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Towards proactive safety measures: Quantifying the upright standing stability after sustained rebar tying postures

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Abstract

Fall accidents (FAs) constitute a substantial proportion of construction accidents. While the predominant prevention strategy relies on passive approaches (e.g. guardrails), research on proactive measures is lacking, which may reduce the incidence of FAs in high-risk construction trades. Literature suggests that rebar work is one of the foremost FA prone construction trades. Since rebar workers spend hours in rebar tying postures with periodic postural transitions, they hypothetically are at risk of post-task loss of balance. While recent research showed that a sitting-stool could significantly alleviate physical discomfort during rebar tying, the current study aimed to investigate temporal changes in standing balance (using a force plate) after simulated rebar tying in squatting, stooping and stool-sitting while the respective postural load during rebar tying was quantified by electromyography and oximeters. Results demonstrated that people in stool-sitting had significantly better post-task standing balance than those in squatting or stooping, which might be attributed to their differential postural loadings. Overall, our findings underpin the importance of using safety informatics to proactively analyze task-specific fall hazards, to monitor workers' balance, and to implement proper prevention strategies for workers at risk of falls.

Keywords

Rebar tying; Occupational safety and health; Fall accidents; Loss of balance, Stool-sitting, Construction ergonomics

Introduction

Fall accidents (FAs) are one of the major barriers to achieve occupational safety in the construction industry worldwide. During 2015, FAs were the major fatal injuries in the US construction industry (BLS 2016). Similarly, they were the leading cause of fatal injuries in the New Zealand construction industry from 2006 to 2009 (DoL 2011). Chinese and Hong Kong construction industries share the same trend, where more than 50% of construction site accidents involved FAs (Chan et al. 2008; Yung 2009). In addition to fatal FAs, non-fatal FAs have also raised a great concern in the industry. It was estimated that non-fatal FAs in the US construction industry caused an average of 10 days of sick leaves between the period of 1992 and 2000 (Bobick 2004). Likewise, the highest number of compensation claims filed for non-fatal injuries in the Hong Kong construction industry from 2004 to 2008 were associated with FAs (Li 2009). Given that FAs can delay/disrupt the construction schedule, decrease productivity, increase economic burden and deprive the supply of skilled workers (Earnest and Branche 2016), there is a pressing need to lower the risk of FAs in the construction industry.

Since more than three-fourth of total FAs are attributed to specialty trade contractors (Huang and Hinze 2003; Kang et al. 2017), specific attentions should be given to individual trades to reduce FAs. Ironworkers (including both structural steel and rebar workers(BLS 2015)) are known to have an increased risk of FAs (Huang and Hinze 2003; Kang et al. 2017). For instance, the incidence rate of fatal falls in the US construction industry was the highest among ironworkers between 2003 and 2008 (Dong and Wang 2011). An injury record also revealed that US rebar workers had a significantly higher incidence of FAs than workers in other construction trades (Hunting et al. 1999). In order to prevent FAs, it is paramount to identify causative behaviors/work practices in the industry that cause the loss of balance (Antwi-Afari et al. 2017; Hsiao and Simeonov 2001). During rebar tying, workers may face multiple personal (e.g. risky behavior), environmental (e.g. height of work, availability of personal protective equipment or weather) and task-specific risk factors that may lead to FAs. While personal and environmental factors may vary significantly among individuals or construction sites, the identification and modifications of task-specific risk factors may mitigate the risk of falls in rebar workers. Task-specific risk factors include, but not limited to: (1) rebar tying in awkward postures with periodic posture transitioning (DiDomenico et al. 2016; Jebelli et al. 2016); (2) working at height (e.g. tying rebar for retaining walls, deck of bridges or multistory buildings) (CPWR 2013); (3) traversing uneven work surfaces (Hunting et al. 1999); and (4) work-related fatigue (Pline et al. 2006).

Prolonged awkward work postures may affect the standing balance of rebar workers. Observational studies have reported that rebar workers spend up to 48% of their worktime in non-neutral (flexed, laterally bent and/or twisted) trunk postures (Forde and Buchholz 2004). Of various awkward postures, squatting and stooping are the two most prevalent postures for manual rebar tying (Umer et al. 2017b). Research has shown that prolonged squatting/stooping postures can elicit back and leg fatigue (Umer et al. 2017b) that may compromise standing stability and balance (DiDomenico et al. 2010). Theoretically, volitional postural transitions from non-neutral work postures to standing can disturb the functioning of vestibular and/or somatosensory system (Gauchard et al. 2001), which can be further disturbed by the presence of simultaneous work tasks or other environmental risk factors for falls at construction sites (DiDomenico et al. 2016). Importantly, since some rebar workers need to work in an environment with a small base of support (e.g. a scaffold) that prevents them from using stepping strategy for maintaining standing balance (Robinovitch 2003), the impact of awkward rebar tying postures on the post-task standing balance of these workers may be more profound (DiDomenico et al. 2011).

Although different rebar tying postures may have differential impacts on the post-task standing balance, the effects or underlying mechanisms of various rebar tying postures on the ensuing standing postural controls remain undetermined. Recent studies have shown that squatting, stooping, and stool-sitting rebar tying postures elicit different back/leg muscle activity and lower limb circulation (Umer et al. 2017a; b). It is plausible that these physical changes may be related to changes in post-task standing balance. Since an in-depth understanding of these relations may help develop proper ergonomic interventions to minimize the risk of FAs in rebar workers, the objectives of the current study were to compare the effects of various prolonged rebar tying postures (squatting, stooping, and stool-sitting) on the ensuing standing stability metrics, as well as to determine the relations among back and leg muscle activity, lower limb circulation during rebar tying, and the subsequent standing stability.

