A low cost ergonomic intervention for mitigating physical and subjective discomfort during manual rebar tying

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Abstract

The construction industry around the globe is facing a massive predicament of work-related musculoskeletal disorders (MSDs), largely attributed to the excessive physical exertion at worksites. While ergonomic interventions are suggested to be an effective approach to mitigate such routine exertion, these ergonomic interventions should be task specific given the unique characteristics of each trade (such as rebar work; a construction trade with a high prevalence rate of MSDs). Despite numerous potential interventions available for rebar workers, none of them have been widely adopted, especially in the Asian market. After considering various reasons impeding their broad usage, the authors coined a simple ergonomic solution by attaching a low height domestic stool to the pants of rebar workers. This would allow them to sit and work instead of squatting, which is the most preferred posture in Asian cultures for working at ground level. The novel intervention was tested against squatting for various physical outcomes (i.e. muscle activity, neuromuscular fatigue, trunk kinematics and lower extremity blood circulation) and self-perceived discomfort, using a simulated rebar tying task in a laboratory. These findings demonstrate that the intervention has beneficial effects on both physical and subjective outcomes, and has a great potential in reducing work-related MSDs among Asian rebar workers. Additionally, the current study highlights that ergonomic interventions in the construction industry should be derived based on both the characteristics of specific construction trades and culture of workers.

Keywords

Construction ergonomics; Rebar tying; Occupational safety and health; Biomechanical evaluation

Introduction

Work-related Musculoskeletal disorders (MSDs) are a substantial burden on the construction industry. A recent systematic review (Umer et al. 2017a) found that more than 50% of the construction workers suffer from symptoms of low back MSDs annually around the globe. The review also noted that approximately one-third of the construction workforce face symptoms of knee, shoulder and wrist MSDs. These MSDs impose substantial direct and indirect costs (Lehtola et al. 2008), work absenteeism (Rinder et al. 2008), schedule delays and lost time claims to the industry (Inyang et al. 2012). Multiple studies have reported the high direct and indirect costs of traumatic and non-traumatic MSDs in the construction industry (Pandey et al. 2012), including loss of productivity (van der Molen et al. 2009), increased insurance premium (Inyang et al. 2012) and permanent disability (Welch et al. 2009). During the year 2014, MSDs resulted in one-third of all work absenteeism related to illness and injuries in the US construction industry (BLS 2015). In Canada, Alberta Construction Safety Association reported that 41.9% of all accepted lost time claims and 46.8% of total injury claims were related to MSDs in 2008 (ACSA 2009).

Work-related MSDs among construction workers are highly related to physically demanding work tasks (Cheng et al. 2013), which exposes these workers to numerous ergonomic risk factors. These risk factors include heavy lifting and carrying, jerky movements, vibrations, and repetitive works in prolonged awkward work postures (Buchholz et al. 1996; Forde and Buchholz 2004; Umer et al. 2017b; Welch et al. 2009). These factors overload the workers` musculoskeletal system and increase the workers` vulnerability to work-related MSDs (Inyang et al. 2012). By reducing or eliminating these risk factors, the propensity of work-related MSDs can be controlled. It is generally agreed that effective technological and ergonomic interventions are crucial for the mitigation of prevalent MSDs in the construction industry (Lehtola et al. 2008; Rinder et al. 2008). However, since each construction trade has a unique set of tasks that may expose the workers to specific ergonomic risk for certain MSDs (Choi et al. 2014), ergonomic interventions should be task specific (Wang et al. 2015; West et al. 2016).

Among workers in different construction trades, rebar workers are highly vulnerable to MSDs because of their task contents (Ontario data:1994-1998; Schneider and Susi 1994; Silverstein and Kalat 1999). In particular, manual rebar workers frequently need to bend forward in stooping or squatting posture in order to tie reinforcement bars with metal tie-wires on the floor (Dababneh et al. 2000). Observational ergonomic studies have revealed that rebar workers remain in non-neutral trunk postures for up to 58% of the workday when they opt for stooping (Buchholz et al. 2003; Forde and Buchholz 2004; Saari et al. 1978). A recent biomechanical study also found that rebar tying in a stooping posture led to flexion-relaxation phenomenon of lower back, which deactivates back muscles and may result in increased loading stress on passive torso tissues (e.g. ligaments or facet joint capsules) (Umer et al. 2017b). As such, prolonged and repetitive highly flexed trunk posture is known to be a risk factor for back MSDs (Garg 1992; McGill and Kippers 1994; Neumann et al. 1999). In Asian culture, squatting is preferred to stooping for rebar tying (Chung et al. 2003; Jung and Jung 2008). In such posture, lower extremities are subjected to surge in postural load (Buchholz et al. 1996; Genaidy et al. 1994). Since squatting increases the contact pressure at knees at the end-range of knee flexion, this biomechanical factor can increase the risk of knee MSDs (Kivimäki et al. 1992; Thun et al. 1987). Additionally, squatting posture may affect the blood circulation of lower extremities (Basmajian and Deluca 1985), which may cause discomfort or compromise functional performance of workers. Given that many postural-related physical risk factors are modifiable, task-specific ergonomic interventions should be implemented (Forde et al. 2005; Vi 2003) to alleviate the high physical workload of manual rebar tying.

To reduce physical workload of the trunk and knees during rebar tying, different commercially available wearable ergonomic devices may be used although the adoption rate is low (Weinstein et al. 2007). These ergonomic interventions include, but are not limited to, Bending Non-Demand Return (BNDR) (Ulrey and Fathallah 2013), Happyback (ErgoAg Company, Aptos, CA) and Personal Lift Assist Device (PLAD) (Lotz et al. 2009). These exoskeletons provide anti-gravity moment to reduce trunk muscular workloads. Although these devices were primarily designed for the agriculture and manufacturing industry rather than the construction industry, the inventors claim that these devices can be used in other physically demanding jobs (e.g. rebar tying) (Ulrey and Fathallah 2013). However, rebar workers rarely use these devices (especially those working in the fastest growing Asian construction market, Horta et al. 2013). To understand the reasons for not adopting these interventions by Asian rebar workers, one of the authors (WU) interviewed four veteran construction project managers in Hong Kong, who have been working in the Asian industry for at least 20 years. These managers were chosen because their experience in project management and their knowledge on construction work-site characteristics, workers` behavior, work demands of construction tasks enabled them to provide comprehensive and pragmatic overview on our interested issues. The interviews revealed several reasons for the reluctance in adopting ergonomic interventions in the industry: inability to use these devices in squatting, high cost, difficulty in handling and storing these tools, and difficulty in repairing and maintenance. Importantly, rebar workers dislike wearing any ergonomic tools that irritate their body parts during the hot and humid season, which is common in Asia.

