Effects of different weights and lifting postures on balance control following repetitive lifting tasks in construction workers

ABSTRACT

Repetitive lifting tasks have detrimental effects upon balance control and may contribute towards fall injuries, yet despite this causal linkage, risk factors involved remain elusive. This study evaluates the effects of different weights and lifting postures on balance control using simulated repetitive lifting tasks. Twenty healthy male participants underwent balance control assessments before and immediately after a fatiguing repetitive lifting tasks using three different weights in a stoop (10 participants) or a squat (10 participants) lifting posture. Balance control assessments required participants to stand still on a force plate with or without a foam (which simulated an unstable surface) while center of pressure (CoP) displacement parameters on the force plate was measured. Results reveal that: i) increased weight (but not lifting posture) significantly increases CoP parameters; ii) stoop and squat lifting postures performed until subjective fatigue induce a similar increase in CoP parameters; and iii) fatigue adversely effected the participant's balance control on an unstable surface vis-a-vis a stable surface. Findings suggest that repetitive lifting of heavier weights would significantly jeopardize individuals' balance control on unstable supporting surfaces, which may heighten the risk of falls. This research offers an entirely new and novel approach to measuring the impact that different lifting weights and postures may have upon worker stability and consequential fall incidents that may arise.

KEYWORDS

Balance control, falls, fatigue, lifting posture, weight.

INTRODUCTION

Fall injuries are a leading cause of fatal injuries and the second most common cause of non-fatal injuries in the construction industry (Center to Protect Workers' Right, 2007). According to the United States Bureau of Labor Statistics (BLS), fall injuries in the construction industry accounted for 32% of all work-related deaths (BLS, 2006a) and 34% of non-fatal injuries (BLS, 2006b). Fall-related injuries are also prevalent amongst the general public, especially among the elderly (Zigel *et al.*, 2009; Jiang *et al.*, 2011). Slips, trips and loss of balance are common contributing factors to fall injuries on a level surface (Hsiao and Simeonov, 2001; Lipscomb *et al.,* 2006). While slips and trips can be mitigated by ergonomic design of the working environment, balance control is inherently far more complex and relies upon the coordination of multiple sensory systems (visual, vestibular, and proprioception/somatosensory), the motor system and central nervous system (Punakallio, 2005; Horak, 2006). Impaired balance control (i.e., increased postural sway) has been linked to an increased risk of falls (Prieto *et al*., 1996; Corbeil *et al.,* 2003; Paillard, 2012). Therefore, any potential interventions to minimize workplace falls and concomitant injuries sustained, must ensure that balance control is not impaired by personal, environmental and task-related risk factors (Hsiao and Simeonov, 2001).

Amongst the many task related hazards confronting construction workers, repetitive lifting tasks presents a prominent and significant risk (Marras *et al*., 1995; Sparto *et al.,* 1997a; Latza *et al*., 2002). Repetitive lifting tasks involving different weights and/or awkward lifting postures (e.g., stoop or squat) are common for tradesmen handling masonry, concrete reinforcement, scaffolding and paving (Goldsheyder *et al*., 2002; Hess *et al*., 2003; Albers and Estill, 2007). For example, rebar workers repetitively lift different weights of rebars (ranging from 7 to 17kg) during their typical working day. In turn, different weights have differential effects upon spinal biomechanics (e.g., causing muscle fatigue) and heavyweights can affect workers' balance control (Hagen and Harms-Ringdahl, 1994; Straker and Duncan, 2000). The stoop lifting posture induces greater back extensor muscle activity and stronger perceived back muscle fatigue than squat lifting (Hagen and Harms-Ringdahl, 1994). However, postural perturbations during repetitive lifting (using either posture) overloads the musculoskeletal tissue and impairs balance control thus elevating the risk of loss of balance, fall incidents and consequential injuries (Chow *et al.,* 2005). This is because postural perturbations during repetitive lifting tasks shift the body's center of mass to move beyond the base of support to create excessive center of pressure (CoP) displacement (Kincl *et al.,* 2002; Chow *et al.,* 2005).

Muscle fatigue is also attributed to impaired balance control and elevated risk of fall injuries (Yaggie and McGregor, 2002; Corbeil *et al.,* 2003). Research into muscle fatigue is well documented and has thus far included assessing: a muscle's peripheral characteristics such as reductions in maximal voluntary contraction and/or relaxation (Davidson *et al.,* 2009; Paillard *et* *al.*, 2010b); a muscle's output using characteristics of its surface electromyogram (sEMG) (Caron, 2004; Paillard *et al.*, 2007); aspects relating to dehydration and different postural stances (Lion *et al.*, 2010; Bisson *et al.*, 2010a); and its affect upon the sensory systems (Hiemstra *et al.*, 2001; Forestier *et al.*, 2002). Muscle fatigue's impact upon the sensory system could be explained by the accumulation of metabolites leading to: altered muscle spindle function (Hiemstra *et al.*, 2001); altered central processing of proprioception via group III and IV afferents (Forestier *et al*., 2002); and effects on the efferent sensory pathways (Taylor *et al*., 2000). However, research illustrates that the mechanisms involved in muscle fatigue are dependent upon the fatigue methods conducted to fatigue the muscles (task dependency) (Enoka and Duchateau, 2008).

