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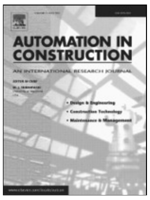

Biomechanical analysis of risk factors for work-related musculoskeletal disorders during repetitive lifting task in construction workers

M.F. Antwi-Afari[a, *], H. Li[b], D.J. Edwards[c, *], E.A. Pärn[c], J. Seo[d], A.L.U. Wong[e]

[a] Dept. of Building and Real Estate, Hong Kong Polytechnic Univ., Room No. ZN1002, Hung Hom, Kowloon, Hong Kong Special Administrative Region
[b] Dept. of Building and Real Estate, Hong Kong Polytechnic Univ., Room No. ZS734, Hung Hom, Kowloon, Hong Kong Special Administrative Region
[c] Faculty of Computing, Engineering and the Built Environment (CEBE), Birmingham City University, UK
[d] Dept. of Building and Real Estate, Hong Kong Polytechnic Univ., Room No. ZN737, Hung Hom, Kowloon, Hong Kong Special Administrative Region
[e] Dept. of Rehabilitation Sciences, Hong Kong Polytechnic Univ., Room No. ST512, Hung Hom, Kowloon, Hong Kong Special Administrative Region

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ABSTRACT

Work-related musculoskeletal disorders (WMSDs) represent major health issues for construction workers yet risk factors associated with repetitive lifting tasks remain unexplored. This study evaluates the effects of lifting weights and postures on spinal biomechanics (i.e. muscle activity and muscle fatigue) during a simulated repetitive lifting task undertaken within a strictly controlled laboratory experimental environment. Twenty healthy male participants performed simulated repetitive lifting tasks with three different lifting weights using either a stoop ($n = 10$) or a squat ($n = 10$) lifting posture until subjective fatigue (a point in time at which the participant cannot continue lifting further). Spinal biomechanics during repetitive lifting tasks were measured by surface electromyography (sEMG). Results revealed that (1) increased lifting weights significantly increased sEMG activity and muscle fatigue of the biceps brachii (BB), brachioradialis (BR), lumbar erector spinae (LES), and medial gastrocnemius (MG) muscles but not the rectus femoris (RF) muscle; (2) sEMG activity and muscle fatigue rate of the LES muscle were higher than all other muscles; (3) a significant difference of sEMG activity of the RF and MG muscles was observed between lifting postures, however no significant difference of muscle fatigue was apparent ($p > 0.05$). These findings suggest that risk factors such as lifting weights, repetitions and lifting postures may alleviate the risk of developing WMSDs. However, future research is required to investigate the effectiveness of using ergonomic interventions (such as using team lifting and adjustable lift equipment) in reducing WMSDs risks in construction workers. This work represents the first laboratory-based simulated testing conducted to investigate work-related musculoskeletal disorders (WMSDs) primarily caused by repetitive lifting tasks and manual handling. Cumulatively, the results and ensuing discussion offer insight into how these risks can be measured and mitigated.

1. Introduction

Extant literature reports that work-related musculoskeletal disorders (WMSDs) are among the most prevalent occupational health problems affecting manual workers [1]. In the United States, WMSDs account for 32% of all injury and illness cases that lead to absence from work for all industries [2]. While in construction and civil engineering, Schneider [3] reported that WMSDs account for over 37% of all injuries. Construction workers (e.g., rebar workers, bricklayers and roofers) are by virtue of their occupation frequently exposed to elevated physical risk factors such as repetitive motions (lifting/lowering), awkward postures and lifting weights, which represent the major causes of WMSDs [4]. Symptoms of WMSDs are myriad but may include lower back pain, neck/shoulder pain, tendonitis and carpal tunnel syndrome [5]. Fung et al. [6] found that musculoskeletal symptoms are particularly common in the upper extremities and lower back region of the human torso. Notably WMSDs not only lead to worker ill-health but also to reduced productivity and concomitant financial loss [7]. Therefore, risk factors associated with WMSDs should be identified in order to develop effective ergonomic interventions to prevent WMSDs in construction workers.