Literature Review

Risk factors for FAs can be classified into three domains: personal, task-related and environmental factors (Hsiao and Simeonov 2001). To identify various risk factors for FAs, many approaches have been documented in the literature. These include (1) site observations (Hallowell and Gambatese 2009), (2) construction site plan and schedule based risk identification (Saurin et al. 2003), (3) investigation of case reports and accidents archival data (Nadhim et al. 2016), (4) semi-structured interviews with the workers involved in FAs (Bentley et al. 2006), and (5) use of virtual reality and 4D computer aided designs (Chantawit et al. 2005). Based on these risk identification strategies, multiple ways are suggested to prevent FAs. These include, but are not limited to, (1) the installation of safety nets, guardrails, personal fall arrest systems and fall protection plans (Hsiao and Simeonov 2001), (2) the use of warning-line strategies and workers monitoring systems (Earnest and Branche 2016), (3) safety audits of construction sites (Kaskutas et al. 2009), (4) scheduled adjustment for safety risk allocation (Yi and Langford 2006) and (5) integration of Building Information Modelling (BIM) with safety checklists to identify potential risks (Zhang et al. 2013).

Although many strategies have attempted to reduce the risk of FAs, FAs remain to be one of the largest contributors of construction accidents (Nadhim et al. 2016). A possible reason for the difficulty in mitigating FAs may be related to the current methods of risk identification (Hsiao and Simeonov 2001). A predominant mitigation approach relies on reviewing the archival data and reports to identify the risk factors. However, this approach may not reveal the actual causes of FAs because the results can be confounded by biases originated from reporters' background, experiences, responsibilities and beliefs (Dekker et al. 2011), and/or the investigators' subjective interpretation of injury reports (Nadhim et al. 2016). Consequently, the retrospective nature of this approach might not be always successful in establishing true cause-effect relations (Dekker et al. 2011). Likewise, other common risk mitigation strategies (e.g. site plan and observation based methods) might not always reduce fall risks because the ever-changing environment of construction sites and resources increase the difficulty in identifying and mitigating fall hazards.

While task-related accident risks for construction activities comprise a large proportion of overall safety risk at a construction site, there is a paucity of research quantifying the task-specific risk factors (Hallowell and Gambatese 2009). Quantifying task-related risks for falls are an important step to reduce FAs, especially for rebar workers who have a higher rate of FAs (Dong and Wang 2011; Hunting et al. 1999). Since rebar tying requires workers to work in a sustained posture, such prolonged activity may increase the fall risk upon post-task upright standing (DiDomenico et al. 2016). Recently, Jebelli et al. (2016) quantified effects of postures (standing and squatting) and carrying weights on postural stability metrics. They found that standing while carrying the load or wearing an asymmetrically loaded toolbelt could result in significantly better stability as compared to performing these tasks in a squatting posture. However, their tasks were limited by the short duration (30 seconds only), absence of construction task simulation, and no post-task balance measurement. DiDomenico et al. (2011) also attempted to quantify the effect of different postures on standing balance. They revealed that the standing balance of individuals after 120 seconds of stooping or squatting posture was better than that after 120 seconds of two-legged kneeling. However, their study was limited by the short duration of maintaining the target posture without performing any simulated work tasks. Importantly, DiDomenico et al. (2011) assessed the standing balance control based on the balance metrics in 1 second, which was deviated from the recommended minimum duration for such test (i.e. 20 seconds) (Paillard and Noé 2015). Further, no study has investigated the physical responses during the performance of a simulated task in a target posture, which may help explain the divergent postural responses among various postural conditions.

Methods

Participants

Thirteen male individuals with a mean age of 27.5 ± 4.4 years and a mean body mass index of 22.8 ±1.5 kg/m^2 participated in the experiment. To be eligible for the study, the participant should have a normal or corrected vision, no known balance problems, and the absence of any musculoskeletal disorders in the past 12 months (DiDomenico et al. 2011).

Procedure

The current experiment adopted a crossover study design in a single laboratory visit (Fig. 1). The experimental procedures were explained to the participant and a written consent was sought prior to data collection. The participant was then instructed to perform three sets of reference contractions (RCs) for bilateral lumbar, thigh and calf muscles while the respective surface electromyography (sEMG) signals were measured. The sEMG signals of the target muscles during RCs were used to normalize the respective muscle sEMG during subsequent simulated rebar tying tasks. The participant was then instructed to stand still barefooted on a force plate for 20 seconds with feet apart at shoulders' width and hands resting aside while looking straight forward at a target (DiDomenico et al. 2011). Prior to the force plate data collection, the outline of the feet placement was traced on a piece of paper adhered to the force plate so as to guide subsequent feet placements. Afterwards, the participant performed simulated rebar tying in one of the three postures (squatting, stooping or stool-sitting, Fig. 1) in a randomized manner. During the rebar tying, muscle sEMG activity and right toe circulation as measured by an oximeter were being monitored. Immediately after the rebar tying, the participant was instructed to repeat the 20-second standing test on the force plate. Participants were instructed to rest on a chair with backrest for 20 minutes before being randomized into one of the remaining two rebar tying work postures. They repeated the same experimental procedure until all three work postures were completed.

