Identification of Biomechanical Risk Factors for the Development of Low Back Disorders during Manual Rebar Tying

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Abstract

High prevalence of musculoskeletal disorders among construction workers pose challenges to the productivity and occupational health of the construction industry. To mitigate the risk of musculoskeletal disorders, construction managers need to deepen their understanding of the physical and biomechanical demands of various construction tasks so that appropriate policies and preventive measures can be implemented. Among various construction trades, rebar workers are highly susceptible to low back disorders (LBDs) given the physically demanding nature of their work tasks. In particular, rebar tying is considered to be closely related to LBDs because it exposes workers to multiple ergonomic risk factors (repetitive works in prolonged static and awkward postures). The objective of the current study was to compare the differences in lumbar biomechanics during three typical rebar tying postures: stooping, one-legged kneeling, and squatting. Biomechanical variables including trunk muscle activity and trunk kinematics were measured by surface electromyography and motion sensors, respectively. Ten healthy male participants performed a simulated rebar tying task in each of the three postures in a laboratory setting. Repeated measures analysis of variance showed that while each posture has its unique trunk kinematic characteristics, all these postures involved excessive trunk inclination that exceeded the recommended trunk inclination angle (60^{o}) proposed by the ISO standards for static working postures. Of the three postures, stooping posture demonstrated a significant reduction in electromyographic activity of lumbar muscles (a reduction in 60-80% of muscle activity as compared to the other two postures). The reduced muscle activity may shift the loading to passive spinal structures (e.g. spinal ligaments and joint capsules), which is known to be a risk factor for LBD development. Collectively, our results may help explain the high prevalence of LBDs in rebar workers. Future studies are warranted to confirm our findings at construction sites, and to develop appropriate ergonomic approaches for rebar workers.

Keywords

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

Introduction

Musculoskeletal disorders (MSDs) are prevalent in construction industry (Boschman et al. 2012). Approximately 33% of annual work absenteeism in the American construction industry are related to MSDs (BLS 2013). Compared to workers in different construction trades, rebar workers are at a higher risk of experiencing low back disorders (LBDs) (Albers and Hudock 2007). Hunting et al. (1999) reported that low back injuries were the most prevalent musculoskeletal injuries in rebar workers. Likewise, another survey on 981 American rebar workers revealed that the prevalence of low back problems was the highest (56%) among all reported MSDs (Forde et al. 2005).

The high prevalence of LBDs in rebar workers may be attributed to their prolonged non-neutral trunk working posture. An early observational study (Burdorf et al. 1991) revealed that rebar workers in the precast unit of five construction sites worked in non-neutral postures for 37% of the total observation time. Similarly, other observational studies found that rebar workers at different construction projects maintained non-neutral trunk postures for approximately 40% to 48% of their working time (Buchholz et al. 2003; Forde and Buchholz 2004). Since working in a static extreme trunk flexion (Solomonow et al. 2003) or in a non-neutral trunk posture for more than 10% of the working time (Punnett et al. 1991) will increase the risk of developing LBDs, rebar workers are prone to LBD development.

While the absolute low back loads of rebar workers may not be substantial, their prolonged static working postures may pose threat for LBDs. Albers and Hudock (2007) estimated that low-back compression load at the L5/S1 joint was lower than the NIOSH (The National Institute for Occupational Safety and Health) defined hazardous load of 3400N during the rebar work on a bridge. However, performing repetitive rebar works in a severely flexed trunk posture throughout the day may lead to high cumulative forces over the years, which will increase the risk of developing LBD (Coenen et al. 2013; Marras et al. 2010; Seidler et al. 2001).

More importantly, workers with prior low back injuries are prone to recurrent LBDs. Forde et al. (2005) found that rebar workers with a previous low-back injury were 6.7 times more prone to LBDs. As such, proper ergonomic intervention is warranted (Forde et al. 2005). Unfortunately, since prior ergonomic studies on rebar workers only used observation approach to assess rebar workers' working postures, they could not provide quantifiable data to understand the biomechanical characteristics of rebar works (e.g. range of movements or muscle activity), which are essential for the evaluation of temporal changes in biomechanical risk factors following ergonomic interventions.