To reduce the physical discomfort of Asian workers during rebar tying in squatting, it is essential to develop a low cost and comfortable wearable ergonomic tool. To this end, the authors derived an idea of attaching a stool (10 to 15 cm height) to the pants of rebar workers using self-adhesive Velcro straps (Fig. 1). This inexpensive tool allows the workers to work in a low sitting posture instead of squat. Having discussed with the interviewed project managers, they unanimously supported the use of this pragmatic tool. Accordingly, the objective of the present study was to compare the physical and subjective responses of asymptomatic individuals during simulated rebar tying in low sitting and squatting. The findings might have a great potential to improve the health and practice of rebar workers.

[Fig. 1]

Methods

Participants

To evaluate the effectiveness of the "squatting-stool" for rebar tying, fourteen healthy male participants aged between 18 and 40 years were recruited. The exclusion criteria were a previous history of cardiac and pulmonary disorders, current disability of lower back and lower extremity (identified using modified Oswestry Disability Index scores > 20%, Wong et al. 2015), and inability to rate discomfort using self-perceived discomfort ratings (Gescheider 1985; Han et al. 1999). The experimental procedures were approved by the Human Research Ethics Committee of The Hong Kong Polytechnic University.

Experimental Procedure

The current experiment adopted a randomized crossover study design in a single visit. Following the detailed explanation of the experiment, written consent was sought from eligible participants. While surface electromyography (sEMG) was used to measure trunk and leg muscle activity, motion sensors and oximeter were used to monitor trunk movement and leg blood circulation, respectively. Prior to the simulated rebar tying task, participants performed a series of reference isometric contraction (RIC) tests of trunk and leg muscles in order to estimate the post-task muscle fatigue (Fig. 2). Participants were then randomly assigned to perform the simulated rebar tying task for 12.5 minutes in one of the two postures: (1) squatting; and (2) low sitting (stool-squatting). Participants needed to report their self-perceived discomfort every 2.5 minutes throughout the rebar tying task. Participants underwent the RIC tests immediately after the task to evaluate muscle fatigue. Thereafter, participants were given a 20-minute sitting break before repeating the entire testing procedures with the untested posture.

[Fig. 2]

Reference Isometric Contractions (RICs)

Each participant performed three 5-second RICs involving the lower back, thigh and calf muscles. A 5-second rest was given between contractions (Lotz et al. 2009). The primary purpose of the RIC test was to compare post-task changes in median frequency (MF) of sEMG signals of different muscles, where decrease in MF indicated muscle fatigue (as explained in the section *Muscle Activity* below). Secondly, the amplitude of sEMG signals of different muscles during the pre-task RIC test was used to normalize the respective sEMG signals collected during the simulated rebar tying task (see below).

The RIC test of lower back muscles involved a modified Sorensen test (Coorevits et al. 2008; Dedering et al. 2000; Mannion and Dolan 1994). Specifically, the participant laid prone on a bench such that his upper body was unsupported (i.e. outer border of the anterior iliac crest was at the edge of the bench) (Fig. 3a). The participant was instructed to keep his hands touching his ears with elbows out to the side at the same level as the trunk, during the test. An examiner fixated the participant’s legs during the test.

[Fig. 3]

To perform RIC test of the thigh muscles, the participant was instructed to perform three forward lunges with alternative legs (Pincivero et al. 2000). The participant should keep his back straight, arms beside the body, and the non-lunging (rear) knee slightly off the ground during the lunges (Fig. 3b). The lunge distance of each participant should be equal to the distance between the anterior superior iliac spine and the respective medial malleolus.

The RIC test of calf muscles involved the performance of an alternative heel rise of each leg (Kasahara et al. 2007; Österberg et al. 1998). The participant raised his heel off the ground (Fig. 3c) while he could touch his index fingers slightly against a wall for balance.

Simulated Rebar Tying

The simulated rebar tying tasks could be performed with or without a stool. To meet individual comfort, participants could choose a plastic stool, either 10cm or 15cm high. Although the originally planned duration of rebar tying task was 20 minutes, the pilot testing on two participants revealed that participants requested to stop the task before the stipulated time due to extreme discomfort. As such, the duration of rebar tying was shortened to 12.5 minutes in each posture. 12.5 minutes was chosen because it was a multiple 2.5 minutes (the time interval for evaluating self-perceived discomfort ratings).

The simulated rebar tying was conducted on a mesh of 5 by 5 plastic pipes of 1.2m length, separated from each other by a center-to-center distance of 20cm as described elsewhere (Umer et al. 2017b). Participants were instructed to repetitively tie rebar using pigtail tool and tie-wires in the first three rows of the simulation setup unless the stipulated time had elapsed. To evaluate the effects of prolonged squatting/low sitting posture on the participant's physical responses, the participant was not allowed to significantly alter the body posture and position (e.g. standing up). However, slight movements were allowed to accomplish the task.

Measurements

a. Muscle Activity

The trunk and leg muscle activity was measured by a 16-channel wireless surface electromyography (sEMG) system (TeleMyo, Noraxon USA, Arizona). Five pairs of muscles were evaluated including bilateral lower back muscles (lumbar erector spinae at the L3 level, and lumbar multifidus at the L5 level), bilateral anterior thigh muscles (rectus femoris) and bilateral calf muscles (gastrocnemius lateralis and gastrocnemius medialis). Surface electrodes were adhered to target muscle locations as recommended by *Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles* (SENIAM, 2005, Fig. 4). Standardized skin preparation (including shaving, abrading with sandpaper and cleaning with alcohol swabs) was performed on the target sites to ensure the skin impedance below 10kΩ. Disposable bipolar electrodes with a diameter of 15mm and an inter-electrode distance of 20mm were used. The sampling rate and common mode rejection ratio were 1,500 Hz and 100 dB, respectively. The sEMG activities of all muscles during RIC tests and rebar tying tasks were measured.