Consequently, the mechanisms involved in muscle fatigue induced by performing repetitive lifting tasks under conditions of postural perturbation are essential to any meaningful analysis conducted. Additionally, construction workers (e.g., masons, rebar workers) perform manual repetitive lifting tasks in which they are exposed to different weights and lifting postures for extended periods of time (Jaffar *et al*., 2011). Although previous studies have investigated the influence of repetitive lifting tasks on spinal movement or paraspinal muscle response, the direct effects of different weights and lifting postures following repetitive lifting task on balance control remained unexplored. Against this contextual setting, this study seeks to evaluate the effects of different weights and lifting postures on balance control following simulated repetitive lifting tasks. With regards to the stated aim, the objectives of the present study were: i) to compare the effects of stoop and squat lifting postures on balance control during quiet standing balance tests, and ii) to assess the effects of the magnitude of weights on balance control following fatiguing repetitive lifting tasks (i.e., by comparing standing balance tests performed on a stable and an unstable supporting surfaces. Two hypothesis are proposed, namely: i) that a stoop lifting posture would induce a significantly greater adverse effect upon an individuals' balance control than a squat lifting posture following a fatiguing repetitive lifting task; and ii) that heavy lifting weight would jeopardize the balance control on both stable and unstable surfaces (although the adverse effect would be greater on an unstable surface).

RESEARCH METHODS

An experimental laboratory controlled test procedure was adopted for this 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. There was no significant difference in age, height, and weight of participants in both groups. Test entry criteria for participants were: i) no history of upper limb, back or lower limb pain/injury; and ii) no history of neurological and/or vestibular disorders or other conditions that might affect balance control. Participants provided their informed consent as approved by the Human Subject Ethics Subcommittee of The Hong Kong Polytechnic University (reference number: HSEARS20160719002). Upon consent being given, participants provided their demographic data and were randomized into either a stoop lifting or a squat lifting group (10 participants each). Each participant's maximum lifting strength (MLS) in a stoop or squat lifting posture was then assessed by a back-leg lift dynamometer (Chattecx Corporation, USA). Each group of participants was assigned an allotted lifting posture (i.e., stoop or squat lifting) and requested to gradually pull up the handle of the dynamometer until they reached their perceived MLS. Each participant performed the test twice with a two-min break in between; the highest value of the two trials recorded on the dynamometer represented the participant's MLS (Piezotronics, New York Inc., USA). As a result, the participants' mean MLS for stoop and squat lifting postures was 95.4 ± 17.4 kg and 110.7 ± 13.86 kg, respectively.

The participant then underwent standing balance tests (pre- and post-fatiguing repetitive lifting tasks) that involved three conditions: i) eyes opened on a force plate (EOS); ii) eyes closed on a force plate (ECS); and iii) eyes closed on a foam placed on a force plate (ECF) (where the foam simulated an unstable surface) (refer to Figure 1). The three standing balance tests were chosen to reflect the variety of visual and support surface conditions encountered by construction workers during their course of workplace activities (Wade and Davis, 2008). Balance tests sought to evaluate shifts in the body's center of pressure (CoP) under these conditions and required participants to stand upright in a relaxed position with their arms by their sides for 15 seconds (c.f. Doyle *et al.,* 2005). Their feet had to remain in the same position marked on a piece of transparent sheet that covered the force plate (except ECF condition). The participant was instructed to look ahead during the EOS test, while vision was occluded by a non-transparent goggle (ANSI Z 136, USA) during ECS and ECF tests. To minimize external sound stimuli, participants wore hearing protection during all tests conducted (CE EN 352, Australian standard). The force plate was positioned next to the lifting task experimental set up to minimize the time interval between the fatiguing lifting tasks and the CoP measurements. Previous studies have demonstrated that CoP displacements from a force plate provide objective, accurate and reliable balance control measurements (Prieto *et al.*, 1996; Lafond *et al.*, 2004).

The CoP displacement test data was collected using a portable 8 channel multiplexing and amplitude modulation circuit force plate (KISTLER Instrumente. AG, Winterthur, Switzerland). The CoP data were sampled at 50Hz and low passed filtered with a second-order Butterworth filter (10Hz). MATLAB 7.9 software (Matlab, The MathWorks Inc., MA, USA) was used to analyze the CoP movements. The displacements of CoP were quantified from: the total sway area, the root mean square (RMS) of the anterior/posterior (A/P) and medial/lateral (M/L) displacements and mean velocity (MV) sway in the A/P and M/L displacement. These CoP parameters have been used in previous studies to evaluate the balance control of an individual; where large displacement of CoP values indicates poor balance control that may increase the risk of falls (Prieto *et al.*, 1996; Bisson *et al.*, 2010a).