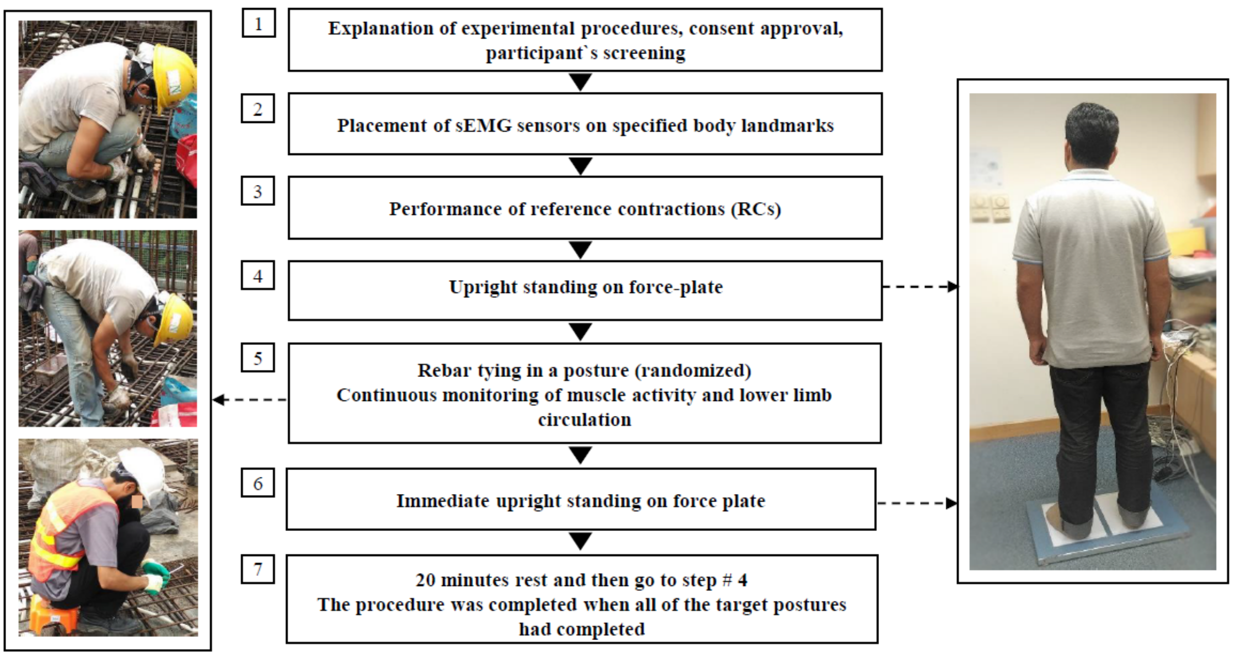


Fig. 1. Experimental procedure

Note: sEMG= surface electromyography

a. Reference Contractions (RCs)

Three sets of reference contractions (RCs) were performed for lower back, and bilateral thigh and calf muscles separately (Umer et al. 2017a). Briefly, each set consisted of three 5-second isometric contractions separated by a rest period of 5 seconds. For lower back muscles, participants performed a modified Sorensen test, which required them to hold their unsupported trunk while lying prone on the bench edge. The RCs for thigh muscles involved one-by-one performance of lunge test with the rear knee (non-lunging) just off the ground. For the calf muscles, participants were instructed to perform an alternated single leg heel-rise test. During heel-rise test, participants could use index fingers to gently touch the wall to maintain balance.

b. Rebar Tying Simulation

The simulated rebar tying was performed using a pigtail tool and tie wires. The setup comprised a mesh of 5-by-5 plastic pipes of 1.2m length separated from each other by 0.2m center-to-center to replicate reinforcement steel mesh. The experiment involved making ties at the first three rows of the replicated mesh. To assess each distinct rebar tying posture, the participants were not allowed to rest or alter their work posture. However, natural movements required for rebar tying were allowed.

Initially, each rebar tying posture was planned to last for 20 minutes. However, the two participants involved in pilot testing requested to shorten the duration because of severe lower leg discomfort. The reported lower leg discomfort increased more rapidly in stooping posture than squatting. Accordingly, the duration for rebar tying was shortened to 12.5 minutes for squatting and stool-sitting, and 5 minutes for stooping. The specific duration of 12.5 and 5 minutes were chosen because these values were multiples of 2.5, which was the chosen interval to solicit perceived discomfort scores in another study (Umer et al. 2017a). For stool-sitting, each participant was given an option to choose a stool with either 10cm or 15cm in height. All participants chose the one with 15cm in height.

Instrumentation

The pre- and post-task standing stability of the participant was evaluated using a portable multicomponent force plate with four load cells (Kistler 9286AA, Kistler Instrument Corp., Winterthur, Switzerland). The data was sampled at 1000Hz. Muscle activity during RCs and rebar tying simulation was measured by a wireless sEMG system (TeleMyo, Noraxon USA, Arizona) at a sampling frequency of 1500Hz with a common mode rejection ratio of 100dB. Bipolar disposable electrodes with a diameter of 15mm and inter-electrode distance of 20mm were placed at five locations of muscles. The target locations of electrode placements for each muscle (Table 1) were chosen in accordance with the recommendation of *Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles* (SENIAM 2005). Each muscle site was shaved, abraded with sandpaper and cleaned with alcohol swabs prior to the electrode placement to keep skin impedance below 10kΩ. Lower limb circulation was measured in terms of the oxygen saturation level (SpO_2) in the plantar digital artery of the right toe. Specifically, a sports grade perfusion resistant pulse oximeter (MightySat Pulse Oximeter 9900, Masimo Corporation, Irvine, CA) was clipped on the right toe to collect data at 0.5Hz throughout the rebar tying simulation.