[Fig. 4]

Muscle fatigue secondary to rebar tying was estimated from the decrease in MF of sEMG signals during the RIC tests before and after the task (Basmajian and Deluca 1985; Mannion and Dolan 1994; Potvin and Norman 1993). This method has been widely used in biomechanical studies to quantify neuromuscular fatigue of lumbar (Coorevits et al. 2008; Mannion and Dolan 1994), thigh (Longpré et al. 2015; Pincivero et al. 2000) and calf muscles (Kasahara et al. 2007; Wim Ament et al. 1993) during functional tasks.

b. Trunk Kinematics

Spinal movements during the rebar tying task were captured by the MyoMotion system (Noraxon USA, Arizona). Three motion sensors were placed at the T4, T12 and S1 spinous processes (Fig. 4). The spinal segment between T4 and T12 was defined as the thoracic spine whereas the segment formed between T12 and S1 sensors was determined as the lumbar spine. Motion data was sampled at 100 Hz. An examiner first guided each participant to maintain an erect standing posture, where the thoracic and lumbar angle was calibrated as zero degree. The trunk segmental flexion angle measured during rebar tying were referenced to this calibration.

c. Lower Extremity Blood Circulation

Blood circulation in the lower extremities was indirectly quantified by measuring the oxygen saturation level (SpO_2) in arterial blood using an oximeter. A perfusion resistant sports grade oximeter (MightySat Pulse Oximeter 9900, Masimo Corporation, Irvine, CA) was placed on the right big toe and data was collected at a rate of 0.5 Hz. The big toe was cleaned by alcohol swabs prior to placing the oximeter for continuous monitoring of SpO_2 levels during rebar tying.

Initially, this measurement was not planned in the experiment. However, during the pilot trial on two participants, they complained of numbness in their legs after a few minutes of squatting. As squatting posture is known for decreasing blood circulation in lower extremities (Basmajian and Deluca 1985), the leg numbness experienced by the participants might be associated with compromised blood circulation (Ogata and Whiteside 1982; Skobelkin et al. 1990), As such, blood circulation measurement was added in the current study.

d. Self-perceived Discomfort

The subjective perceived discomfort of each participant was measured by the method of Magnitude Estimation. Magnitude Estimation has been widely used to estimate perceived discomfort in psychophysical research (Chung et al. 2003). In the current study, participants utilized whole numbers to rate discomfort levels in various parts of the body (lower back, upper legs, lower legs, and whole body) every 2.5 minutes. The participants chose any arbitrary number (such as zero) to express their discomfort at the beginning of each task. As the task continued and the discomfort increased, the participant could continue to report higher numbers (such as 40, 50, 100 and so on) at each time point, to indicate the heightened self-perceived discomfort (Han et al. 1999). To compare the discomfort rating among participants, min-max normalization was used where minimum and maximum discomfort values were used as references for normalization (Chung et al. 2003). The normalized self-perceived discomfort was calculated as follow

$$PD_{ij} = \frac{x_{ij} - Min_j}{Max_j - Min_j} \times 100\%$$

where PD_{ij} is the normalized self-perceived discomfort rating for i^{th} reading of the j^{th} participant, x_{ij} is the non-normalized i^{th} discomfort rating for the j^{th} participant, Min_j and Max_j are minimum and maximum discomfort rating perceived by the j^{th} participant throughout the experiment.

To evaluate the participant's capability in making correct ratio judgments for Magnitude Estimation, two protocols of "line production" and "numerical estimation" were used. For "line production", the participant was instructed to draw seven lines with appropriate lengths to represent seven given random numbers. For "numerical estimation", the participant was asked to estimate the length of seven presented lines (Chung et al. 2003). Separate linear regression analyses were performed for the two protocols by logarithmic plotting of the information provided by the examiner (i.e. random numbers or the length of lines) versus the corresponding participant's responses (Han et al. 1999). If the slopes (i.e. regression coefficients) of the two lines of a given participant were not significantly different from the value of 1.0 (Gescheider 1985), the participant was deemed to be able to make correct ratio judgements. Elsewise, the corresponding data was not included in data analysis.

Data Processing

Noraxon MyoResearch MR3.8 (Noraxon USA Inc., USA) software was used for all sEMG signal processing. Raw sEMG data during rebar tying were filtered to remove electrocardiography signals using adaptive filter methods, bandpass filtered at 20-500 Hz, notched filtered at 50 Hz to remove electrical noise, and then smoothen using 50 ms root mean square (RMS) moving window (Xie et al. 2015). The maximum sEMG signal of a given muscle during the pre-task RIC test was identified by applying a moving window of 1000ms with a step size of 50ms to the sEMG signals. To enable between-participant comparison, the sEMG data of each muscle recorded during rebar tying was normalized to and expressed as the percentage of the respective maximum sEMG signal at the pre-task RIC test (%RIC).

Amplitude Probability Distribution Function (APDF) was used to compare the muscle activity in the two rebar tying postures. Specifically, 50% APDF was used to indicate average muscle activity during the rebar tying task (Xie et al. 2015). Although sEMG data were captured from both sides of muscles, paired t-tests with false detection rate (FDR, see below) correction revealed no significant difference in the amplitude of sEMG signals from both sides of any given muscle. Therefore, left and right side values were averaged for further statistical analysis.

To calculate MF from a raw sEMG power spectrum, each 5-second RIC test was divided into five 1-second segments (without overlapping). A Hanning window was applied to the sEMG signals of each 1-second segment followed by the calculation of MF using Fast Fourier Transformation. The five MF values during each RIC test were averaged to obtain a single MF value (Lotz et al. 2009). As three repetitions of RIC tests were performed for each muscle, MF values of these three RIC tests were averaged for subsequent statistical analysis (Lotz et al. 2009). The post-task MF value of each muscle was then normalized to pre-task MF values (considered as 1.0) to identify fatigue.

Spinal movement data from the motion sensors were smoothened using Kalman filter prior to statistical analysis. The average thoracic, lumbar, and total trunk flexion angles at 50% APDF of the two rebar tying postures were compared. Blood oxygen saturation (SpO_2) values obtained through oximeter were unfiltered. The temporal changes in SpO_2 values between the two rebar tying postures were estimated from the differences in SpO_2 values at 10%, 50% and 90% APDF.