<Insert Figure 1 about here>

In order to eliminate any possible biases and differences between and within the two lifting posture groups, each participant was randomly assigned to either a stoop or squat lifting postures, and then performed three separate sets of fatiguing repetitive lifting tasks at 5%, 10% and 15% of MLS. As such, the mean weights for 5% MLS, 10% MLS, and 15% MLS were (stoop lifting posture: 4.77 ± 0.87 kg, 9.54 ± 1.74 kg, and 14.31 ± 2.61 kg) and (squat lifting: 5.54 ± 0.69 kg, 11.07 ± 1.39 kg, and 16.61 ± 2.08 kg), respectively. These three percentages of MLS were chosen because previous pilot study research observed that rebar workers on construction sites usually lifted reinforcement bars within these boundaries. Specifically, the repetitive experimental task (using either stoop or squat lifting posture) involved each participant standing upon a demarcated area, with explicit instructions not to move their feet, and lifting a wooden box (of dimensions 30 x 30 x 25 cm) that contained the target weight (refer to Figure 2). Each participant had to lift the box from the floor to the waist level using the assigned lifting posture until subjective fatigue was reached despite strong verbal encouragement (that is, a point in time at which the participant could not continue lifting further). Immediately after each lifting task, the standing balance tests were repeated. To standardize the lifting cycle, a metronome was used to guide the lifting at a rate of 10 cycles per minute. Participants received a 20-minute rest between each lifting task to prevent muscle fatigue.

<Insert Figure 2 about here>

Statistical Analysis

Independent *t*-tests were conducted to compare between-group differences (stoop vs. squat) and each balance test for all CoP parameters. Once results of the Shapiro-Wilks test confirmed data normality ($p > 0.05$), a separate three-way (3×3×2) repeated measures analyses of variance (ANOVA) for weights (5% MLS vs. 10%MLS vs. 15% MLS), balance tests (EOS vs. ECS vs. ECF) and fatigue (pre- vs. post-fatigue) were conducted for each CoP parameter. Given statistically significant *F* ratios (refer to Table 1), post-hoc pairwise comparisons were conducted with Bonferroni adjustment. Partial eta squared (η_p^2) values were reported to estimate the effect sizes. Statistical Package for the Social Science (SPSS) version 20.0 (IBM, USA) was used for the statistical analysis and statistical significance was set at $p < 0.05$.

RESULTS

Figure 3a-e summarizes the arithmetic mean and standard deviation (SD) for RMS of CoP A/P displacement, RMS of CoP M/L displacement, MV of CoP A/P displacement, MV of CoP M/L displacement and total sway area for each balance test condition immediately after the stoop and squat lifting tasks. All CoP parameters revealed no significant difference between lifting postures in the three balance test conditions ($p > 0.05$) although the absolute value of all CoP parameters following the repetitive squat lifting task were larger than those following a stoop lifting posture under all balance test conditions (refer to Figure 3a-e).

<Insert Figure 3a-e about here>

Balance Stability Parameters Comparison of Different Weights, Balance Tests, and Fatigue

The ANOVA results for CoP parameters are presented in Table 1. Since the main effect of the lifting posture groups (stoop vs. squat) and all relevant interactions were not significant ($p > 0.05$)

(see Figure 3a-e), the following results only described the effects of different weights, balance test conditions and fatigue on CoP parameters based on pooled data from the two lifting postures.

<Insert Table 1 about here>

Total Sway Area

Three-way repeated measures ANOVA revealed no significant interaction between weight by balance test by fatigue for total sway area (F = 0.66, p = 0.53, η_p^2 = 0.03) (refer to Table 1). The total sway area demonstrated a significant interaction between weight and fatigue (F = 127.27, p = 0.00, η_p^2 = 0.87) but all other two-way interaction effects were not significant. Significant main effects for weight (F= 127.27, p = 0.00, η_p^2 = 0.87) and fatigue (F=112.98, p = 0.00, η_p^2 = 0.86) were found. The effect of weight significantly increased the total sway area immediately after lifting tasks. The total sway areas after lifting 5%, 10%, and 15% of MLS were 92.16%, 218.17%, and 412.97% larger than the respective pre-fatigue conditions (Figure 4).

<Insert Figure 4 about here>

Root Mean Square (RMS) of CoP Displacement

At baseline, balance test conditions revealed no significant difference of RMS of CoP A/P or M/L displacement across all balance test conditions (EOS, ECS and ECF). However, significant two-way and three-way interactions (i.e. weight and fatigue, and balance test condition) were observed on RMS of CoP A/P and M/L displacement (refer to Table 1 and Figure 5a-b).

<Insert Figure 5a-b about here>

Repetitive lifting at 5% MLS had no significant effect on RMS of CoP A/P displacement across all balance test conditions ($p > 0.05$). However, repetitive lifting at 10% MLS or 15% MLS significantly increased RMS of CoP A/P displacement as compared to the baseline. Interestingly, the effect of weight induced significantly larger RMS of CoP A/P displacement in the ECF condition when compared to the EOS and ECS conditions. Similarly, repetitive lifting at 15% MLS caused significantly larger RMS of CoP A/P displacement under ECF condition than EOS and ECS conditions (refer to Figure 5a). For 15% MLS lifting, ECF caused an increase in RMS of CoP A/P displacement by 70.37% and 55.96% when compared to EOS and ECS, respectively. When compared to the baseline, repetitive lifting at 5% MLS, 10% MLS and 15% MLS increased RMS of CoP A/P displacement by 75.97%, 197.73%, and 325.65%, respectively. Taken together, 3-way interaction revealed that repetitive lifting at 10% and 15% MLS caused significantly greater RMS of CoP A/P displacement under ECF condition (at 10%MLS: 82.70% and 76.02%) and (at 15%MLS: 77.74% and 59.88%) as compared to EOS and EOS respectively (Figure 5a).