Table 1. Target location for sEMG electrode placement

Bilateral muscle	Electrode placement
Erector spinae	L3 level of the lumbar spine (5cm laterally from midline)
Multifidus	Aligned with a line joining from the caudal tip posterior iliac spine to the L1-L2 joint (2cm laterally from the midline at the L5 level)
Rectus femoris	At 50% of the line distance formed by joining the anterior iliac spine and the superior part of a patella
Gastrocnemius lateralis	At one third of the line distance formed by a line joining the head of fibula to the heel
Gastrocnemius medialis	At the most prominent bulge of the muscle

Dependent Variables

Standing Stability Metrics

Balance stability of a person can be defined as an individual's ability to restore or maintain upright posture (Maki et al. 1990). It is usually quantified by the magnitude of postural sway that refers to the displacement of an individual's center of mass (Schiffman et al. 2006). Center of pressure (COP) is the vertical projection of an individual's center of mass and is one of the most widely used indices to measure postural sway using the force plate data (Prieto et al. 1996). The current study used two types of COP metrics to examine the pre- and post-task standing stability of the participant: (1) global metrics, and (2) time-to-stabilize (TTS). Global metrics characterize the magnitude of COP traces in the time and frequency domains. A large magnitude of any of these variables indicates a poor postural/balance stability (Paillard and Noé 2015). Whereas TTS refers to the duration required by an individual to recover from postural instability (Johnson et al. 2003). As such, a larger TTS indicates an increased risk of FAs (DiDomenico et al. 2016).

Three global metrics were chosen in this study to investigate the pre- and post-task standing stability. These metrics included COP mean velocity (in anterior-posterior (AP) and medio-lateral (ML) direction separately), total path length and 90% eclipse area. All of them are believed to be highly correlated to changes in COP (Prieto et al. 1996).

These metrics were calculated to identify the most appropriate parameter for future posture-induced standing instability studies. Prior to calculation of COP metrics, the raw force plate data was filtered using a second-order Butterworth filter with a cut-off frequency of 3 Hz. The global COP sway metrics for 20-second pre- and post-task upright stance were calculated as follow:

$$Mean\ Velocity_{AP} = \frac{\sum_{n=1}^{N-1} |AP[n+1] - AP[n]|}{t} \quad (1)$$

$$Mean\ Velocity_{ML} = \frac{\sum_{n=1}^{N-1} |ML[n+1] - ML[n]|}{t} \quad (2)$$

$$Total\ path\ length = \sum_{n=1}^{N-1} [(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2]^{1/2} \quad (3)$$

$$90\%\ eclipse\ area = \pi\chi_2^2 \sqrt{\lambda_1\lambda_2} \quad (4)$$

AP[n] and ML[n] are COP coordinates in AP and ML directions, respectively. n refers to nth value and N is the last value in the respective force plate dataset. t is the time duration for COP data collection. χ_2^2 is the chi-square cumulative distribution function with two degrees of freedom at 90% probability and $\lambda_1\lambda_2$are eigen values of sample variance-covariance matrix (Schubert and Kirchner 2014). Although pre-task standing stability was computed for each rebar tying posture, separate one-way repeated measures analyses of variance (ANOVA) revealed no significant temporal difference in any pre-task COP global metrics across all postures. This indicated that the 20-minute rest period between two rebar tying simulation tasks was sufficient to allow recovery from post-task standing instability, if any. Therefore, three pre-task stability values for each global parameter were averaged for subsequent comparisons with the respective post-task COP global parameter.

Post-task TTS (calculated separately for AP and ML directions) was estimated by calculating the time taken by COP to return to stable velocity. Stable velocity was defined as COP velocity lying within 3 times of standard deviations of the pre-task velocity within an epoch of 25 milliseconds identified using a moving window of 1ms. A customized MATLAB program (Version 2015a, MatchWorks, Inc., Natick, MA, USA) was used for all COP data processing.

Physical Measures

Respective muscle activity in the three rebar tying postures was compared using average muscle activations (50% amplitude probability function, APDF) (Umer et al. 2017b). The raw sEMG data was bandpass-filtered between 20 and 500Hz, notch filtered for the electrical noise of 50Hz, and smoothened using a 50ms root mean square (RMS) moving window. sEMG data was then normalized to the maximum sEMG signals during RCs (identified using 1000ms moving window and step size of 50ms) to enable within-subject comparison of various rebar tying postures (using 50% APDF) and represented as a percentage of RC maximum sEMG. Noraxon MyoResearch MR3.8 (Noraxon USA Inc., USA) software was used for sEMG data processing. Although sEMG data was collected bilaterally from target muscles, multiple paired t-tests with false detection rate (FDR, (Benjamini and Hochberg 1995)) correction revealed no significant difference between left and right side muscle activity for all rebar tying postures. Accordingly, left and right-side muscle activity data was averaged for further statistical analysis. Lower limb circulation data was expressed as average SpO_2 values (50% APDF) during each rebar tying posture.

Statistical Analysis

Separate one-way repeated measures ANOVAs were used to compare various averaged pre- and post-task COP global metrics, and TTS for the three postures. Rebar tying postures were chosen as between-group variable whereas various COP global metrics and TTS were the within-group variables. Paired t-tests with FDR correction were used for post-hoc pairwise comparisons. Similarly, separate one-way repeated measures ANOVAs and post-hoc paired t-tests (with FDR correction) were used to compare average muscle activity of different muscles and lower limb circulation across the three postures. All statistical analyses were conducted using SPSS (Version 19.0, IBM Corporation, Armonk, NY) software with significance level set at 0.05. Additionally, in order to examine the variability in standing stability metrics of individual participants, the between-participant differences in various baseline (pre-task) and standing balance stability metrics following different postures were visually inspected.