Statistical Analysis

Table 1 summarizes various statistical tests conducted on different variables of interest in the current study. Multiple paired t-tests with false detection rate (FDR) correction were used to compare the between-posture difference in the average sEMG activity (50% APDF) of various muscles. FDR was chosen instead of the overly conservative Bonferroni adjustment because it was more suitable for multiple comparisons (Benjamini and Hochberg 1995; Lotz et al. 2009). One-way repeated measures analyses of variance (ANOVA) were used to explore the differences in the normalized pre- and post-rebar tying MF values. Rebar tying postures were chosen as the independent variable, whereas pre- and post-task MF values were the dependent variables. Post-hoc tests involved paired t-tests with FDR correction. Similarly, the differences in the spinal flexion angles and SpO_2 values between the two rebar tying postures were analyzed by multiple paired t-tests with FDR correction. Two-way repeated measures ANOVA was used to investigate the effect of time and stool condition (independent variables) on the normalized self-perceived discomfort ratings (dependent variable). Significant main effects were explored by using paired t-tests. SPSS (version 19.0, IBM Corporation, Armonk, NY) software was used for the statistical analysis with significance value set at $p < 0.05$.

[Table 1]

Results

The fourteen participants (including two participants in the pilot testing) had a mean age of 27.6 years (SD ± 4.2 years, 10 participants aged between 20 and 29 years and 4 participants aged between 30 and 39 years) and BMI 22.7 kg/m^2 (SD ± 1.5 kg/m^2). The mean and standard deviation of the participants' Oswestry Disability Index score was 2.3 ± 4.0%. All participants chose the stool with a height of 15 cm. When tested, all participants were found able to make correct ratio judgements.

Muscle Activity

Fig. 5 demonstrates the normalized 50th percentile sEMG amplitudes of the various muscles (along with standard deviations) during rebar tying in the two postures. The average sEMG activities of different muscles during rebar tying varied between 1.2% and 3.8%RIC. The lumbar muscles tended to show the least activity whereas gastrocnemius lateralis muscles showed the highest magnitude of activity.

[Fig. 5]

Lower back muscles (i.e. lumbar erector spinae and multifidus) and the calf muscle - gastrocnemius medialis exhibited no significant difference in activity during rebar tying in the two postures. The thigh muscle, rectus femoris, tended to have a higher absolute muscle activity in the squatting posture as compared to stool-squatting (a mean difference of 1.6%RIC, p=0.12). On the contrary, gastrocnemius lateralis muscles showed significantly higher muscle activity during stool-squatting rebar tying than squatting rebar tying task [mean difference = 1.6%RIC (95% CI = 0.1 to 3.1%RIC)].

The pre- and post-task changes in normalized MF in the two rebar tying postures are depicted in Fig. 6. Depending on the muscles, there were variations in post-rebar tying MF values (ranging from a decrease of 4.3% in right lumbar erector spinae after stool-squatting to an increase of 3.9% in right gastrocnemius lateralis after squatting rebar tying). However, one-way repeated measures ANOVA revealed no significant temporal changes in pre-task, post-squatting, and post-stool-squatting MF.

[Fig. 6]

Trunk Kinematics

The average total trunk flexion angles at 50% APDF were 57.3º and 66.0º for rebar tying with and without stool, respectively (Fig. 7). For both rebar tying postures, the average total trunk flexion angles were mainly contributed by lumbar flexion (average values of 43.0º to 48.8º), whereas thoracic flexion only contributed to less than 18º in both postures. Squatting demonstrated significantly larger thoracic, lumbar, and total trunk flexion angles as compared to stool-squatting rebar tying. Specifically, the mean difference was 3.0º for thoracic flexion (95% CI = 0.2º to 5.7º), 5.8º for lumbar flexion (95% CI = 1.3º to 10.3º) and 8.7º for total trunk flexion (95% CI = 5.6º to 11.9º).

[Fig. 7]

Lower Extremity Blood Circulation

Fig. 8 depicts the lower extremity SpO_2 values at 10%, 50% and 90% APDF of the two rebar tying postures. The SpO_2 values varied from 73.9% to 96.8%. Regardless of the APDF percentile chosen for the comparison, rebar tying using the stool demonstrated significantly larger SpO_2 values than rebar tying in squatting. Specifically, the mean difference in SpO_2 values for 10%, 50% and 90% APDF of the two rebar tying postures was 13.2% (95% CI = 5.2 to 21.2%), 10.6% (95% CI = 4.1 to 17.2%) and 7.1% (95% CI = 1.2 to 12.9%), respectively.

[Fig. 8]

Self-perceived Discomfort

Two-way repeated measures ANOVA revealed significant interaction between stool condition and time ($p < 0.01$, Table 2) for various body parts (i.e. lower back, upper legs, lower legs, and whole body) examined in this study. Post-hoc tests revealed that the use of a stool yielded significantly lower (better) self-perceived discomfort ratings of all aforementioned body parts as compared to squatting. These differences began from the first 2.5 minutes to the end of the task (Fig. 9). The maximum difference in the normalized self-perceived rating for rebar tying with and without stool was noted at lower legs toward the end of experiments [mean difference = 65.1% (95% CI = 50.8 to 79.3%)]. On the other hand, there was minimum difference in lower back discomfort at the end of the tasks [mean difference = 23.9% (95% CI = 10.0 to 37.9%)]. For upper legs and whole body, normalized self-perceived discomfort ratings at end of the experiments varied in two rebar tying postures with a mean value of 44.5% (95% CI = 33.3 to 55.6%) and 53.9% (95% CI = 40.1 to 67.6%) respectively (Fig. 9).

[Fig. 9]

[Table 2]

Discussion

The current results indicate that multiple biomechanical and physiological measurements are necessary to understand physical demands of occupational work tasks comprehensively. Specifically, the two rebar tying postures elicited comparable muscle activity and muscle fatigue in back and lower limb muscles. However, trunk kinematics, blood circulation and self-perceived discomfort significantly differed between the two postures. Importantly, the current findings suggest that a small change in work practice may bring significant ergonomic benefits.