Similarly, significant 3-way interaction revealed that repetitive lifting at 10% MLS and 15% MLS significantly increased RMS of CoP M/L displacement at ECF condition (10% MLS: 82.09% and 72.09%; 15% MLS: 66.25% and 56.52%) compared to EOS and ECS conditions, respectively ($p < 0.05$; Fig. 5b), while there was no significant difference of 5% MLS lifting weight on RMS of CoP M/L displacement across all balance test conditions. Moreover, the main effect results revealed that RMS of CoP M/L displacement under ECF condition was 70.09% and 60.08% greater than ECS and EOS after fatiguing repetitive lifting ($p < 0.05$) (Figure 5b). Furthermore, lifting weight (at 5% MLS, 10%, MLS, and 15% MLS) significant increased RMS of CoP M/L displacement by 69.39%, 183.16% and 307.14% after fatiguing.

Mean Velocity (MV)

The MV of CoP A/P and M/L displacement analyses revealed significant main effects of weight, balance and fatigue, and significant two-way and three-way interactions (refer to Table 1, Figure 6a-b). Repetitive lifting at 5% MLS, 10% MLS, and 15% MLS increased MV of CoP A/P displacement under the ECF condition by 207.79% and 153.74%; 180.86% and 144.91%; and 163.26% and 135.23% when compared to EOS and ECS conditions respectively (refer to Figure 6a). In addition, increased lifting weight significantly increased MV of CoP A/P displacement in all EOS and ECS pairwise comparisons ($p < 0.05$). Fatigue significantly increased MV of CoP A/P displacement in all balance tests ($p < 0.05$). Repetitive lifting at 5% MLS, 10% MLS and 15% MLS increased MV of CoP A/P displacement by 27.66%, 59.04%, and 88.53% respectively. The 3-way interaction test revealed that heavier fatiguing repetitive lifting task had significantly greater effect on MV of CoP A/P displacement under ECF condition when compared to EOS or ECS conditions (*p* < 0.05). Specifically, repetitive lifting at different weights (at 5% MLS: 190.98% and 146.56%; at 10% MLS: 154.40% and 133.87%; at 15% MLS: 134.73% and 121.31%) had differential increases in MV of CoP A/P displacement under the ECF condition when compared to EOS or ECS conditions.

Similarly, greater MV of CoP M/L displacements (at 5% MLS: 252.62% and 229.88%; at 10% MLS: 228.13% and 207.74%; at 15% MLS: 214.02% and 194.66%) at the ECF condition were noted as compared to both the EOS and ECS conditions (Figure 6b). However, no significant difference of MV of CoP M/L displacement was observed for all EOS and ECS pairwise comparisons (*p* > 0.05). Fatigue significantly increased MV of CoP M/L displacement in all balance test conditions (*p* < 0.05). Moreover, lifting at 5%, 10%, and 15% MLS significantly increased MV of CoP M/L displacement by 27.74%, 63.76% and 99.06%, respectively. The 3-way interaction revealed that although post-fatigue MV of CoP M/L displacement under the ECF condition was consistently higher than either the EOS or ECS conditions, heavier repetitive lifting weights (5% MLS: 186.87% and 182.10%; at 10% MLS: 168.45% and 161.63%; at 15% MLS: 160.82% and 152.57%) caused differential increases in MV of CoP M/L displacement under ECF condition when compared to the EOS and ECS conditions.

<Insert Figure 6a-b about here>

DISCUSSION

Analysis results revealed no significant difference between lifting postures after the fatiguing lifting task across all balance test conditions. This finding indicates that fatiguing repetitive stoop and squat lifting postures induce a similar balance control deficit. Consequently, this finding refutes our first hypothesis that the stoop lifting posture would induce greater variations in balance control than squat lifting postures following fatiguing repetitive tasks. In addition, while increased repetitive lifting weight significantly produced a larger increase in CoP parameters (both RMS and MV of CoP A/P and M/L displacement analyses), under ECF condition (when compared to either EOS or ECS condition), increased lifting weight caused no significant difference in CoP parameters (total sway area, RMS of CoP A/P and M/L displacement and MV of CoP M/L displacement) between EOS and ECS conditions. These findings confirm our second hypothesis that the fatiguing repetitive lifting tasks cause poorer balance control on an unstable surface when compared to the stable surface (Yaggie and McGregor, 2002; Corbeil *et al.,* 2003).

Comparison of Repetitive Lifting Postures: Stoop and Squat

Test results demonstrate that fatiguing repetitive stoop and squat lifting postures induced similar impairments in balance control, which is contrary to findings reported upon in previous studies (c.f. Sparto *et al.*, 1997a; Commissaris and Toussaint, 1997; Chow *et al.*, 2005). Chow *et al.* (*ibid*) reported a significant difference in CoP parameters during a test that involved lifting four different weights (20, 40, 60, 80N) at a rate of five lifting cycles per minute using two different lifting postures (symmetric stoop and squat lifting) after a sudden release of weight. Although the lifting postures were similar to the present study, the discrepancy in results may be attributed to differences in lifting weights, lifting speed, and the absence of a sudden release of weight. Sparto *et al.,* (1997a) found a significant effect of lifting postures upon balance control by instructing their participants to lift at their maximal lifting rate until they: i) cannot continue; and ii) attained an aerobic limit (heart rate of 180 beats/minute). Several methodological differences exist in the literature regarding the contradictory effects of lifting postures on balance control as comparted to previous studies. First, the current study performed the stoop or squat lifting posture from ground floor to the waist level of each participant, which was contrary to Commissaries and Toussaint (1997) study, where participants underwent the same lifting postures at acromion height. Second, there was no vertical distance between the load and the ground in the present study, however, these authors standardized the lowest position at 14% of the participant's body height. . Consequently, these results cannot be directly compared to the present study due to differences between research protocols adopted. However, our experimental protocol reflects the vertical height of static repetitive lifting posture since we conducted a pilot site observational study of construction workers (e.g., rebar workers) lifting postures in Hong Kong.