Results

Standing Stability Metrics

Repeated measures ANOVA revealed a significant difference among the pre- and post-task postural sway values for all global metrics ($p<0.01$), except the 90% eclipse area ($p = 0.09$) (Fig. 2). Post-hoc tests indicated that COP velocity in the AP direction and the total path length found significant differences in post-task postural controls among all rebar tying postures. Specifically, the squatting posture caused the worst post-task standing stability (as indicated by COP velocity in the AP direction and the total path length) while stool-sitting had no significant adverse effect on standing stability. However, COP velocity in ML direction could not discriminate any difference in post-rebar tying postural balance deficits between squatting and stooping postures (Fig. 2b). The COP 90% eclipse area also indicated a greater imbalance for post-squatting and post-stooping standing task than post-stool sitting but no significant difference was observed, which could be attributed to a large variance of data and a relatively small sample size. Overall, all global metrics indicated that pre-task upright standing had the least absolute postural sway, followed by post stool-sitting, post-stooping and post-squatting rebar tying.

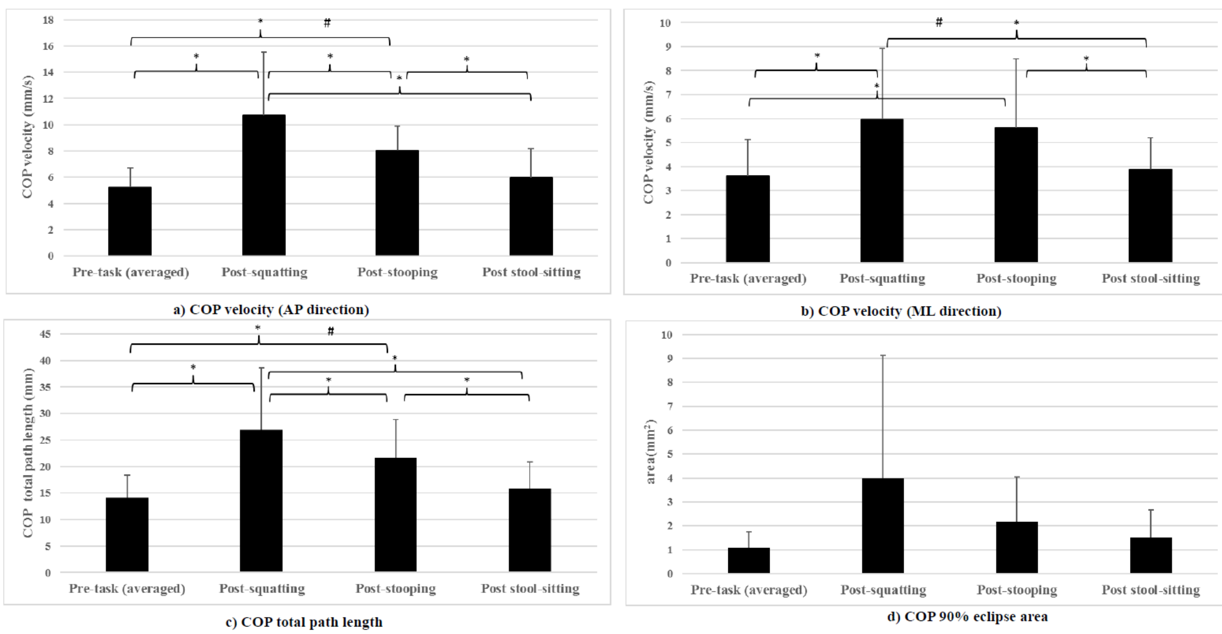


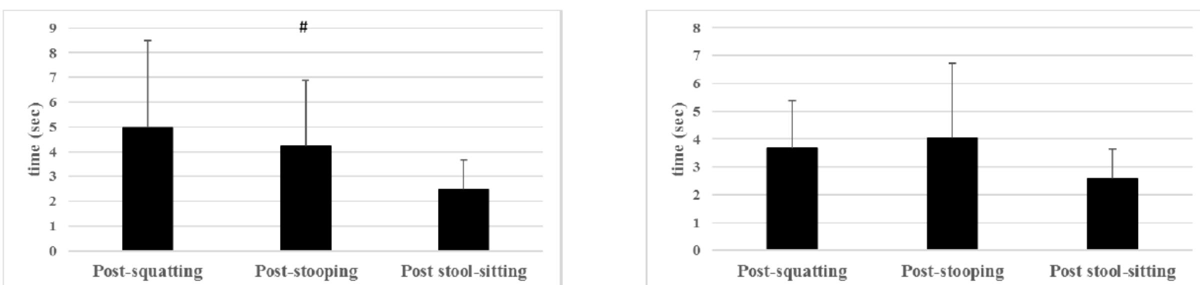
Fig.2. Pre- and post-task differences in upright standing stability

Note: # indicates significant results for one-way repeated measures ANOVA (analysis of variance); * indicates p < 0.05 for post-hoc paired t-tests (with FDR (false detection rate) correction); COP= center of pressure; AP= anterior-posterior direction; ML= mediolateral direction; bars indicate standard deviation

Although COP velocity in the AP direction and the total path length displayed similar statistical differences among various rebar tying postures (Fig. 2a and 2c), only the post-hoc test results of COP total path length are reported here to avoid unnecessary repetition of similar findings. Specifically, post-squatting COP total path length was significantly greater than pre-task, post-stooping and post-stool sitting postural sway values [mean differences were

12.8 mm (95% CI= 6.7 to 19.0 mm), 5.2 mm (95% CI= 0.9 to 9.5 mm) and 11.1 mm (95% CI= 5.6 to 16.6 mm), respectively]. While post-stooping standing demonstrated significantly larger COP total path length than the respective pre-task and post stool-sitting values [mean difference = 7.6 mm (95% CI= 3.4 to 11.9 mm) and 5.9 mm (95% CI= 2.7 to 9.2 mm) respectively], the difference between pre-task and post stool-sitting postural sway was non-significant, regardless of the COP sway parameter used.