Application of Ergonomic Assessment Methods in the Construction Industry

Four assessment techniques have been adopted to examine ergonomic risk factors of construction workers in the research literature: 1) self-reported, 2) observation-based, 3) camera-based, and 4) direct measurements. Self-reported technique involves distributions of questionnaires to workers to assess their MSDs or conduction of face-to-face interviews by an investigator. However, since this method relies on subjective (self-reported) assessments, it is subjected to biases (e.g. recall bias).

Observation-based technique requires an experienced observer to use a work-sampling technique to evaluate the relative positions of various body segments of a worker in order to estimate the potential ergonomic risk factors for developing MSDs (Buchholz et al. 1996; Hajaghazadeh et al. 2012; Mebarki et al. 2015). This technique is common in ergonomic research because it involves minimum disturbance to the worker, and does not require sophisticated equipment. Unfortunately, this method relies heavily on the observer's experience and judgement, and the inter-rater reliability of this assessment is questionable.

Camera-based approach has been used to identify occupational hazards and unsafe postures at construction sites (Ray and Teizer 2012; Seo et al. 2014; Starbuck et al. 2014). While camera-based assessments allow remote analysis of construction tasks without disturbing the work process, it is prone to occlusion and requires direct line of sight for proper recording. Further, this approach cannot differentiate whether a person is standing stably or is struggling to regain balance (Chen et al. 2014). Additionally, those depth cameras cannot work properly to detect postures of construction workers under bright light conditions (Chen et al. 2014).

Direct measurement technique includes attachments of sensors or devices to the worker in order to identify potential risk factors of MSDs in both laboratory and work field environment. Cheng et al. (2012) and Gatti et al. (2010) used physiological status monitoring devices to measure heart rate and torso angle in addition to real-time location of construction workers in a laboratory environment. Alwasel et al. (2013) devised joint angle measurement devices to monitor MSDs risk factors for construction workers. Jebelli et al. (2012) and Yang et al. (2014) used inertial measurement units to identify near-miss fall incidents and assessment of fall risks for construction activities in a laboratory setting. Recently, Chen et al. (2014) presented a framework by fusing inertial measurement units with Kinect to detect hazards during construction activities like lifting and carrying loads. While this technique might help identify work-related risk factors for MSDs, no research has adopted this technique to assess ergonomic risk factors of rebar workers.

Current Understanding of Ergonomic Risk Factors in Rebar Work

While there is no guideline regarding the optimal working postures for rebar workers, the International Organization for Standards (ISO) has published standards regarding the optimal static working posture to minimize the risk of developing MSDs in healthy adults (ISO 11226:2000) . The standards specify the safe limits for the angles of various body parts, and their respective holding times for static working postures involving no or minimal external forces at the job sites.

Although the ISO standards for optimal static working postures can be applied to rebar workers, prior research approaches (using questionnaires or observation-based method) could not quantify the actual postures of rebar works (Marras et al. 2010). Therefore, it remains unclear whether certain rebar works (e.g. rebar tying) meet the ISO standards for optimal static working postures. Additionally, since previous research only considered trunk posture of rebar workers in the sagittal plane, other potential risk factors for LBDs (e.g. the lateral movement/axial rotation of the trunk, or the trunk muscle activity during rebar works) have yet been studied. Importantly, although the analysis of trunk inclination angles provides the kinematic data of a given working posture, it is recommended to analyze the concurrent trunk muscle activity in order to help understand the effects of a particular construction activity on the corresponding spinal biomechanics or future MSD development (Wang et al. 2015a).

Given the above, it is essential to use quantitative biomechanical assessments to measure both joint motions (kinematics) and muscles` activity (kinetics) during the high-risk rebar work so as to identify the risk factors for LBD development in these workers. Although previous research has identified rebar tying as the high risk task for LBD development, different rebar workers may adopt many different postures during rebar typing.

In order to identify the common working postures during rebar tying, several site visits were conducted locally. Three typical postures were identified: stooping, one-legged kneeling and squatting position (see Fig.1: (a), (b), and (c)). These observed working postures differ from those reported in literature. Specifically, workers in western countries mainly perform the task using tools in standing or stooping with full trunk flexion, while Asian workers commonly squat during rebar tying. Of the three working positions, squatting was the most commonly observed one during the site visits conducted. On average, a worker could stay in the squatting position for 3 to 4 hours in an 8-hour shift. The second most commonly observed posture was stooping followed by one-legged kneeling.