Effects of Different Weights, Balance Tests, and Fatigue on Balance Control

Research results presented indicated that increased weight significantly increased postural sway (i.e., poorer balance control) following a fatiguing repetitive lifting task. This suggests that repetitive lifting with relatively heavy weights may indirectly increase the risk of fall injuries (Corbeil *et al.,* 2003; Paillard, 2012). Findings presented concur with previous research that evaluated the impact of adding weights until fatigue and its impact upon balance control (Ledin and Odkvist, 1993; Punakallio *et al.,* 2003; Lee *et al.,* 2008). Punakallio *et al.* (2003) reported significant increase in CoP parameters in the A/P and M/L directions after wearing firefighting clothing weighing 25.9 kg for 40 seconds in an upright standing position. Similarly, Ledin and Odkvist (1993) found that putting weight (totaling 20% of body mass) on the chest and back of participants' impaired their ability to remain in equilibrium during 45 seconds. Unfortunately, these studies did not compare the effects of different weights on CoP parameters; whereas the present study reveals increases in CoP parameters as lifting weight is increased from 5% to 15% of the participant's MLS. Overall, the findings of the current study can be used to improve the balance control with subsequent fall injuries of construction workers involved in repetitive lifting tasks of weight in range between 5 to 17 kg.

The current study revealed that lifting weights have a differential effect upon balance controls. Repetitive lifting had similar effect on balance control in A/P and M/L direction on a stable support surface regardless of the presence/absence of vision. In the current study, the visual system is thought not to be a contributing factor to impair balance control for two reasons: firstly, during the eyes open standing balance test (i.e., EOS), the participants focused on a standard white sheet at a uniformed distance, and secondly the participants eyes were closed during the eyes closed standing balance test condition (i.e., ECS). Previous studies have suggested that visual target placed at informed distance can impair balance control (Vuillerme *et al.,* 2001; Vuillerme *et al.,* 2006). Vuillerme *et al*. (2001) showed that a visual target placed at 1 m can attenuate the effect of fatigue on balance control during quiet standing balance task. Conversely, the impact of lifting weight on balance control was more profound on an unstable supporting surface with vision occlusion (i.e., ECF) than the other two standing balance conditions. Since an individual relies more on proprioceptive inputs from lower limb and trunk to maintain balance on an unstable surface during vision occlusion (Derave *et al.,* 2002; Maurer *et al.,* 2006; Horak and Macpherson 1996; Bhattacharya *et al.,* 2003), the presence of fatigue may affect an individual's ability to provide correct proprioceptive signals to the brain for balance control (Simeonov *et al.,* 2003). Therefore, repetitive lifting of heavy weights may heighten the risk of fall injuries (Corbeil *et al.,* 2003; Paillard, 2012). Hence, the lifting weight should be reduced for repetitive lifting tasks in order to minimize the risk of falls among workers working on an unstable supporting surface. Since reducing the lifting weight may sometimes be practically infeasible, construction workers should adopt proper ergonomic interventions (e.g. exoskeletons, back belts and lifting equipment) to enhance the mechanical advantages of workers during lifting tasks (Kraus *et al.,* 1996).

The effect of muscle fatigue upon balance control was consistent with several previous studies using different fatigue protocols (c.f. Vuillerme *et al.,* 2001; Yaggie and McGregor, 2002; Corbeil *et al.,* 2003). These findings support the notion that repetitive lifting induces muscle fatigue, which may cause proprioceptive deficiency and suboptimal efferent muscle responses that compromise balance control (Hiemstra *et al.,* 2001; Forestier *et al.,* 2002). Although the evidence of muscle fatigue in the current experimental protocol was subjective, our previous studies measured muscle fatigue by using normalized median frequency (MF) and root mean square (RMS) of normalized sEMG amplitude based on similar protocols (Antwi-Afari *et al.,* under review). Although these objective assessment of muscle fatigue are outside the scope of the current study, the results shown decreased MF values and increased muscle activity at the lumber erector spinae and quadriceps muscles, which also concur with previous studies during repetitive lifting tasks (Sparto *et al*., 1999; Davis *et al*., 2010). The interaction effects of weight and fatigue after repetitive lifting task were significant for all CoP parameters. This finding indicates impaired balance control with increased weight after fatigue is in line with previous studies (c.f. Punakallio *et al.,* 2003; Schiffman *et al.,* 2006; Lee *et al.,* 2008). The current study assessed balance control by using CoP parameters measured from a force plate. With regards to the directional-specific effects of muscle fatigue, the research findings indicated that balance control in the A/P and M/L directions showed a similar increase in perceived lower back and calf/quadriceps muscles fatigue following stoop and squat lifting postures, respectively. These results are in accordance with findings of Gribble and Hertel (2004a) and Soleimanifar *et al.,* (2012) which observed that balance control in sagittal and frontal planes was impaired after the fatigue of either hip, knee or ankle muscles. Overall, these findings suggest that the effects of fatigue on balance control are specific to the fatigue location and measures of balance control used.