Muscle Activity

The normalized average sEMG amplitude of various muscles during simulated rebar tying indicated that the tasks did not involve extensive muscle activity irrespective of the adopted posture (i.e. muscle activity was less than 4%RICs in all muscles) (Fig. 5). However, this does not imply that such small muscle activity cannot induce neuromuscular fatigue. Literature suggests that tasks involving sustained contractions as low as 2% of maximum voluntary contraction in the lumbar erector spinae muscles can significantly decrease tissue oxygen levels, and cause muscle fatigue that may lead to work-related MSDs in the long run (McGill et al. 2000). Further, the comparison of muscle activity in the two rebar tying postures reveals a tradeoff between the thigh and calf muscles. Specifically, rectus femoris muscles showed larger average activity in the squatting posture whereas gastrocnemius lateralis muscles were more active during stool-squatting rebar tying. These results concur with those from Sriwarno et al. (2007) who also reported this shift in thigh and calf muscle activity between squatting and stool-squatting postures for a paper cutting task. Unfortunately, Sriwarno et al. (2007) did not investigate the neuromuscular fatigue and blood circulation of lower limbs, which might improve the understanding of differences in biomechanical and physiological demands of lower extremities in the two postures. Further, the negative MF findings suggest that both rebar tying tasks did not induce neuromuscular fatigue of lumbar and calf muscles (Fig. 6). It indicates that the increases in self-perceived discomfort following the rebar tying task (especially in the squatting posture) may be unrelated to local muscle fatigue of lower extremities.

Trunk Kinematics

The use of a stool during stool-squatting rebar tying helped reduce the average total trunk flexion angle by approximately 9º as compared to squatting (Fig. 7). This ergonomic tool helps restore the trunk flexion angle back to the limit (60º) recommended by the international organization for standards (ISO) for static working postures [ISO 11226:2000 (*ISO 2006*)]. Sriwarno et al. (2007) also reported a decrease in trunk flexion after using a stool for a paper cutting task as compared to squatting posture. However, their findings could not be directly compared with the present study given the discrepancy in the definitions of "trunk" in the two studies. Despite significant reduction in the total trunk flexion angle in the current study, no significant differences in the muscle activity or normalized MF values of lower back muscles between the two rebar tying postures were observed. This finding may be attributed to the flexion-relaxation phenomenon which involves myoelectric silence of lumbar paraspinal muscles when asymptomatic individuals maintain an almost fully flexed lumbar spine (McGill and Kippers 1994; Shirado et al. 1995). Literature suggests that such silence in lower back muscle activity starts at around 50º of trunk flexion (Solomonow et al. 2003). With the mean trunk flexion angle of > 55º and lower back muscle activity of < 1.5%RIC in the current study, the flexion-relaxation phenomenon might occur during both rebar tying tasks. The notion is further supported by previous studies that found a significant decrease in paraspinal muscle activity during passive sitting postures (i.e. slump sitting) as compared to active sitting (Sullivan et al. 2002, 2006).

Lower Extremity Blood Circulation

To the knowledge of the authors, no prior study has compared the lower extremity SpO_2 levels between the two rebar tying postures. The significantly higher SpO_2 values of legs during stool-squatting rebar tying as compared to squatting (Fig. 8) indicate a potential temporary ischaemia of lower extremities in the squatting posture. As a result, this may reduce the oxygen supply (local hypoxia) to skeletal muscles which is necessary for their normal functioning. It is well known that reduced oxygen supply to muscle tissues can adversely affect human muscle performance (e.g. increased rate of muscle fatigue, and decreased time to exhaustion and muscle numbness (Chung et al. 2003; Cymerman et al. 1989; Hepple 2002)). The local hypoxia of lower limb muscle during squatting rebar tying might explain the significant temporal increases in self-perceived discomfort during the squatting rebar tying despite the absence of decreases in MF values. It also explains the lower self-perceived discomfort during stool-squatting rebar tying given the better blood circulation of lower extremities.

Self-perceived Discomfort

As aforementioned, the difference in self-perceived discomfort in the two postures could be associated with differential decreases in blood circulation in lower extremities. Additionally, different body weight transfer mechanisms might explain the difference in self-perceived discomfort ratings. Sriwarno et al. (2007) revealed that using a stool in squatting could significantly reduce the feet-ground reaction force up to 25% by providing an alternate path for body weight transfer through a stool. Overall, these findings substantiated that the effect of stool significantly decreased the self-perceived discomfort rating and this beneficial effect became more obvious as time elapsed (Fig. 9).

Implications

Work-related MSDs are one of the leading causes of occupational disability among construction workforce (Arndt et al. 2005). Ergonomic interventions are one of the effective avenues for preventing MSDs in the construction industry (Denis et al. 2008). Construction professionals, specifically project managers and policymakers can play a vital role in this regard. By deepening their understanding of physical demands and postural practices employed by workers in various construction trades, it may help identify the root causes of the trade specific MSDs and derive new solutions to alleviate high physical workload in each trade. For instance, the current results help construction professionals recognize a simple stool can reduce discomfort of manual rebar tying in Asian culture.

The use of such a squatting-stool might serve even a wider construction worker community. As most Asian construction workers squat down to undertake work tasks near or at ground level (e.g. floor dismantling, tile fixing, welding and electrical works) (Fig. 10). Given the simplicity and low cost of the squatting-stool, it may have a great potential to be widely adopted among Asian construction workers.

[Fig. 10]

Although the results of the current study might help alleviate the physical workload of manual rebar tying, the use of squatting-stool should be a part of a wider management policy rather being the only strategy for managing MSDs. Other work-related MSD management approaches such as regular muscle strengthening and stretching exercises (Parker and Worringham 2004), postural variation, adjustment of the work schedule to make physically demanding tasks intermittent should also be included in a broader mitigation scheme (Umer et al. 2017b). Additionally, manufacturing alternatives such as offsite prefabrication might be considered to eliminate the need of onsite fabrication/assembling of certain items, which demands strenuous physical work and/or awkward postures.

Limitations and Future Works

Despite our promising findings, future research is warranted. First, the biomechanical effectiveness of the squatting-stool and its acceptance/feasibility should be verified in actual rebar workers at construction sites. Second, the biomechanical and physiological effects of prolonged use of squatting-stool (three to four hours work shift) should be investigated prior to its onsite adoption. Third, the design of the squatting-stool should be refined. For example, the interviewed construction project managers suggested the legs of the stool to be modified to prevent the legs from being stuck in the rebar mesh. Other design variables of the stool (e.g. material, height, weight and foldability) should also be considered.