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* Corresponding authors.
Email addresses: maxwell.antwiafari@connect.polyu.hk (M.F. Antwi-Afari); heng.li@polyu.edu.hk (H. Li); drdavidedwards@aol.com (D.J. Edwards); joonoh.seo@polyu.edu.hk (J. Seo); arnold.wong@polyu.edu.hk (A.L.U. Wong)

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Radwin et al. [8] found that biomechanical and anthropometric parameters are significant determinants of the risk factors that instigate the development of WMSDs but their true extent remains unclear. Other researchers such as De Looze et al. [9] and Norman et al. [10] demonstrated a causal link between developing WMSDs and physical work exposure parameters. Specifically, Norman et al. [10] identified four risk factors for lower back disorders in automotive workers, namely: i) load moment; ii) hand forces; iii) peak shear force; and iv) peak trunk velocity. However, these studies only reported upon a specific body part (e.g., lower back and shoulder) and on an isolated risk factor (e.g., repetitions and lifting postures). In contrast, construction workers may sustain multiple injuries during repetitive lifting tasks [11]. The most important WMSDs risk factors relate to lifting weights and awkward postures because such requires maintaining muscle force over an extended period of time [12–14]. Repetitive and prolonged lifting tasks cause muscle fatigue and discomfort for a worker and invariably this activity increases the risk of developing WMSDs. Even though previous studies have widely advocated appropriate lifting postures (e.g., stoop and squat) [15,16], their effect upon spinal biomechanics remains unclear. Therefore, laboratory-based simulated repetitive lifting tests are needed to gain a better understanding of spinal biomechanics and in turn, develop effective lifting procedures and processes which may elevate the risk of developing WMSDs. Given this contextual background, this study seeks to evaluate the effects of lifting weights and postures on spinal biomechanics (i.e. muscle activity and muscle fatigue) during a laboratory-based simulated repetitive lifting task. To mitigate the risks of construction workers developing WMSDs, the research culminates by suggesting a number of potential pragmatic ergonomic interventions such as team lifting and adjustable lift equipment.

2. Research background

2.1. Current state of practice in WMSDs prevention

To reduce the risk of developing WMSDs among construction workers, general ergonomic practices have been promoted by safety and health organizations such as the Occupational Safety and Health Administration (OSHA) and the National Institute of Occupational Safety and Health (NIOSH). Instead of focusing on hazards to lower back disorders, general ergonomic practices typically focus on risk exposures associated with all WMSDs. For example, NIOSH published guidance which contains simple and inexpensive methods to help prevent injuries [17]. In a similar vein, OSHA offers training materials and programs to help workers recognize, avoid and control safety and health hazards in their workplaces [18]. Despite these efforts, current ergonomic practices designed for general manual handling tasks still lack practicality for repetitive lifting tasks because: i) most guidelines are presented in a brief and generic manner that is largely inappropriate to WMSDs prevention practices [19]; and ii) differences in work settings (e.g., repetitive lifting tasks, the weight being lifted and worker postures adopted during the lift) are often overlooked.

2.2. Risk assessment methods to identify potential risk factors of WMSDs

Within contemporary construction practice, techniques for assessing exposure to risk factors associated with WMSDs include self-reports, observations, direct measurement and remote sensing methods [20]. Despite the usefulness of these techniques, several limitations are apparent [21]. For instance, self-reports (e.g., the Borg Scale) vary from the inter-rater difference of workers' perception and are consequently imprecise and unreliable [22]. An extensive array of observational tools for ergonomic and posture analysis have also been developed and include: Quick Exposure Check (QEC) [23], the Assessment of Repetitive Arts (ART) [24], the Manual Handling Assessment Chart (MAC) [25], the Rapid Upper Limb Assessment (RULA) [26,27], the Rapid Entire Body Assessment (REBA) [28], Washingston State's ergonomic rule (WAC 296-62-051) [29], Posture, Activity, Tools and Handling (PATH) [30], Strain Index [31], The Liberty Mutual Manual Material Handling Tables (SNOOK tables) [32], the NIOSH lifting equation [33,34] and 3D Static Strength Prediction Program (3DSSPP) [35].