However, akin to other proprioception studies that examined repetitive lifting tasks (Sparto *et al.,* 1997a; Lin *et al.,* 2012) the current study has some limitations. First, the sample size was relatively small albeit, significant and second, the study was conducted on student participants in a laboratory setting. Future work should therefore evaluate the impact of different lifting parameters on a larger sample size experienced construction workers working on on-site. Third, the study results may not be general with respect to repetitive lifting tasks in construction workers. Although designed to evaluate risk factors in relatively realistic conditions, the current study involved only a static controlled repetitive lifting/lowering task. Also, balance control was evaluated during quiet standing tests, while the majority of fall injuries may occur during dynamic tasks that are initiated by slip, trip and loss of balance events. Earlier research has suggested that balance control system utilizes the same control mechanisms under quiet standing and dynamic test conditions (Lauk *et al*., 1998). However, future research is warranted to evaluate balance control during real dynamic repetitive lifting tasks, and to investigate how they can be translated to fall prevention in real construction sites. Fourth, it remains unknown how a change in specific lifting posture (i.e., either stoop or squat) may affect balance control. How balance may be associated with increased risk of falls among construction workers remains to be seen given that we did not find a significant change in lifting postures across standing balance tests. Future research is needed to examine other index of fatigue in lifting postures such as reduction maximal voluntary contraction and/or relaxation (Davidson *et al.*, 2009; Paillard *et al.*, 2010b), aspects relating to dehydration (Lion *et al.*, 2010) and physiological effects (Nardone *et al*., 1997; Mello *et al*., 2010a).

CONCLUSIONS

This is the first study to evaluate the effects of different lifting weights and lifting postures on balance control following simulated fatiguing repetitive lifting tasks. The results revealed that: i) increased weight regardless of lifting postures significantly increased CoP parameters; ii) stoop and squat lifting postures performed until subjective fatigue induce a similar increase in CoP parameters; and iii) fatigue adversely effected the participant’s balance control on an unstable surface than on a stable surface. These results suggest that fatiguing repetitive lifting tasks may alter the proprioception of the lower limb/back that leads to increased postural sway and suboptimal balance control on an unstable supporting surface. Consequently, fatigued-related loss of balance control may limit the safety range of movement of the body’s center of gravity, and thus increase the risk of fall injuries. The findings of the present study have research and practical implications. First, the magnitude of weight during repetitive lifting task can significantly impair balance control and as such reduce the risk of loss of balance events with subsequent fall injuries. Second, surface support conditions are dependent on balance control; as such unstable supporting surfaces can significantly reduce the effort for balance control and therefore could be useful in preventing fall injuries among construction workers. To reduce the possibility of losing balance, unstable supporting structures (e.g., scaffold, ramp) used as working surfaces should be minimized when performing static repetitive lifting tasks. Third, the findings demonstrate the potential of the suggested objective balance stability parameters in measuring static repetitive lifting task associated with fall risk resulted from extrinsic (e.g., weights of lift) and intrinsic (e.g., fatigue) factors. Construction workers can benefit from receiving adequate training in recognizing the role of lifting weights and fatigue during static repetitive lifting tasks, which would result in enhanced balance control through redesign of work and improved workers' behaviour. Overall, these findings provide preliminary and invaluable information to researchers and practitioners seeking to develop practical interventions to reduce the risk of falls in construction workers (e.g., masons, rebar workers) involved in repetitive lifting tasks. Future studies should investigate the optimal working and rest durations among workers involving in repetitive lifting works in order to reduce the risk of fatigue-related balance deficit.

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Figure 1 - A Foam (39 cm × 39 cm × 10 cm thickness) on a Force Plate

Figure 2 – Two lifting postures: (a) Stoop posture; and (b) Squat posture

(a) (b)

Figure 3a-e - The Different Center of Pressure (CoP) Parameters during Balance Test Following Fatiguing Repetitive Lifting Tasks with Different Weights and Lifting Postures.