Since the observed static awkward postures during rebar tying may impose considerable risks for developing LBDs, it is imperative to conduct a biomechanical analysis to compare the respective kinetic and kinematic data so as to guide the future ergonomic intervention. Given the complexity and variability of the construction site environment, laboratory research is considered to be an appropriate first step to examine work-related biomechanics within a standardized and controlled environment prior to conducting subsequent field study.

Given the above, the objective of the current study was to compare the differences in trunk biomechanical characteristics of the three postures during simulated rebar typing in a laboratory setting.

[Insert Figure 1]

Methods

Participants

Ten healthy male participants aged between 18 and 60 years were recruited from the Hong Kong Polytechnic University using convenient sampling. Exclusion critiera were a history of low back pain, the Oswestry Disability Index ≥ 20%, and low back pain intensity > 2 out of 10 on an 11-point numeric pain rating scale where 0 measns no pain and 10 means the worst imaginable pain (Wong et al. 2015). Before the data collection, experimental procedures were explained to the participants and their written consent was obtained.

Experimental Design and Setup

This is a cross-sectional study. Participants were instructed to perform simulated rebar typing tasks in three working postures (stooping, one-legged kneeling and squatting) in a laboratory. The participants were instructed to kneel on the right knee for the one-legged kneeling task. Ten plastic pipes of 2 cm diameter were arranged in form of a mesh (Fig.2). The spacing between pipes were set to 12 cm center-to-center. Spacers were used to provide concrete cover of 4 cm as depicted in the simulation setup.

[Insert Figure 2]

The participants had to complete 2 sets of rebar tying in the front 3 rows of the simulation setup while they should keep their feet within a defined area (40cm by 50cm) located at one side of the pipe mesh setup. The same procedure was repeated for each of the three postures. It took on average approximately 6 to 8 minutes to complete the rebar tying in a given posture. The sequence of the postures was randomized for all participants. A 5-minute break was given between different postures to prevent fatigue. An 11-point numeric pain rating scale was used to collect subjective perception of pain at different body parts before, and after performing the rebar tying in each posture. A body diagram was used to facilitate the participants in describing the pain at different body regions.

Data Acquisition

Kinematics Measurements

The Noraxon MyoMotion system (Noraxon, USA) was used to capture the spinal motions in three dimensions. Three inertial measurement unit motion sensors were attached to the T4, T12, and S1 levels (Fig.3). The kinematics data was captured at a rate of 100 Hz. Inertial measurement units are small and portable devices (often termed as motion sensors) that estimate spatial orientation of a body segments by combining the outputs of multiple electromechanical sensors (accelerometers, gyroscopes, and/or magnetometers) through specific sensor fusion algorithms. Such algorithms can overcome the limitations of each individual sensor component and provide more precise motion tracking. Thoracic kinematics were defined by the relative movement between the sensors placed between the T4 and T12 levels, while lumbar kinematics were defined by the relative movement between the sensors placed between the T12 and S1 levels (Fig.3). At the beginning of the session, a physiotherapist guided the participant to maintain an erect standing posture. In this position, all the spinal angles of the participant were calibrated as the "zero" degree reference of the spinal segments in the three Cartesian planes. All the subsequent movement data were referenced to the "zero" degrees.

Measurements of Surface Electromyography (sEMG)

A 16-channel wireless Noraxon TeleMyo sEMG system (Noraxon USA Inc., USA) was used to record the muscle activities of the rebar workers. Standardized skin cleansing procedures (use of sand paper, alcohol swabs and shaving if necessary) were used to minimise the impedance of surface electrodes to below 10 kΩ levels (Xie et al. 2015). The data was recorded at a sampling frequency of 1500 Hz whereas CMRR was 100db. Eight pairs of electrodes were attached to the bilateral erector spinae (ES) at the cervical, thoracic spine and lumbar spine, as well as at bilateral multifidus muscles (Fig.3, Table 1). The surface electrodes were 15mm in diameter with inter-electrode distance of 20mm. The erector spinae and multifidus muscles were examined as they directly impact the load on the spine (Jin et al. 2009; Wang et al. 2015b).