The RULA observational tool is a postural targeting method for estimating the risks of work-related upper limb injuries based upon the positions of upper arms, wrists, neck and upper trunk; while the REBA estimates the entire body's risks according to the positions of arms, wrists neck, trunk and legs. All risk assessment methods provide an expeditious, systematic and quantitative assessment of the worker's postural risks with regard to major body joints and angles between joints [7]. However, these posture assessment approaches usually collect data through observations, questionnaires or scorecards which are subject to the assessor's individual bias and judgement [36], as well as being inefficient and inaccurate [37,38]. Remote sensing methods are potentially an attractive solution for assessing biomechanical risks and ill-health [39–41]. For example, Weerasinghe and Ruwanpura [41] proposed infrared cameras for identifying worker activity status based upon heat emitted from the worker's body in conjunction with video images and acoustic data. However, remote sensing methods use expensive cameras and have difficulties with moving backgrounds and varying light conditions as experienced within the dynamic and inclement construction environment [22]. Direct laboratory measurements provide accurate and reliable data by using relatively simple instruments such as surface electromyography (sEMG) sensors [42]. Moreover, sEMG sensors are useful for biomechanical studies in laboratory settings [43]. Hence, this study adopts sEMG sensors to supplement existing methods to identify risk factors of WMSDs.

2.3. Theories and models of WMSDs

There are several theories and models of WMSDs causation that have been discussed in the literature, however, based on the scope of the current study only biomechanical theories and models of risk factors for WMSDs causation were reviewed. During the 1970s, Chaffin and his colleagues [44–47] and others developed simple, 2- and 3-D, static biomechanical models to estimate compressive and shear forces on lumbar spine as well as static strength requirements of jobs in occupational settings. These static biomechanical models generally tend to underestimate stresses on the low back predominately because they ignore the inertial loads [9,48] as well as muscle cocontraction [49,50]. Using a multiple internal muscle model, Schultz and Andersson [51] demonstrated that lifting of weights could generate large spinal forces due to the coactivation of trunk muscles. However, this modelling approach led to muscle contraction force calculations that were statistically indeterminate; therefore, optimisation techniques were used to make those calculations [52,53]. Dynamic, 3-D, anatomically complex and sEMG driven models were also developed to predict individual lumbar tissue loads [16,54–58]. Most of these models overcame limitations such as static or isokinetic mechanics, inaccurate prediction of muscle coactivity, static interpretation of myoelectric activity and physiologically unrealistic force per unit area. These models employ dynamic load in the hands, kinematic input, moment about the three orthopaedic axes of the low back normalized sEMG, muscle-cross section area, a gain factor to represent muscle force per unit area and modulation factors describing EMG and force behavior as a function of muscle length and velocity to determine tensile load in each muscle. The model developed by McGill and colleagues [50,59,60] also accounted for passive spinal and ligamentous forces. These theories and models represent significant improvements in biomechanical modelling to predict loads on the lumbar spine under different loading conditions.

Similarly, extant literature indicates that many factors with a biomechanical impact are strong risk factors for WMSDs to the upper extremities. Repetitiveness of the work activity has been shown to be a strong risk factor for cumulative trauma disorders (repetitive strain injury) [61–67]. Repeated load application may result in cumulative fatigue, reducing the stress-bearing capacity of the upper extremities muscles. Besides, forcefulness/overexertion of job activities has similarly been strongly associated with these upper extremities injuries [61,62,65,66,68,69]. In summary, Kumar [70] reported that relatively recent and epidemic increase of upper limb repetitive strain injury in many occupations has been largely attributed to the external loads, postural load levels, and repetition of posture and/or force application. Moreover, duration of exposure was reported by Hales and Bernard [62] and Spurgeon et al. [71] as an important variable in precipitation of WMSDs of the upper extremities. Hales and Bernard stated that sustained activities with insufficient recovery time led to such afflictions. Overall, increased biomechanical loads whether due to posture [20,61,62,65] or to differential exposure due to handedness [72] or to another combination of factors [66,73,74] is a significant risk factor in precipitation of WMSDs of the upper extremity. Hence, the current study supplements previously developed theories and models of WMSDs causation by evaluating the effects of lifting weights and postures on spinal biomechanics during a simulated repetitive lifting task undertaken within a strictly controlled laboratory experimental environment. Taken together, these biomechanical models can provide a quantitative assessment of the musculoskeletal loads during occupational tasks, given spinal biomechanics information of different body parts (e.g., upper limbs, lower back and lower limbs muscles). They can also help to identify how hazardous loading conditions exceed a worker's physical capability. Although, it may be considered questionable to compare and contrast these models and theories due to different populations, and work settings; this was done to highlight the types of considerations that should be made when conducting ergonomic intervention research to alleviate WMSDs.