Similar to global metrics, TTS also varied distinctly among the three postures (Fig. 3). The stool-sitting rebar tying task induced the smallest TTS on standing (2.5 and 2.6 seconds for AP and ML directions, respectively), followed by stooping (4.2 and 4.0 seconds) and squatting postures (5.0 and 3.7 seconds). One-way repeated measures ANOVA revealed a significant between-posture difference in TTS in the AP direction (p = 0.04). However, post-hoc pairwise comparison tests (with FDR correction) could not differentiate among various post-task TTS values, Specifically, TTS (AP direction) for post stool-sitting was 2.5 seconds shorter than post-squatting (p = 0.09) and 1.8 seconds shorter than post-stooping rebar tying (p = 0.07). The non-significant results might be attributed to a large variance in TTS values and a relatively small sample size (Fig. 3).



a) TTS (AP direction) **a) TTS (ML direction)**

Fig.3. Time-to-stabilize for various rebar tying postures

Note: # indicates significant results for one-way repeated measures ANOVA (analysis of variance); TTS= time to stabilize; AP= anterior-posterior direction; ML= medio-lateral direction; bars indicate standard deviation

Individual pre- and post-task postural sway (in terms of COP total path length) are shown in Fig. 4. Participants showed a large variation in pre-task total path length, ranging from 8.6 mm (participant 2) to 23.5 mm (participant 9). Post-task increase in baseline (pre-task) total path length for different rebar tying postures did not reveal a clear trend across participants. Some of the participants experienced a relatively smaller increase in post-task total path length, whereas the other depicted a much larger increase. Specifically, five participants (participant number: 4,6,8,9 and 10) exhibited a maximum post-rebar tying increase in COP total path length by 70% of averaged pre-task postural sway. Three participants (participant number: 1,5 and 11) showed a maximum post-task increase in total path length by 70% to 100% of the pre-task total path length, and four participants (participant number: 2,7,12 and 13) demonstrated a maximum increase of 100% to 150% in baseline COP total path length. Participant number 3 even exhibited a 300% increase in post-rebar tying COP total path length as compared to its baseline.

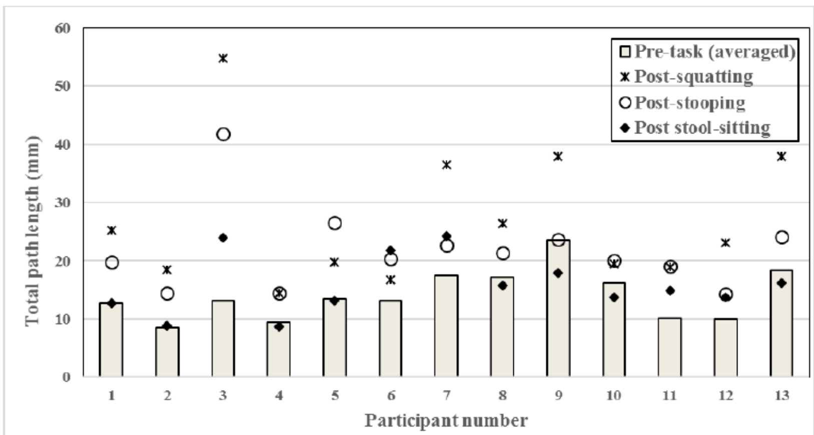


Fig.4. Post-task increase in total path length across the participants

Physical Measures

Normalized sEMG of the lower back and major lower limb muscles during rebar tying are shown in Fig. 5. Generally, the average muscle activity during the stooping posture was the largest regardless of muscle observed. One-way repeated measures ANOVA revealed a significant difference in sEMG activity among various postures for all muscles. Post-hoc tests revealed that sEMG of multifidus, gastrocnemius lateralis and gastrocnemius medialis during stooping were significantly larger than the respective values during squatting and/or stool-sitting (Fig. 5), while the sEMG activity of rectus femoris during stooping posture was significantly larger than that of stool-sitting posture.

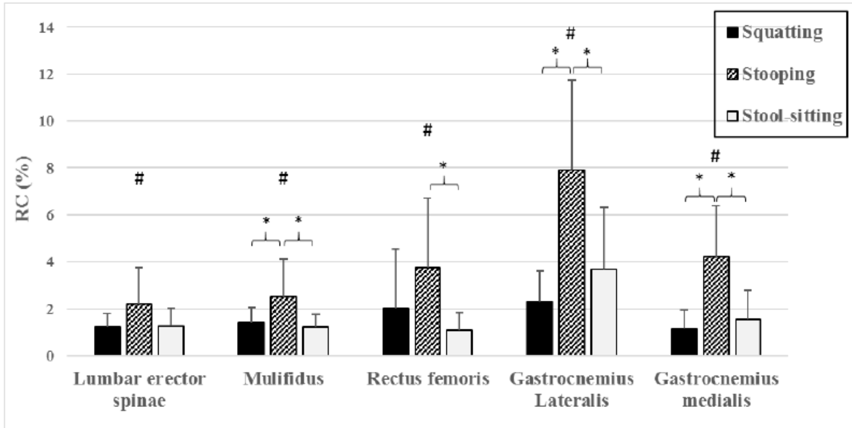


Fig.5. Average muscle activity (50% APDF) during rebar tying

Note: # indicates significant results for one-way repeated measures ANOVA (analysis of variance); * indicates p < 0.05 for post-hoc paired t-tests (with FDR (false detection rate) correction); RC= reference contraction; bars indicate standard deviation

One-way repeated measures ANOVA also showed that the average lower limb circulation (50% APDF of SpO_2 values) significantly differed across the three postures (p = 0.001) (Fig. 6). Specifically, the stooping and stool-sitting postures had significantly better blood circulation than squatting with the mean differences of 8.9% (95% CI= 3.6 to 14.1%) and 11.3% (95% CI= 4.3 to 18.2 %), respectively.