[Insert Table 1]

Upon completion of the simulated rebar tasks, the participant was instructed to perform maximum voluntarily contractions (MVCs) of various erector spinae and multifidus muscles. Specifically, the prone participant was instructed to maximally extend the trunk and neck against manual resistance for 5 seconds (Konrad 2005). Three 5-second MVCs were performed for each target muscle while the corresponding sEMG signals were collected. A 20-second rest was given between MVCs (Hong et al. 2008). The maximum sEMG signal of each target muscle was identified using a 1000ms moving window passing through the three MVCs, and this value was adopted as the 100% MVC to which the experimental data were normalised. The technical data acquired in the current experiment are summarized in Table 2.

[Insert Figure 3]

[Insert Table 2]

Data Analysis

Kinematics data from the motion sensors and kinetics data from sEMG were synchronized using Noraxon MR3.8 (Noraxon USA Inc., USA) software, which was also used for offline data analysis.

Kinematics data was processed without any smoothing or filtering. Positive and negative values of kinematics data denoted opposite directions. Flexion and extension were considered as positive and negative, respectively. Right and left lateral bending in the frontal plane were termed as positive and negative, respectively. Similarly, clockwise and counter clockwise rotation were labelled as positive and negative, respectively (Fig.4).

[Insert Figure 4]

The raw sEMG data was processed by the Finite Impulse Response filter to remove electrocardiography signal. The signals was also bandpass filtered between 20 Hz and 250 Hz to remove the noise associated with biological and non-biological artefacts, and a notch filter was used to remove the electronic noise at 50 Hz. Then the signal was full-wave rectified and smoothen using 50 ms mean window. The resulting sEMG data of each muscle collected during the three experimental trials was normalized to the respective sEMG values during MVCs and averaged. The sEMG activity from each pair of bilateral muscles were averaged for analysis because Wilcoxon signed-rank tests indicated no significant difference between left and right side sEMG values except for the thoracic ES muscles, which showed greater right side activity than left side in all postures. Separate analyses of median left and right thoracic ES sEMG values were done to compare the activity of these muscles in the three postures. However no significant difference was seen across the three postures. As such, only averaged muscle activity for all bilateral muscles are reported in this paper.

Amplitude Probability Distribution Function (APDF) was used to study the amplitude variations of kinematics and kinetics data during the three work tasks (Szeto et al. 2005). The 10^{th} percentile, 50^{th} percentile (median) and 90^{th} percentile were computed for APDF as the representative data collected for the experiments. The 50^{th} percentile is used as an indicator of the average value of a given dependent variable during the data collection period in each posture, whereas the difference between 10th and 90th percentiles is a measure of range of movements of joint segment kinematics during the data collection period in a given posture.

Statistical Analysis

Repeated measures analyses of variance were used to examine differences between dependent variables (kinematics or kinetic data) in three different tying postures. Specifically, the posture during the simulated rebar work was chosen as the independent variable whereas APDF data for sEMG and spinal movements were the dependent variables. Post-hoc pairwise comparisons were conducted with Bonferroni adjustment. Spearman rank correlation tests were planned to investigate the correlations between the highest thoracic/low back pain intensity and the corresponding median trunk angles or average normalized sEMG activity of each trunk muscle during each of the three postures. The significance value was set at $p < 0.05$. SPSS version 19.0 (IBM, NY, USA) was used for all of the statistical analysis.

Results

Ten male volunteers were recruited from the Hong Kong Polytechnic University (mean age: 28.9±4.1 years; mean body mass index: 23.36±2.80 kg/m^2). Their mean Owestry Disability Index score was 5.64±4.90%. Three participants reported mild bilateral knee pain after the stooping posture (mean score 1.2 out of 10). All participants reported mild to moderate right knee pain (mean score 3.7 out of 10) after the one-legged kneeling except one participant. Seven participants complained of mild bilateral knee pain (mean score 2.9 out of 10) in squatting posture. None of the participants reported thoracic/low back pain (mean score 0 out of 10) in any of the rebar tying posture.