3. Research approach

A laboratory simulated experiment was used to conduct the research. Twenty healthy participants (all males) were recruited from the student population of the Hong Kong Polytechnic University to participate in this study. The participants mean age was 27.9 ± 4.0 years, weight was 71.0 ± 8.97 kg, and height was 1.74 ± 0.09 m. All participants had no medical history of mechanical upper limbs and back pain or lower extremities injuries. Participants provided their informed consent as approved by the Human Subject Ethics Subcommittee of The Hong Kong Polytechnic University (reference number: HSEARS20160719002). Participants performed lifting of three different weights using either a stoop or squat lifting posture (see Fig. 1); where these weights were 5%-, 10%-, and 15% of participant's maximum lifting strength (MLS). Lifting weights were randomized among participants and they were allowed to practice each lifting posture for 10 s prior to undertaking the trial. During the first session, participants performed a stoop lifting posture in a sagittal plane. A specified location was demarcated on the floor for participants to place a wooden box (measuring 30 × 30 × 25 cm and containing dumbbell weights) with the target weight during lifting cycles. The lifting cycle started from the floor up to a bench at the waist level, rest for 3 s (without losing contact with the box) and then lowered the box down to the floor. The participants were instructed not to move their feet during the lifting cycle which was fixed at 10 cycles/min and controlled by a metronome. Participants performed each weight of repetitive lifting until subjective fatigue was reached (i.e. the participant could not complete a cycle of lifting after strong verbal encouragement). Another group of participants conducted a squat lifting posture in a sagittal plane using the same experimental procedures and set-up. A rest period of 20 min was allowed between each different weights to prevent accumulation of fatigue. To determine the MLS, participants performed a test using an isometric strength testing device (Chattecx Corporation, USA). Each participant was instructed to start in either a stoop or a squat position and then gradually brought the handle/lever of a dynamometer upward until the perceived MLS was achieved; where the dynamometer measures the strength of the whole body (Kg). This procedure was repeated after a 2-minute break. The highest value generated on the digital force monitor during the two trials was assumed to be the participant's MLS (Piezotronics, New York Inc., USA).

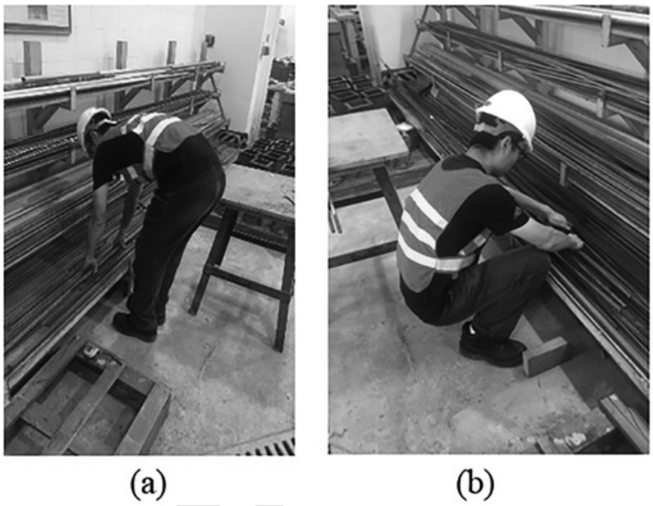

Fig. 1. Two lifting postures: (a) Stoop posture; and (b) Squat posture.

3.1. Surface electromyography measurements

Two pairs of wireless bipolar Ag/AgCl surface electrodes (Noraxon TeleMyo sEMG System, Noraxon USA Inc., USA) were attached bilateral to the left and right muscle of the: biceps brachii (BB); brachioradialis (BR); lumbar erector spinae (LES); rectus femoris (RF) and medial gastrocnemius (MG) [75,76]. The diameter of the electrode was 15 mm and the inter-electrode distance was 20 mm. A standardized skin preparation procedure was used to ensure the skin impedance was below 10 kΩ (cf. [77]). Raw electrocardiography signals were filtered for all sEMG channels [78]. Prior to the lifting task, the participant was instructed to perform two trials of maximum voluntary contraction (MVC) against manual resistance of each muscle [75]. The participant maintained the MVC for 5 s with 2-minute rest between trials [76]. The maximum root mean square (RMS) of sEMG signal of each muscle was identified using a 1000 ms moving window passing through the sEMG signals during the two MVCs. The highest RMS sEMG signal of each muscle was chosen to normalization.