Figure 3(a) - RMS of Anterior/Posterior Displacement of CoP

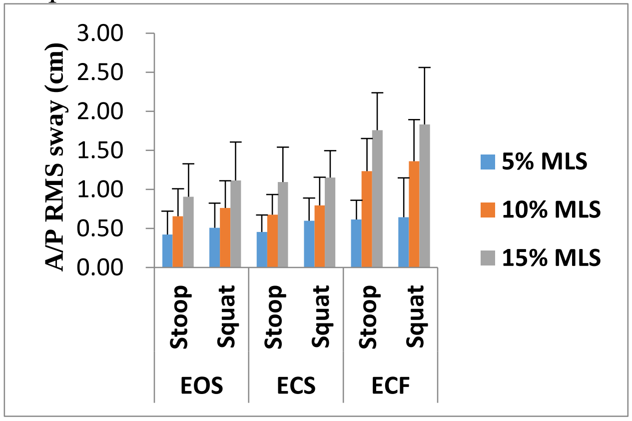


Figure 3(b) - RMS of Medial/Lateral Displacement of CoP

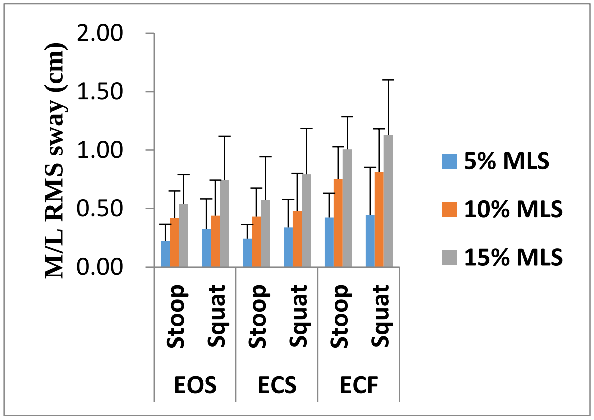


Figure 3(c) - MV of Anterior/Posterior Displacement of CoP

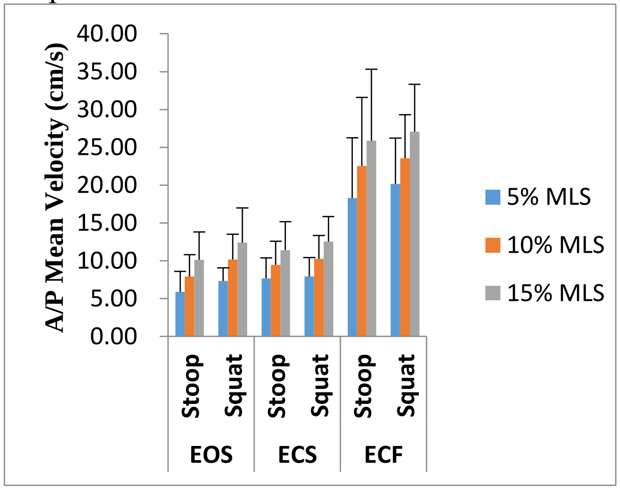


Figure 3(d) - MV of Medial/Lateral Displacement of CoP

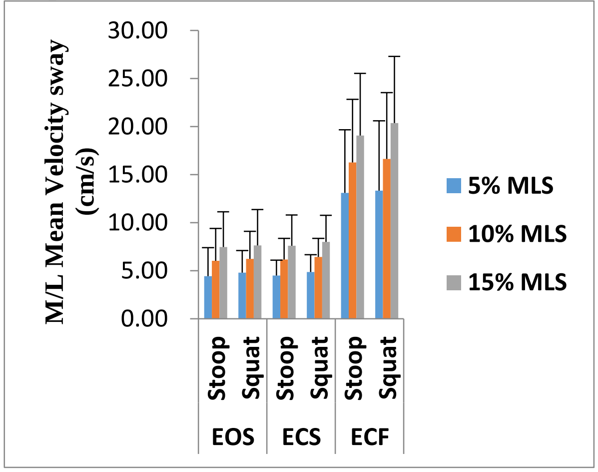


Figure 3(e) - Total Sway Area

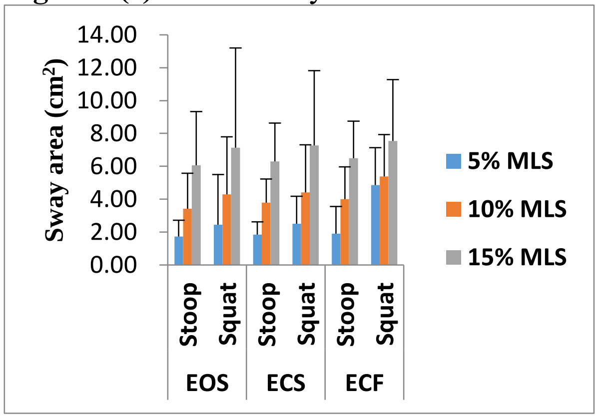
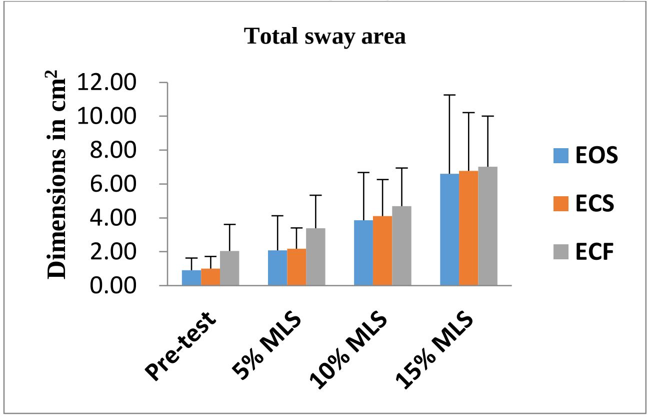


Table 1 - Analysis of Variance Results for Center of Pressure (CoP) Parameters: *F* Ratios and P-values

Effects	**Sway area**	**A/P RMS**	**M/L RMS**	**A/P MV**	**M/L MV**
	***F* ratio**	***F* ratio**	***F* ratio**	***F* ratio**	***F* ratio**
Main effect					
Weight	127.27*	137.40*	92.21*	105.69*	149.58*
Fatigue	112.98*	346.17*	114.85*	174.41*	179.91*
Postural task	2.17	7.56*	6.07*	61.11*	51.37*
Interaction					
Weight × balance test	0.66	10.81*	3.09*	6.22*	12.15*
Fatigue × balance test	0.17	16.49*	11.16*	15.39*	31.76*
Weight × fatigue	127.27*	137.40*	92.21*	105.69*	149.58*
Weight × balance test × fatigue	0.66	10.81*	3.09*	6.22*	12.15*

Note: A/P RMS = Root mean square of anterior/posterior CoP displacement; M/L RMS = Root mean square of medial/lateral CoP displacement; A/P MV = Mean velocity of CoP in anterior/posterior directions; M/L MV = Mean velocity of CoP in medial/lateral directions. *Indicates statistically significant effects with $p < 0.05$.