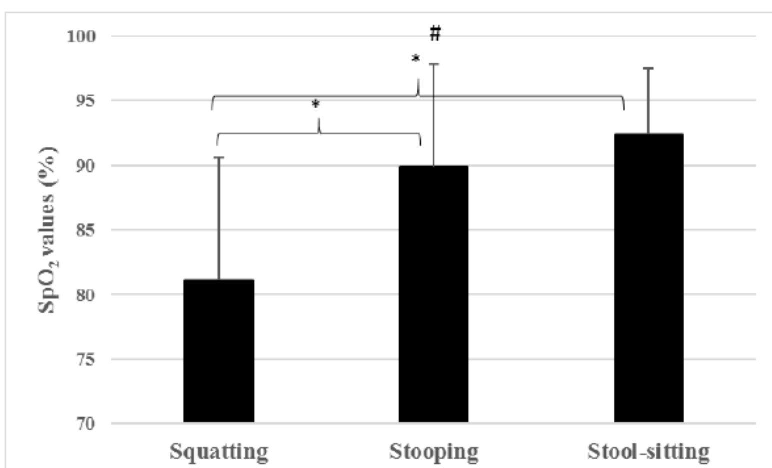


Fig.6. Lower limb circulation variation among rebar tying postures

Note: # indicates significant results for one-way repeated measures ANOVA (analysis of variance); * indicates p < 0.05 for post-hoc paired t-tests (with FDR (false detection rate) correction)

Discussion

From the management perspective, it has been suggested that what cannot be measured, cannot be managed (Cioffi 2006). In other words, the quantification of risk factors for FAs is essential for minimizing relevant occupational safety hazards. This study is the first one to quantify the standing balance ability following various prolonged rebar tying postures and to evaluate the effect of an ergonomic stool on reducing standing instability. The results highlighted that work postures could significantly affect post-task postural stability and a simple ergonomic intervention could minimize such adverse effects.

Effects of work postures on standing balance

The post-rebar tying stability metrics indicated that traditional work postures (squatting and stooping) induced significant increases in several COP global metrics, while the use of a sitting-stool significantly minimized the post-task postural sway (Fig. 2). Since an increased postural sway following a work task may indicate an elevated risk of falling (Pline et al. 2006), our findings substantiate the use of a simple ergonomic intervention during rebar tying to minimize the balance disturbance in rebar workers. Rebar tying is a labor-intensive construction trade, which largely depends on the manual execution of work tasks. These tasks may expose rebar workers to multiple risk factors of FAs (such as carrying heavy rebars or walking on the rebar mesh). Fortunately, rebar workers can modify their methods to perform their work so that better post-task standing postural control can be achieved. In fact, the modification of such human-factor or adoption of ergonomic based mitigation strategies have been suggested to be profoundly efficacious in reducing FAs in the construction industry (Robinovitch 2003).

The TTS results highlight the importance of standing balance recovery time after getting up from prolonged work postures (Fig. 3). Since multiple environmental factors (such as adverse environmental conditions, working on slopes and heights) at construction sites may increase the risk of FAs (Earnest and Branche 2016) by affecting TTS after finishing a work task, construction managers/foremen should be aware of these factors and provide rebar workers with ample recovery time prior to their involvement in another risky tasks (such as transporting heavy rebars). Importantly, this awareness should be imparted to frontline workers through education and training, which are known to be an effective and proactive forefront measure against FAs (Nadhim et al. 2016).

The great variability in pre- and post-tasks standing balance of participants (Fig. 4) implies variable risks of FAs for individuals. Since increased postural sway is an indicator of elevated risk of ankle sprains in the teenagers (Trojian and McKeag 2006) and falls in the older population (Piirtola and Era 2006), this might suggest that workers with larger baseline sway may be at a greater risk of FAs. Nevertheless, the pre-task postural sway may not necessarily predict the post-task sway. For example, Participant number 3, 5 and 10 demonstrated similar pre-task COP total path lengths (13.1 to 16.1mm) but their individual responses to rebar tying postures were very diverse. For instance, Participant number 10 showed a maximum increase of 24% in COP total path length after the stooping task, while Participant number 5 had a 96% increase in baseline COP total path length following the same task. Interestingly, the post-stooping COP total path length of Participant number 3 was 219% higher after post-stooping. These results signify the importance of examining individual outcomes alongside conducting group analysis for this type of balance studies. Collectively, despite the individual differences, it is generally agreed that a person with a larger post-task increase in postural sway is more likely to fall (Lin et al. 2009).