All sEMG signals were processed with a band-pass filter of 20–500 Hz. A notch filter centered at 50 Hz was used to reduce power-line interference. Full-wave rectification and signal smoothing with a constant window of 100 ms RMS algorithm were also applied [79]. The left and right of each muscle were averaged because no significant difference was observed between the left and right side in sEMG signals. The sEMG signals recorded were expressed as mean RMS sEMG activity (mean EMG RMS). The sampled RMS sEMG data were normalized to the highest RMS sEMG during MVC and expressed as a percentage MVC (%MVC) sEMG. The signals from sEMG electrodes were recorded using the Noraxon MR 3.8 software (Noraxon USA Inc., USA). The sEMG activity levels during repetitive lifting were analyzed as average Standard Amplitude Analysis (SAA). The mean SAA was used to represent the average value during repetitive lifting to allow comparisons between different lifting weights and lifting postures to be made. The normalized RMS sEMG amplitude was used to predict the presence of muscle fatigue of each muscle. De Luca [80] found that an observed increase in the RMS sEMG amplitude can be regarded as an indicator of localized muscle fatigue during repetitive lifting tasks. The muscle fatigue rate was determined as the average RMS sEMG activity over the endurance time.

3.2. Statistical analysis

The Saphiro-Wilk test was used to confirm that the data was normally distributed. A mixed-model repeated measures analysis of variance (ANOVA) was then adopted to evaluate the effect of different lifting weights (5%- vs. 10%- vs. 15% MLS) and lifting postures (stoop vs. squat) on spinal biomechanics. Post hoc pairwise comparisons were conducted with the Bonferroni adjustment. All statistical analyses were analyzed by the Statistical Package for the Social Science version 20.0 (IBM, USA). Statistical significance was set at $p < 0.05$.

4. Results

4.1. Effects of lifting weights on spinal biomechanics

Table 1 presents the results of mean and standard deviation of the normalized sEMG activity for each muscle during repetitive lifting tasks. Fig. 2 represents the comparison of normalized sEMG activity between all muscles at different lifting weights and postures. Muscle activity of all muscles (BB, BR, LES, RF, and MG) increased with lifting weight (see Fig. 2). Heavier lifting weights (15% MLS) had the highest sEMG activity for all muscles (see Table 1). The LES muscle displayed the highest mean sEMG activity (i.e. 52.04% MVC). Conversely, the RF muscle showed the lowest sEMG activity (see Table 1). Interestingly, the results revealed that increased lifting weights significantly increased sEMG activity of all muscles, except the RF muscles (see Table 1). The non-significant different sEMG activity of the RF muscle in the 5% MLS compared with 10% MLS and 15% MLS were [mean difference = − 0.49% MVC (95% confident interval (CI) = − 2.39% to 1.41% MVC), standard error = 0.72; eta-square = 0.16; $p = 1.00$] and [mean difference = − 1.40% MVC (95% CI = − 3.40% to 0.59% MVC), standard error = 0.76; eta-square = 0.61; $p = 0.24$], respectively.

Table 2 reveals that a significant difference of muscle fatigue of all muscles in lifting weights was apparent, except the RF muscle (Table 2). Moreover, the highest muscle fatigue rate occurred at the LES muscle. Based upon participants' subjective fatigue, it was found that muscle fatigue occurs earlier for 15% MLS and 10% MLS compared to 5% MLS. The average endurance time were 205.6 s, 131.6 s, and 87 s for 5% MLS, 10% MLS, and 15% MLS respectively.

Table 1
Mean (standard deviation) of normalized muscle activity of different muscles.