Although the use of the stool has resulted in significant physical and self-perceived benefits, the outcomes indicate that squatting-stool rebar tying still requires large trunk flexion (mean flexion angle = 57º). This underpins the necessity of improving this domain. Power tying tools may have the potential to solve this shortcoming by allowing rebar workers to perform rebar tying in standing (Albers and Hudock 2007; Vi 2003). However, power tying tools also have their drawbacks including higher initial cost, frequent maintenance cost, inability to handle all sizes of rebars (in terms of diameter), substantial weight, need for special tying wire, operational vibrations, and loss of productivity in case of machine breakdown (Albers and Hudock 2007; Dababneh et al. 2000; Vi 2003). It is hoped that future power tools will solve some or all of these limitations. Alternatively, semi-automatic ergonomic tools could be developed to replace electric motors with hydraulic/mechanical components so as to lower the cost and weight of these tools. Nevertheless, till then squatting-stool could serve as an interim low-cost intervention which can significantly mitigate the physical workload in manual rebar tying.

Conclusions

This was the first study to investigate the effectiveness of using a squatting-stool for manual rebar tying against squatting in Asian workers. While the results revealed similar trunk and leg muscle activity and no significant difference in neuromuscular fatigue level of trunk and leg muscles between both rebar tying postures, stool-squatting rebar tying demonstrated significantly better: (1) lower extremity blood circulation; (2) trunk flexion angle (within the ISO recommended limits for static working postures); and (3) self-perceived discomfort ratings. These encouraging findings highlight the potential prospects of such a simple and low cost intervention for Asian workers in various construction trades (including rebar tying). Future field research is warranted to evaluate the acceptance/feasibility of using this stool in the construction industry. Importantly, the current study highlights that it is essential to consider both the characteristics of individual construction trades and cultures of workers in order to derive proper task-specific ergonomic interventios for the construction industry. Given the high physical demands of construction workers, more ergonomic studies should be conducted in the construction industry to help construction managers and policy makers design effective mitigation strategies to reduce work-related MSDs.

Data Availability Statement

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

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References

Albers, J. T., and Hudock, S. D. (2007). “Biomechanical assessment of three rebar tying techniques.” *Int J Occup Saf Ergon*., 13(3), 279–289.

Alberta Construction Safety Association. (2009). "Lost-time claims, disabling injury claims and claim rates—2004 to 2008." < https://archive.org/details/losttimeclaimsdi2008albe> (Mar. 7, 2017).

Arndt, V., Rothenbacher, D., Daniel, U., Zschenderlein, B., Schuberth, S., and Brenner, H. (2005). “Construction work and risk of occupational disability: a ten year follow up of 14474 male workers.” *Occup Environ Med*., 62(8), 559–567.

Basmajian, J. V., and Deluca, C. J. (1985). *Muscles alive: their functions revealed by electromyography*, Williams and Wilkins, Baltimore.

Buchholz, B., Paquet, V., Punnet, L., Lee, D., and Moir, S. (1996). “PATH : A work sampling-based approach to ergonomic job analysis for construction and other non-repetitive work.” *Appl Ergon.*, 27(3), 177–187.

Buchholz, B., Paquet, V., Wellman, H., and Forde, M. (2003). “Quantification of ergonomic hazards for ironworkers performing concrete reinforcement tasks during heavy highway construction.” *AIHA J.*, 64(2), 243–250.

Bureau of Labor Statistics. (2015). “Nonfatal Occupational Injuries and Illnesses Requiring Days Away from Work, 2014.” ⟨ https://www.bls.gov/news.release/archives/osh2_11192015.pdf⟩ (Mar. 7, 2017).

Cheng, T., Migliaccio, G. C., Teizer, J., and Gatti, U. C. (2013). “Data fusion of real-time location sensing and physiological status monitoring for ergonomics analysis of construction workers.” *J. Comput. Civ. Eng.*, (JUNE), 10.1061/(ASCE)CP.1943-5487.0000222.

Choi, S. D., Yuan, L., and Borchardt, J. G. (2014). “Critical analyses of work-related musculoskeletal disorders and.” *Proceedings of the Human Factors and Ergonomics Society 58th Annual Meeting*, 1633–1637.

Chung, M. K., Lee, I., and Kee, D. (2003). “Effect of stool height and holding time on postural load of squatting postures.” *Int J Ind Ergon.*, 32(5), 309–317.

Cymerman, A., Reeves, J. T., Sutton, J. R., Rock, P. B., Groves, B. M., Malconian, M. K., Young, P. M., Wagner, P. D., and Houston, C. S. (1989). “Operation Everest II : maximal oxygen uptake at extreme altitude.” *J Appl Physiol*., 66(5), 2446–2453.

Dababneh, A. J., Waters, T. R., Schneider, S., and Editor, C. (2000). “Ergonomics of rebar tying.” *Appl Occup Environ Hyg*, 15(10), 721–727.

Denis, D., St-Vincent, M., Imbeau, D., Jette´, C., and Nastasia, I. (2008). “Intervention practices in musculoskeletal disorder prevention : A critical literature review.” *Appl Ergon*., 39(1), 1–14.

Forde, M. S., and Buchholz, B. (2004). “Task content and physical ergonomic risk factors in construction ironwork.” *Int J Ind Ergon.*, 34(4), 319–333.

Forde, M. S., Punnett, L., and Wegman, D. H. (2005). “Prevalence of musculoskeletal disorders in union ironworkers.” *J Occup Environ Hyg.*, 2(4), 203–212.

Garg, A. (1992). “Occupational biomechanics and low-back pain.” *Occup Med: State of the Art Rev*, 7(4), 609–628.

Genaidy, A. M., Al-Shedi, A. A., and Karwowski, W. (1994). “Postural stress analysis in industry.” *Appl Ergon*., 25(2), 77–87.

Gescheider, G. A. (1985). *Psychophysics: Method, Theory, and Application*. Lawrence Erlbaum Associates, Hillsdale, New Jersey.

Han, S. H., Song, M., and Kwahk, J. (1999). “A systematic method for analyzing magnitude estimation data.” *Int J Ind Ergon*., 23(5-6), 513–524.

Happyback, ErgoAg Company, Aptos, California.

Hepple, R. T. (2002). “The role of O_2 supply in muscle fatigue.” *Can. J. Appl. Physiol.*, 27(1), 56–69.