Spinal Movements Comparing Three Postures in Rebar Tying

Table 3 shows the median trunk angles and range of movements in different planes in the thoracic and lumbar regions during the simulated tasks. The median lumbar flexion angle in the three postures ranged from 54° to 58°, while median thoracic flexion angles were < 10° in the three postures. Unlike the flexion angles, the median lateral bending and axial rotation angles were similar in the lumbar and thoracic regions (Table 3). The median lateral bending and axial rotation angles in both segments ranged from 0.63° to 4.13°. The lumbar region demonstrated that lateral bending had the largest range of movements during rebar tying as compared to the corresponding variations in flexion and axial rotation in all working postures.

[Insert Table 3]

Regarding the differences in kinematics of the three postures, stooping posture had the highest median lumbar flexion angle (58.4°) during rebar tying while one-legged kneeling showed the smallest median lumbar flexion (54.2°) (Table 3). The post-hoc test revealed that only median lumbar flexion angle in stooping was statistically larger than that in one-legged kneeling (mean difference =4.2°, 95% CI ranged from 0.13° to 8.3°, eta square 0.38). No statistically significant difference was noted in median lumbar lateral bending/axial rotation angles, or in any of the thoracic kinematics in the three postures.

Overall, lumbar segment exhibited larger range of movements in flexion and lateral bending during rebar tying, whereas thoracic spine showed greater range of movements for axial rotation

(Fig.5) during rebar tying. The range of movements of lumbar lateral bending and axial rotation, as well as the range of movements of thoracic lateral bending and axial rotation were the smallest during stooping (Fig.5). Working in one-legged bending had significantly larger range of movements in lumbar lateral bending and axial rotation, as well as thoracic lateral bending and axial rotation as compared to stooping (mean difference = 5.2°, 3.12°, 3.74° , 5.82° and eta square 0.75, 0.73, 0.77, 0.66 respectively). Similarly, squatting posture depicted significantly larger range of movements of lumbar and thoracic axial rotation (mean difference = 3.46°, 3.44° and eta square 0.68, 0.77 respectively) and larger range of movements in thoracic lateral bending (mean difference 3.74°, eta squared 0.77) with reference to stooping.

[Insert Figure 5]

Differences in Muscles` Activity during Rebar Tying in Three Different Postures

Table 4 depicts the normalized sEMG activity of different muscles based on the 10th, 50th, and 90th percentiles of sEMG amplitude in the three postures. The activity of the muscles ranged from 0.57% to 25.16% of MVC values. Across all working postures, the cervical ES had the largest absolute values of muscle activity, followed by thoracic ES.

The median values of lumbar ES activity during one-legged kneeling and squatting were significantly larger than that during stooping [mean difference= 5.1% MVC (95% CI= 0.64 to 9.48 %MVC), eta square 0.43 and 2.9%MVC (95% CI=0.13 to 5.75%MVC), eta square 0.38

respectively] (Fig.6). Similarly, multifidus muscles tended to show higher median muscle activity during one-legged kneeling and squatting than stooping (eta square 0.33 and 0.34, p values ranged from 0.06 to 0.07 respectively). Conversely, no significant difference was found in median cervical ES nor thoracic ES activities across all postures.

[Insert Table 4]

[Insert Figure 6]

Correlations between low back pain intensity and trunk kinematics or trunk muscle activity

Since none of the participants experienced spinal pain during the rebar tying postures, no correlation analysis was conducted to investigate the correlation between low back pain intensity and trunk kinematics or trunk muscle activity.

Discussion

Occupational safety management has always been an important concern to construction managers. High prevalence of musculoskeletal disorders among the construction workers hamper the productivity and occupational safety of the industry globally. Construction managers need to have a better understanding of the physical and biomechanical demands of various construction trades so that better policies and/or interventions can be introduced to minimize the risk of musculoskeletal disorders at the workplace. The current study is the first of its kind to quantify the biomechanical characteristics of three common rebar tying postures. The results showed that performing rebar tying in stooping posture resulted in significantly larger median lumbar flexion angles and significantly smaller median muscle activity of lumbar ES and multifidus muscles as compared to one-legged kneeling and squatting postures. Conversely, there was no significant difference in kinematic and kinetic data between one-legged kneeling and squatting posture.