Figure 4 - Total Sway Area (Mean and Standard Deviation) of the Different Postural Tasks Before (Baseline) and After Fatiguing Repetitive Lifting Task.



NB: No significant difference was found in all conditions.

Figure 5a - RMS of anterior/posterior (A/P) CoP displacement

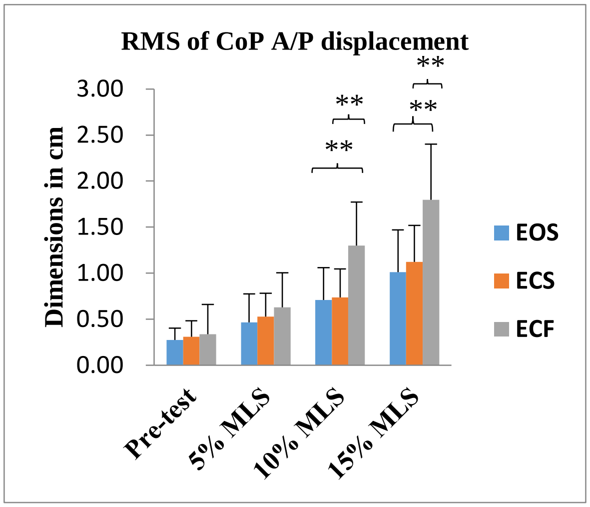
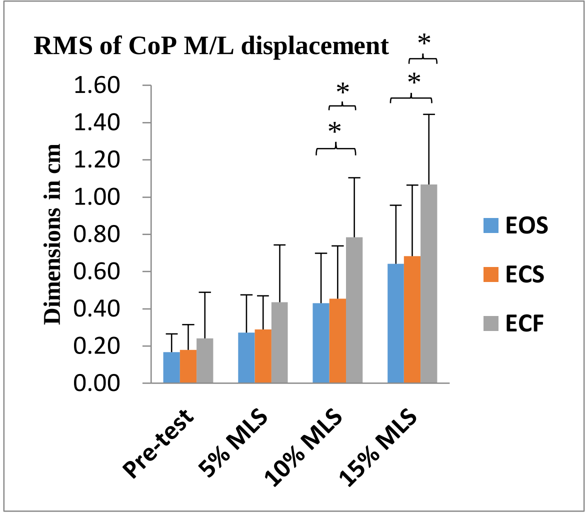


Figure 5b - RMS of medial/lateral (M/L) CoP displacement



NB: *p significant at <0.05, **p significant at <0.01.

Figure 6a - MV of Anterior/Posterior (A/P) CoP Displacement

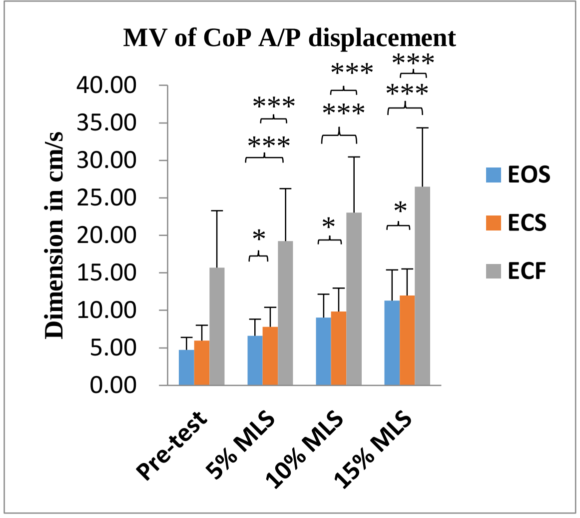
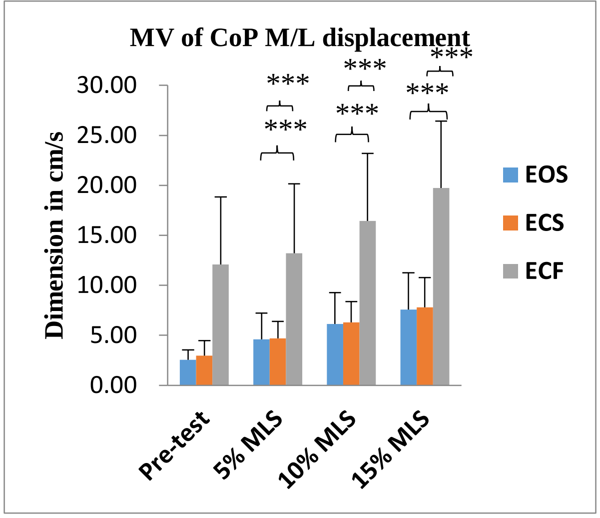


Figure 6b - MV of medial/lateral (M/L) CoP displacement



NB: **p* significant at <0.05, ****p* significant at <0.001.