Horta, M., Camanho, A. S., Johnes, J., and Johnes, G. (2013). “Performance trends in the construction industry worldwide : an overview of the turn of the century.” *J. Product. Anal*., 39(1), 89–99.

Inyang, N., Al-Hussein, M., El-Rich, M., and Al-Jibouri, S. (2012). “Ergonomic analysis and the need for its integration for planning and assessing construction tasks.” *J Constr Eng Manag.*, 10.1061/(ASCE)CO.1943-7862.0000556.

ISO. (2006). “Ergonomics-evaluation of static working postures.” *ISO 11226:2000*, Geneva.

Jung, H. S., and Jung, H.-S. (2008). “Evaluation of proper height for squatting stool.” *Ergonomics*, 51(5), 671–690.

Kasahara, S., Ebata, J., and Takahashi, M. (2007). “Analysis of the repeated one-leg heel-rise test of ankle plantar flexors in manual muscle testing.” *J Phys Ther Sci*., 19(4), 251–256.

Kivimäki, J., Riihimäki, H., and Hänninen, K. (1992). “Knee disorders in carpet and floor layers and painters.” *Scand J Work Env Heal*., 18(5), 310–316.

Lehtola, M. M., Molen, H. F. Van Der, Lappalainen, J., Hoonakker, P. L. T., Hsiao, H., Haslam, R. A., Hale, A. R., and Verbeek, J. H. (2008). “The effectiveness of interventions for preventing injuries in the construction industry: A systematic review.” *Am J Prev Med.*, 35(1), 77–85.

Lotz, C. A., Agnew, M. J., Godwin, A. A., and Stevenson, J. M. (2009). “The effect of an on-body personal lift assist device (PLAD) on fatigue during a repetitive lifting task.” *J Electromyogr Kinesiol*., 19(2), 331–340.

McGill, S. M., Hughson, R. L., Parks, K., Mcgill, S. M., Hughson, R. L., and Lumbar, K. P. (2000). “Lumbar erector spinae oxygenation during prolonged contractions : implications for prolonged work.” *Ergonomics*, 43(4), 486–493.

McGill, S. M., and Kippers, V. (1994). “Transfer of loads between lumbar tissues during the flexion-relaxation phenomenon.” *Spine*, 19(19), 2190–2196.

Neumann, W. P., Wells, R. P., Norman, R. W., Andrews, D. M., Frank, J. W., Shannon, H. S., and Kerr, M. S. (1999). “Comparison of four peak spinal loading exposure measurement methods and their association with low-back pain.” *Scand J Work Env Heal*., 25(5), 404–409.

Noraxon MR3.8 [Computer software]. Noraxon, Redmond, Washington, DC.

Ogata, K., and Whiteside, L. A. (1982). “Effects of external compression on blood flow to muscle and skin.” *Clin Orthop Relat Res*., Aug(168), 105–107.

Ontario Data: 1994–1998, "Non-traumatic musculoskeletal injury by construction rate group." Workplace Safety and Insurance Board of Ontario Data: 1994–1998.

Österberg, U., Svantesson, U., Takahashi, H., and Grimby, G. (1998). “Torque, work and EMG development in a heel-rise test.” *Clin Biomech*., 13(4-5), 344–350.

Pandey, V., Chakraborty, T., and Mukhopadhyay, S. (2012). “Prevalence of musculoskeletal disorders, levels of physical activity and perceived quality of life amongst construction site managers in Mumbai: A case study.” *Work*, 43(4), 447–451.

Parker, T., and Worringham, C. (2004). “Fitness for work in mining: Not a “one size fits all” approach.” ⟨http://eprints.qut.edu.au/1039/1/Fitness_for_Work_in_Mining.pdf⟩ (Dec. 13, 2016)

Rinder, M. M., Genaidy, A., Salem, S., Shell, R., and Karwowski, W. (2008). “Interventions in the construction industry : A systematic review and critical appraisal.” *Hum Factors Ergon Manuf*., 18(2), 212–229.

Saari, J., Wickström, G., Saari, J., and Wickstrom, G. (1978). “Load on back in concrete reinforcement work.” *Scand J Work Env Heal*., 4(1), 13-19.

Schneider, S., and Susi, P. (1994). “Ergonomics and construction: a review of potential hazards in new construction.” *Am Ind Hyg Assoc J*., 55(7), 635–649.

SENIAM (2005), Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles . Netherlands. ⟨http://www.seniam.org/⟩ (Dec. 13, 2016)

Shirado, O., Ito, T., Kaneda, K., and Strax, T. E. (1995). “Flexion-relaxation phenomenon in the back muscles.” *Am J Phys Med Rehabil*., 74(2), 139-144.

Silverstein, B., and Kalat, J. (1999). "Non-Traumatic Soft Tissue MSDs, 1990–1997 . Safety and Health Assessment and Research for Prevention (SHARP).", Program Report #40- 3-99, Washington State Department of Labor & Industries.

Skobelkin, O. K., Kozlov, V. I., Litwin, G. D., Builin, V. A., Gurovo, O. A., and Azizov, G. A. (1990). “Blood microcirculation under laser physio-and reflexotherapy in patients with lesions in vessels of low extremities.” *Laser Ther*., 2(2), 69–77.

Solomonow, M., Baratta, R. V, Banks, A., Freudenberger, C., and Zhou, B. H. (2003). “Flexion – relaxation response to static lumbar flexion in males and females.” *Clin Biomech*., 18(4), 273–279.

SPSS 19.0 [Computer software]. IBM Corporation, Armonk, NY.

Sriwarno, A. B., Shimomura, Y., Iwanaga, K., and Katsuura, T. (2007). “The influence of different lower seat height on the muscular stress during squatting for a ground level job.” *J Hum Ergol (Tokyo)*., 36(1), 25–33.

Sullivan, P. B. O., Grahamslaw, K. M., Kendell, M., Lapenskie, S. C., Moller, N. E., and Richards, K. V. (2002). “The effect of different standing and sitting postures on trunk muscle activity in a pain-free population.” *Spine*, 27(11), 1238–1244.

Sullivan, P. B. O., Dankaerts, W., Burnett, A., Chen, D., Booth, R., Carlsen, C., and Schultz, A. (2006). “Evaluation of the flexion relaxation phenomenon of the trunk muscles in sitting.” *Spine*, 31(17), 2009–2016.