Spinal Kinematics during Rebar Tying

Our results, for the first time, indicate that rebar tying demands large lumbar flexion (approximately 60-65°) irrespective of the working posture. The lumbar flexion angles exceed the recommended limits (60°) suggested by ISO 11226 for static working postures (ISO 11226:2000). Previous observation-based studies for construction activities only stratified trunk bending angles into different categories (e.g. >45° or severe flexion) and considered the entire trunk as single straight line segment (Buchholz et al. 1996; Forde and Buchholz 2004; Hajaghazadeh et al. 2012; Lee and Han 2013).The current study overcame these limitations and quantified spinal angles at different trunk segments based on the relative movements of multiple motion sensors placed along the spine. Our findings provide an indirect explanation for the high prevalence of LBDs in rebar workers. The results suggest that this method can be adopted for studying the physical demands of rebar work on the spinal joints and muscles at the actual worksite.

Our results also highlight that rebar tying tasks require the participants to work over a moderate range of lumbar lateral bending (25-30° including left and right side range of movements) and axial rotation (15-20° including clockwise and anti-clockwise range of movements). The end range of motion of lateral bending and axial rotation during the simulated tasks are approximately 30% to 40% of the normal total thoracic or lumbar range of motion in healthy individuals (Van Herp et al. 2000; Oatis 2004). Since asymmetric trunk inclination together with end range forward bending may increase the risk of LBDs (Szeto et al. 2013), the non-neutral working postures of rebar tying may increase the risk of future back injury. In addition, because there was only limited variations in trunk flexion angles in all postures during rebar tying (e.g. < 10° on average), it implied that rebar workers may need to remain in a relatively static and excessive flexion posture during rebar tying, which might heighten the risk of LBDs development (Garg 1992; Neumann et al. 1999).

Spinal Muscle Activity during Rebar Tying

Lumbar ES and lumbar multifidus were the only two muscles that demonstrated significant (or almost significant) differences in activity among different postures. This observation may be attributed to the possibility that biomechanical demand for cervical or thoracic paraspinal muscles during rebar tying in different postures are comparable. Since the lumbar region contributes to the majority of the trunk inclination, the relative differences in kinematics of neck or upper trunk in different postures may be minimal. As such, only lumbar paraspinal muscles demonstrate distinct muscle activity in different postures specifically, the differences in posture-related trunk muscle activity can be explained by the flexion-relaxation phenomenon, which involves a myoelectric silence of lower back muscles when an asymptomatic individual bends forward fully in a standing position (see below).

Differences in Trunk Biomechanics in the Three Postures

Among the three rebar tying postures, stooping involved the largest median trunk flexion angle (approximately 65°) but the lowest sEMG activity of back muscles (lumbar ES and multifidus).

The median activities of lumbar ES and multifidus during rebar tying in stooping were approximately 20 to 40% of the respective muscle activity in the other two postures. This observed ‘myoelectric silence’ of lumbar muscles during stooping can be explained by the flexion-relaxation phenomenon (Ahern et al. 1990; McGill and Kippers 1994; Shirado et al. 1995). It is known that as an asymptomatic individual bends to the end range of trunk flexion in standing, the passive spinal structures (e.g. spinal ligaments) will become taut and take up the loading of the body with minimal back extensor activity. While this phenomenon is common in asymptomatic individuals (Solomonow et al. 2003), it substantially increases the loading on facet joints and the anterior shear stress on the lumbar vertebrae (Kent 2006, p. 265; McGill and Kippers 1994). Solomonow et al. (2003) found that prolonged static trunk flexion caused creep in the viscoelastic lumbar structures and resulted in subsequent spontaneous spasms of multifidus muscles, which indicated protective muscle responses to micro-damage of spinal tissues (e.g. ligaments). Although flexion relaxation phenomenon in stooping may not appear in sufferers with low back pain, these sufferers may need to recruit more back extensors in order to support the trunk in a stooping posture, which may increase the risk of back muscle fatigue after prolonged stooping. Since our pilot observational visit has revealed that stooping is the second most commonly adopted rebar tying posture, it is conceivable that this posture may predispose some rebar workers to develop/maintain LBDs.