Muscle	Lifting posture	5% Maximum lifting strength	10% Maximum lifting strength	15% Maximum lifting strength	Lifting weight *p*-value	Lifting posture *p*-value	Lifting weight × lifting posture *p*-value
BB	Stoop	17.58 (7.97)	21.53 (9.18)	28.52 (13.80)	0.00*	0.55	0.33
	Squat	18.55 (11.39)	27.09 (20.08)	34.66 (26.67)			
BR	Stoop	13.32 (7.24)	19.41 (11.21)	28.24 (18.33)	0.00*	0.59	0.51
	Squat	13.82 (5.17)	23.36 (7.93)	31.46 (12.65)			
LES	Stoop	39.64 (12.99)	42.51 (9.61)	52.04 (13.67)	0.00*	0.28	0.19
	Squat	35.41 (7.24)	39.61 (7.74)	44.71 (7.44)			
RF	Stoop	3.96 (3.08)	4.72 (4.02)	5.87 (5.27)	0.12	0.00#	0.65
	Squat	21.21 (8.94)	21.43 (8.85)	22.11 (9.21)			
MG	Stoop	26.97 (11.04)	31.00 (13.67)	36.73 (18.41)	0.00*	0.04#	0.45
	Squat	16.62 (5.26)	20.77 (6.74)	24.23 (6.38)			

Note: Biceps brachii (BB); Brachioradialis (BR); Lumbar erector spinae (LES); Rectus femoris (RF); Medial gastrocnemius (MG).
* Indicates that there was a significance difference between different lifting weights at $p < 0.05$.
\# Indicates that there was a significance difference between stoop and squat lifting postures at $p < 0.05$.

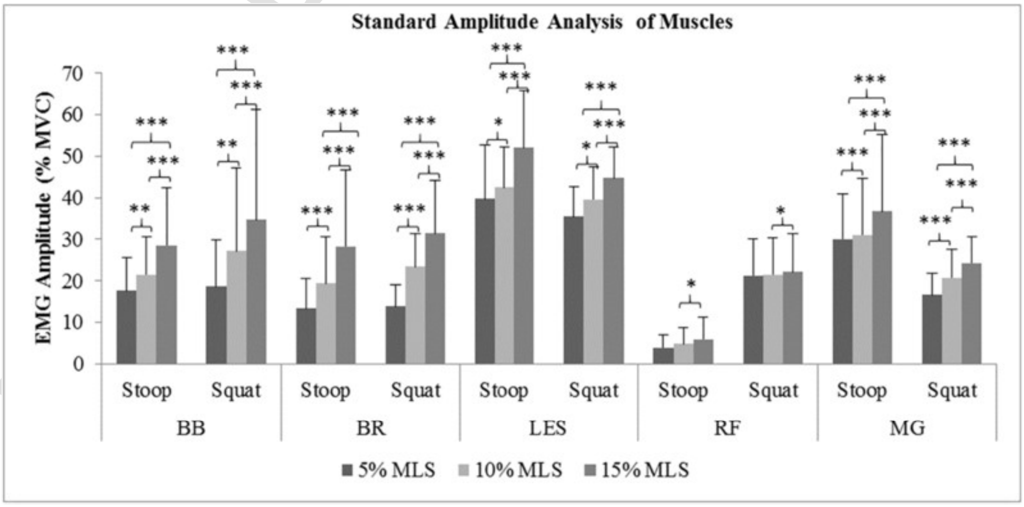

Fig. 2. Comparison of muscle activity from the biceps brachii (BB), brachioradialis (BR), lumbar erector spinae (LES), rectus femoris (RF) and medial gastrocnemius (MG) among stoop lift posture group and squat lift posture group during 5%-, 10%-, and 15% maximum lifting strength (MLS).Note: EMG = Electromyography; MVC = maximum voluntary contraction. *$p < 0.05$, **$p < 0.01$; ***$p < 0.001$; bars indicate standard deviation.

Table 2
Muscle fatigue rate.

Maximum lifting strength	Muscle fatigue rate				
	BB*	BR*	LES*	RF	MG*
5%	0.176	0.132	0.365	0.122	0.212
10%	0.369	0.325	0.624	0.199	0.393
15%	0.726	0.686	1.112	0.321	0.701

Note: Biceps brachii (BB); Brachioradialis (BR); Lumbar erector spinae (LES); Rectus femoris (RF); Medial gastrocnemius (MG).

