044-5.

Van Dieen, J. H., Hoozemans, M .J. M., Toussaint, H. M. and Kingma, I. (1994) Repetitive Lifting and Spinal Shrinkage, Effects of Age and Lifting Technique, Clinical Biomechanics, Vol. 9, No. 6, pp. 367–374. DOI: https://doi.org/10.1016/0268-0033(94)90067-1.

Van Dieen, J. H., Hoozemans, M. J. and Toussaint, H. M. (1999) Stoop or Squat: A Review of Biomechanical Studies on Lifting Technique, Clinical Biomechanics, Vol. 14, No. 10, pp. 685 – 696. DOI: https://doi.org/10.1016/S0268-0033(99)00031-5.

Wang, J. L., Parnianpour, M., Shirazi-Adl, A. and Engin, A. E. (2000) Viscoelastic Finite-Element Analysis of a Lumbar Motion Segment in Combined Compression and Sagittal Flexion: Effect of Loading Rate, Spine (Philadelphia, Pa.), Vol. 25, No. 3, pp. 310 - 318.

Wang, D., Dai, F. and Ning, X. (2015) Risk Assessment of Work-Related Musculoskeletal Disorders in Construction: State-Of-The-Art Review, Journal of Construction Engineering and Management, Vol. 141, No. 6, pp. 1–15. DOI: http://dx.doi.org/10.1061/(ASCE)CO.1943-7862.0000979#sthash.LhRFzC4B.dpuf.

Washington State Department of Labor and Industries (2010) WAC 296–62-051 Ergonomics Rule Documents. Available via: http://Www.Humanics-Es.Com/Ergorulewithappendices.Pdf [Accessed: May, 2017].

Wong, A. Y. L., Parent, E. C., Prasad, N., Huang, C., Chan, K. M. and Kawchuk, G. N. (2016) Does Experimental Low Back Pain Change Posteroanterior Lumbar Spinal Stiffness and

Trunk Muscle Activity? A Randomized Crossover Study, Clinical Biomechanics, Vol. 34, pp. 45–52. DOI: https://doi.org/10.1016/j.clinbiomech.2016.03.006.

Wong, W. Y. and Wong, M. S. (2008) Trunk Posture Monitoring with Inertial Sensors, European Spine Journal, Vol. 17, No. 5, pp. 743–753. DOI: 10.1007/s00586-008-0586-0.

Xie, Y., Szeto, G. P. Y., Dai, J. and Madeleine, P. (2015) A Comparison of Muscle Activity in Using Touchscreen Smartphone Among Young People with and without Chronic Neck-Shoulder Pain, Ergonomics, Vol. 28, No. 1, pp. 1–12. DOI: 10.1080/00140139.2015.1056237.

Yingling, V. R. and McGill, S. M. (1999) Mechanical Properties and Failure Mechanics of the Spine Under Posterior Shear Load: Observations from a Porcine Model, Journal of Spinal Disorders, Vol. 12, pp. 501–508.

Yoon, J., Shiekhzadeh, A. and Nordin, M. (2012) The Effect of Load Weight vs. Pace on Muscle Recruiting During Lifting, Vol. 43, No. 6, pp. 1044–1050. DOI: https://doi.org/10.1016/j.apergo.2012.03.004.