Thun, M., Tanaka, S., Smith, A. B., Halperin, W. E., Lee, S. T., Luggen, M. E., and Hess, E. V. (1987). “Morbidity from repetitive knee trauma in carpet and floor layers.” *Br J Ind Med*., 44(9), 611–620.

Ulrey, B. L., and Fathallah, F. A. (2013). “Effect of a personal weight transfer device on muscle activities and joint flexions in the stooped posture.” *J Electromyogr Kinesiol.*, 23(1), 195–205.

Umer, W., Antwi-Afari, M. F., Li, H., Szeto, G. P., and Wong, A. Y. (2017a). “The global prevalence of musculoskeletal disorders in the construction industry: A systematic review and meta-analysis.” (*under review*)

Umer, W., Li, H., Szeto, G. P. Y., and Wong, A. Y. L. (2017b). “Identification of biomechanical risk factors for the development of lower-back disorders during manual rebar tying.” *J Constr Eng Manag.*, 10.1061/(ASCE)CO.1943-7862.0001208.

van der Molen, H. F., Sluiter, J. K., and Frings-Dresen, M. H. W. (2009). “The use of ergonomic measures and musculoskeletal complaints among carpenters and pavers in a 4.5-year follow-up study.” *Ergonomics*, 52(8), 954–963.

Vi, P. (2003). “Reducing risk of musculoskeletal disorders through the use of rebar-tying machines.” *Appl Occup Environ Hyg.*, 18(9), 649–654.

Wang, D., Dai, F., and Ning, X. (2015). “Risk assessment of work-related musculoskeletal disorders in construction : State-of-the-art review.” *J Constr Eng Manag.*, 10.1061/(ASCE)CO.1943-7862.0000979.

Weinstein, M. G., Hecker, S. F., Hess, J. A., and Kincl, L. (2007). “A roadmap to diffuse ergonomic innovations in the construction industry: There is nothing so practical as a good theory.” *Int. J. Occup. Environ. Health*, 13(1), 46–55.

Welch, L. S., Haile, E., Boden, L. I., and Hunting, K. L. (2009). “Musculoskeletal disorders among construction roofers—physical function and disability.” *Scand J Work Env. Heal.*, 35(1), 56–63.

West, G. H., Dawson, Ã. J., Teitelbaum, C., Novello, R., Hunting, K., and Welch, L. S. (2016). “An analysis of permanent work disability among construction sheet metal workers.” *Am J Ind Med.*, 59(3), 186–195.

Wim A., Bonga, G. J. J., Verkerke, A. L. H., and Verkerke, G. J. (1993). “EMG median power frequency in an exhausting exercise.” *J Electromyogr Kinesiol.*, 3(4), 214–220.

Wong, A. Y. L., Parent, E. C., Dhillon, S. S., Prasad, N., and Kawchuk, G. N. (2015). “Do participants with low back pain who respond to spinal manipulative therapy differ biomechanically from nonresponders, untreated controls or asymptomatic controls?” *Spine*, 40(17), 1329–1337.

Xie, Y., Szeto, G. P. Y., Dai, J., and Madeleine, P. (2015). “A comparison of muscle activity in using touchscreen smartphone among young people with and without chronic neck–shoulder pain.” *Ergonomics*, 28, 1–12.

Fig. 1. Attachment of a stool to the trousers using self-adhesive Velcro straps

Fig. 2. Experimental flowchart

Note: sEMG = surface electromyography; MF = median frequency

Fig. 3. Performance of reference isometric contractions (RICs) for the muscles under study

Fig. 4. sEMG and motion sensors` placement on various body parts

Note: T4, T12 and S1 refers to body landmarks of various spinal levels; LES = lumbar erector spinae; MultF = multifidus; for lumbar erector spinae (a), the electrodes were placed at L3 level of lumbar spine (5cm laterally from midline); for multifidus, electrodes were placed along the line joining caudal tip posterior iliac spine to L1-L2 joint (2cm laterally from midline at L5 level); for rectus femoris (b), at 50% of the line distance formed by joining anterior iliac spine and superior part of patella; for gastrocnemius lateralis (c), at one third of the line length formed by joining the head of fibula and the heel and at the most prominent bulge of the muscle for gastrocnemius medialis muscles (SENIAM 2005).

Fig. 5. Muscles` activity comparison between two rebar tying postures for average activation levels (50% APDF)

Note: * indicates $p < 0.05$; RIC = reference isometric contraction; bars indicate standard deviation

Fig. 6. Pre and post-task normalized median frequency analysis for the two rebar tying postures

Note: MF = median frequency; Lt= left side muscle; Rt= right side muscle; bars indicate standard deviation

Fig. 7. Comparison of spinal flexion variables

Note: * indicates $p < 0.05$; bars indicate standard deviation

Fig. 8. Comparison of blood oxygen saturation levels (SpO2)

Note: * indicates $p < 0.05$; APDF = amplitude probability distribution function

Fig. 9. Normalized self-perceived discomfort ratings comparison between the two postures

Note: where * indicates $p < 0.05$; bars indicate standard deviation

Fig. 10. Other construction tasks requiring squatting postures

Table 1. Summary of the statistical tests conducted in the current study

Variables under consideration	**Statistical tests conducted**	**Objectives of the tests**
Muscle activity	Paired t-tests (with FDR correction)	To identify changes in muscle activations between the two rebar-tying postures
MF (sEMG)	One-way repeated measures ANOVA, paired t-tests for post-hoc analysis	To quantify post-task muscle fatigue
Spinal flexion angles	Paired t-tests (with FDR correction)	To compare trunk flexion angles during rebar tying
SpO_2 levels	Paired t-tests (with FDR correction)	To quantify temporal changes in SpO_2 levels of lower limbs during rebar tying
Self-perceived discomfort	Two-way repeated measures ANOVA, paired t-tests for post-hoc analysis	To compare the self-perceived discomfort levels of the two postures at various time points during rebar tying

Note: MF = median frequency; sEMG = surface electromyography; SpO_2 refers to blood oxygen saturation levels; FDR = false detection rate; ANOVA = analysis of variance

Table 2. ANOVA Results for Discomfort Rating

Body part	**Factors**		
	p (stool condition)	p (time)	p (stool x time)
Lower back	.001	<.001	.008
Upper legs	<.001	<.001	<.001
Lower legs	<.001	<.001	<.001
Whole body	<.001	<.001	<.001