* Indicates a significance difference between different lifting weights at $p < 0.05$.

4.2. *Effects of lifting postures on spinal biomechanics*

Conversely, mixed design ANOVA revealed a significant difference of sEMG activity between lifting postures of RG and MG muscles (see Table 1). Squat lifting postures had consistent higher sEMG activity (mean difference = 16.73% MVC) compared to stoop lifting postures in RF muscles. Alternatively, the MG muscle resulted in a higher sEMG activity of stoop lifting posture (mean difference = 11.01% MVC) compared to squat lifting postures. However, no significant difference of sEMG activity between lifting postures of BB, BR and LES muscles was recorded. The two upper limb muscles (BB and BR) showed higher sEMG activity in squat lifting postures as compared to stoop lifting postures. The mean difference between the two lifting postures of BB and BR muscles were 4.23% MVC and 2.55% MVC, respectively. In the LES muscles, stoop lifting postures had higher sEMG activity than squat lifting postures with a mean difference of 4.82% MVC. No significant interaction was found between lifting weights and lifting postures on muscle activity, and lifting posture had no main effect and non-significant interaction on muscle fatigue ($p > 0.05$).

5. Discussion

This study sought to quantify the effects of lifting weights and lifting postures on spinal biomechanics during a laboratory-based simulated repetitive lifting task. Results of analysis revealed that increased lifting weights significantly increased sEMG activity and muscle fatigue of all muscles, except the RF muscle. The highest sEMG activity occurred at the LES muscles. Moreover, the results revealed a significant difference of sEMG activity of the RF and MG muscles between lifting postures. Mixed design ANOVA did not reveal any significant interactions between lifting weights and lifting postures on spinal biomechanics. Overall, the findings suggest that increased lifting weights, increased muscle activity and muscle fatigue during repetitive lifting tasks and may elevate the risk of developing WMSDs.

5.1. *Effects of lifting weights on spinal biomechanics*

Muscle activity expressed as the RMS sEMG value (% MVC) was found to increase significantly with increased lifting weights. Moreover, the maximum muscle activity occurred at the LES muscle with a value of 52% MVC. The average muscle activity of LES muscle increased by 10.9% MVC for heavier lifting weight (15% MLS) as compared relatively to the lower lifting weight (5% MLS). The LES muscle exhibited the highest muscle activity followed by BB, MG, BR and RF. These results concur with the findings of previous studies that focused upon repetitive lifting tasks during which the LES muscle activity increases with lifting weights [81,82]. In addition, lifting weight significantly increased sEMG activity of the upper limb muscles (BB and BR), which concur with the findings of McBride et al. [83]. Cumulatively, this study's findings suggest that increased lifting weights increase sEMG activity and may increase the risk of developing WMSDs.

Analysis results also found that muscle fatigue (measured by RMS sEMG activity) increased over time for all muscles which indicates the development of muscle fatigue at different lifting weights. The LES muscle exhibited the highest muscle fatigue rate, which indicates the reference muscle in detecting muscle fatigue - that is, the muscle that indicates when an operator should stop performing the lifting task. The greater the motor unit recruitment and electric signals-firing rate (where the later is produced by muscle expansion and contraction), the greater is the generated muscle force [84]. During repetitive lifting tasks, the muscle force generated caused a gradual rise in sEMG activity, which results in muscle fatigue [85]. As such, these findings explain the highest indication of muscle fatigue in the LES muscle and suggest that increased lifting weight increases sEMG activity with a corresponding increase in muscle fatigue rate. Overall, this research concurs with the findings of previous studies in which increased lifting weight resulted in an increase in muscle activity and muscle fatigue, to indicate an elevated risk of developing WMSDs [86,87].

5.2. *Effects of lifting postures on spinal biomechanics*

The present study found inconsistent results of sEMG activity between lifting postures. The study revealed a significant difference of sEMG activity between lifting postures of the RF and MG muscles. Muscle activity of the RF muscle was higher during squat lifting posture compared to stoop lifting posture. Conversely, the stoop lifting posture had higher sEMG activity of the MG muscle compared to squat lifting posture. This result is consistent with the findings of previous biomechanical studies, which reported a significant effect of lifting postures on lower limbs sEMG activity (and thus elevated risk of developing WMSDs in the lower extremities) [88]. Alternatively, no significant difference of sEMG activity was found between lifting postures of the BB, BR and LES muscles and this may be be due to differences in experimental protocols adopted. This research also found peak sEMG activity of the LES muscle at 7% less for squat lifting posture than stoop lifting posture – this compares to the research of Van Dieen et al. [89], who reported significant peak sEMG activity of the LES muscle at 8% less for stoop lifting posture than squat lifting posture.