Physical changes compromise standing balance

Physical measures, as used in this study help better explain the distinct effects of various postures in affecting target muscles and blood circulation. In particular, a stooping posture was associated with significantly higher muscle activity in bilateral lower back, thigh and calf muscles as compared to squatting and stool-sitting postures (Fig. 5). As such, sustained work-task postures with large muscle activity could easily cause muscular discomfort, fatigue and post-transition loss of balance (Pline et al. 2006). Importantly, despite relative low activity of lumbar muscles during stooping (average activity ≈ 2% of RC sEMG), such low lumbar muscle activity can still cause neuromuscular fatigue. Mcgill et al. (2000) suggested that work tasks entailing exertion of lower back muscles as low as 2% of maximum voluntary contraction can elicit fatigue after sustained for a long duration, which in turn may induce postural instability during standing (Lin et al. 2009). Moreover, transitioning from a sustained stooping work posture (involving tilting and non-neutral head postures) to a standing posture may compromise the ability of the vestibular system to anticipate the orientation of gravity (Paloski et al. 2006), making a rebar worker more vulnerable to FAs.

Contrary to stooping, squatting rebar tying posture involves significantly less muscle activations in the lumbar and calf muscles (Fig. 5) and does not require full trunk flexion as required in stooping. However, opting for a squatting posture during rebar tying can significantly compromise the blood circulation in the lower extremities (Fig. 6). Reduced blood circulation in the muscles is linked to poor muscle endurance and an increased rate of muscle fatigue (Hepple 2002). Besides, decreased blood circulation in the legs can adversely affect joint proprioception that decreased standing balance (DiDomenico et al. 2010). In short, prolonged squatting may leave rebar workers more susceptible to FAs.

On the contrary, working in stool-sitting posture has multiple physical advantages over traditional rebar tying postures. It involves significantly less muscle activity for both trunk and leg muscles as compared to stooping (Fig. 5) and better lower limb circulation as compared to squatting (Fig. 6). These physical responses might explain the non-significant changes in the post-task postural sway (Fig. 2) and minimum TTS (Fig. 3) as compared to other rebar tying postures.

Implications

Safety against construction FAs demands a comprehensive set of strategies. Current onsite fall protection measures rely on the use of passive protection systems. In many instances, these measures are either nonpragmatic or unavailable (Hsiao and Simeonov 2001; Kang et al. 2017), leaving construction workers vulnerable to FAs. To better prevent FAs, conventional protection methods should be supplemented with some proactive measures such as Prevention through Design (PtD). The PtD concept involves identification of safety hazards during the design phase of construction activities and taking proactive measures to counter/avoid safety hazards (Dewlaney and Hallowell 2012). Aside from early diagnosis of various safety hazards, PtD should also include management of anticipated fall risk factors (task, environment and person related) such as prolonged awkward work postures during rebar tying. Essentially, as this study persuasively shows that the PtD concept can be used to improve the design of construction activities and ultimately reduce the number of accidents.

Limitations and Future Works

Although the current study has deepened the knowledge pertaining to potential loss of balance among rebar workers, there are some limitations that should be addressed in future studies. First, participants involved in the current experiment were inexperienced rebar workers. Accordingly, future research is warranted to compare the findings in experienced rebar workers. Second, this experiment only tested a single duration of rebar tying postures. Future studies should evaluate the impacts of different time durations of work postures on the resulting standing balance of rebar workers. Collectively, the results from these studies may help design proper work-rest schedule to avoid substantial fatigue and/or loss of balance, which may lead to FAs (Pline et al. 2006). Third, the current study only explored the effects of various rebar tying postures on static balance. Future studies should explore how dynamic balance is affected by prolonged working postures.

Fourth, while exploratory studies are essential to identify individual risk factors for FAs, the importance of their interactions cannot be downplayed. Multiple risk factors could present simultaneously at a typical construction site. In fact, FAs are barely the consequence of a single risk factor (Dekker et al. 2011). Hence, future studies should explore FAs from a holistic approach by investigating multiple risk factors simultaneously (i.e. task, environment and personal factors). Lastly, while many FAs on construction sites have been attributed to loss of balance (Hsiao and Simeonov 2001), no quantitative tool has been developed to quantify the baseline and post-task/post-work shift postural stability of construction workers onsite. Although force plates which have been widely used in laboratory-based studies to evaluate standing balance, it is not feasible to use force plates at construction sites given their substantial weight and other requirements (such as allied electronic/power equipment, leveled and firm surfaces for measurements). As such, new tools should be developed to measure onsite postural stability of the construction workers in different times of the day and under different circumstances. This may enable early identification of workers with poorer postural control, and the prescription of tailor-make postural control exercises or balance training measures for these workers.

Conclusions

The current study highlighted that conducting rebar tying in conventional work postures (squatting and stooping) significantly impaired static standing balance, which might be attributed to prolonged recruitment of back and leg muscles in the stooping and reduced blood circulation to legs in the squatting posture. Compared to stooping or squatting, the adoption of an ergonomic intervention (stool-sitting) significantly improves lower limb circulation, reduces back and leg muscle activities during rebar tying, and improves post-rebar tying standing balance. Since different individuals have different balance recovery time after sustained work postures, future research should investigate optimal resting time before taking part in other risky tasks to avoid the risk of FAs. Importantly, given high interpersonal variability in both pre- and post-task standing stability, future works should focus on the development of individualized balance monitoring systems to proactively identify workers with poor pre- and post-task standing balance so as to provide tailor-make preventive measures. Meanwhile, simple validated functional balance tests (e.g. Start Excursion Balance Test) can be used to identify workers with balance deficits. Regular balance training exercises and biofeedback based devices can be adopted to improve rebar workers' balance ability. Collectively, the current study applied prevention through design concept to identify and mitigate task-specific fall risks of rebar workers and has demonstrated the usefulness of safety informatics in improving our understanding of various aspects of balance monitoring for proactive measures against FAs.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request.

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