6. Recommendations for alleviating risk factors for WMSDs

The findings provide strong empirical implications that justify the industry's obligation to reduce the risk of developing WMSDs in construction workers; six key interventions are identified. First, a worker not only needs to reduce the weight of load being lifted but also avoid lifting below their knee height. Davis et al. [86] found that a 50% reduction in the lifting weight decreased the peak loads to the lumbar back muscles by 22.5%, and noted that the negative impact of heavy weights on the lumbar region increased sagittal trunk loading by approximately 33% to 55% if the lifting weight was below knee height. Second, the research has also estimated the normative duration of repetitive lifting at different lifting weights prior to the worker experiencing subjective fatigue. Construction workers and health and safety managers should refer to these figures when attempting to mitigate the risks posed by repetitive lifting tasks. Third, team lifting (i.e., two or more rebar workers) or use of mechanical lifting equipment is recommended for lifting heavy rebar in order to minimize the risk of developing WMSDs [90,91]. Fourth, although the research found no statistically significant difference in spinal biomechanics between the two lifting postures (except muscle activity in lower limb muscles), it does not preclude the necessity of adopting proper ergonomic interventions. For example, adjustable lift tables (and other lifting equipment/machinery) can be used to improve the body posture during work [92]. Similarly, education on physical and psychosocial risk factors for WMSDs and proper lifting techniques can improve the awareness of WMSDs and cultivate proper work behavior [92–94]. Fifth, construction managers should also plan the work schedule of workers based on individual's physical capability to mitigate the risks posed by WMSDs during repetitive lifting tasks. For instance, rebar workers or masons can perform alternative tasks with different physical exposures, and use frequent breaks to minimize their back muscle fatigue [39]. Sixth, assistive devices (e.g. cranes, exoskeletons, forklift, back belts or hoists) [95] may be introduced to provide construction workers with better mechanical advantages during repetitive lifting tasks. For instance, knee pads can be worn to minimize the risk of knee inflammation and bursitis during kneeling postures [96]. However, the cost-effectiveness of these devices should be further investigated and measured against the cost saving afforded by improved productivity and enhanced safety performance [97].

7. Conclusions and future directions

The results of analysis revealed that increased lifting weights significantly increased sEMG activity and muscle fatigue of the BB, BR, LES and MG muscles, except the RF muscles. Moreover, muscle activity and muscle fatigue of LES muscle were higher than all other muscles during repetitive lifting tasks. Furthermore, the results found a significant difference of sEMG activity of the lower limb muscles (RF and MG) between lifting postures. These findings indicate that workers frequently involved in risk factors such as lifting weights, lifting durations and lifting postures during repetitive lifting tasks may increase their risk of developing WMSDs. The identified risk factors can contribute to understanding WMSDs risk assessment methods to enhance worker health and productivity. Although the conclusions support the effectiveness of implementing potential interventions to reduce WMDS risks, some limitations persist and hence future research is required in five key areas. First, a larger sample of participants is needed to generate a more robust evaluation and comparison between the different lifting postures and how these impact upon spinal biomechanics and the risk of developing WMSDs. Second, experienced construction workers who have accrued considerable experience of repetitive lifting should be evaluated in any future study conducted (vis-à-vis the novice participants used in this study). Third, a construction site should be used in future experiments as opposed to the strictly controlled laboratory experimental environment adopted – such work would seek to excoriate any differences between a real and simulated lifting task. Fourth, future biomechanical studies are required to investigate the effects of external risk factors such temperature and humidity during repetitive lifting tasks performed by construction workers on a construction site. Fifth, the current study was limited to only repetitive lifting tasks in construction workers, and therefore the study results may not be generalized to other construction activities (e.g., sawing, hauling)—future research should consider different types of construction workers' activities. Such work will invariably improve the accuracy of any future guidance developed.

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