Although the one-legged kneeling rebar tying posture showed the smallest median trunk flexion angle (approximately 60°), the absolute values of median sEMG activity of lumbar ES and multifidus were the highest. This observation implied that lumbar muscles were activated to resist the flexion moment in this posture. Furthermore, the range of movements in lateral bending and axial rotation of the thoracic and lumbar regions during one-legged kneeling posture were significantly greater than those of the stooping posture (Fig.5). This indicates that one-legged kneeling posture involves non-neutral trunk postures. If such asymmetrical trunk posture is adopted repetitively, it may increase the risk of future LBDs (Szeto et al. 2013). Importantly, all participants complained of mild to moderate pain over the kneeling knee after performing several minutes of rebar tying in the one-legged kneeling posture. This highlights that working in one-legged kneeling posture may increase the risk of both low back and knee pain.

The absolute values of spinal kinematics and sEMG data during squatting were in between those for stooping and one-legged kneeling postures. Although this observed angle is smaller, it still exceeds the recommended static trunk working posture limit suggested by the ISO 11226 standard (60°) (ISO 11226:2000). Importantly, our pilot construction site visits revealed that rebar workers performed rebar tying in squatting posture for an average 3 to 4 hours per duty shift. Prolonged squatting not only may increase the risk of LBDs but also may reduce blood circulation to the lower extremities and increase tensile stresses in the knee intra-articular structures. Altogether, these factors may contribute to fatigue and MSDs of back and lower extremities. (Basmajian and Deluca 1985).

Collectively, our results have showed that all the tested postures involve extensive lumbar bending while one-legged kneeling has an additional disadvantage of asymmetrical trunk posture. Prolonged working in these postures may explain the high prevalence of LBDs in rebar workers. The current findings warrant ergonomic intervention to minimize the risk of LBDs development in these workers.

Limitations

Although our study has deepened the current knowledge regarding the biomechanical risk factors of LBDs in rebar workers, there were some limitations. Firstly, this study was performed in a laboratory environment. Future on-field studies should be conducted to confirm the findings. Secondly, since the asymptomatic participants were novel to rebar tying and each of their work tasks only lasted for 6 to 8 minutes, the results should be interpreted with caution. Future research should quantify the trunk kinematics and trunk muscle activity of rebar workers during a typical work shift of 3 to 4 hours. Thirdly, the current experimental protocol might be insufficient to elicit spinal pain/discomfort in our participants. Given the short duration of the task, thoracic/low back pain was not experienced by our participants. Interestingly, mild to moderate knee pain/discomfort was reported by some participants during the rebar tasks. Future studies should examine the biomechanics of both the trunk and lower extremities during the rebar tying task so that the effects of different postures on different body parts can be comprehensively investigated. Despite these limitations, our findings have revealed that the trunk flexion angle in all postures exceeded the recommended ISO 11226 standard for static work. Fourthly, like other ergonomic studies in the construction industry (Pan and Chiou 1999; Vi 2003), the current sample size was relatively small. Despite this limitation, significant differences in spinal biomechanics among different rebar tying postures was noted. Based on our results, an ad-hoc sample size analysis was conducted. The analysis revealed that a sample of 13 participants would be sufficient to demonstrate significant difference in activity of lumbar erector spinae and multifidus muscles among the three postures.

Ways to Alleviate LBD Risk Factors

Based on the current results, a number of recommendations can be considered to improve the spinal biomechanics of rebar workers. Postural variation has been recommended for workers who maintain prolonged static working postures because holding a particular posture in an anti-gravity position for a prolonged duration will increase the risk of postural tissue overload (Delleman and Dul 2007). Rebar workers should understand this concept, and practise regular variation of their working postures. Postural training and education should be provided to emphasize the importance and techniques of postural variations. Since both one-legged kneeling and squatting can increase the risk of knee degeneration/pain, knee pads or small stool can be distributed to workers so that they can switch between different postures (e.g. one-legged kneeling of alternate knee or sitting). Strengthening and endurance exercises can also be introduced to target specific back and lower limb muscles (Parker and Worringham 2004).

Other interventions involving the modification of equipment and daily routine can be introduced. Prefabricated rebar mesh can be used to decrease the exposure of rebar tying in highly-flexed posture during hectic climate conditions of construction sites. Ergonomic smart stools, such as power rebar tier (Albers and Hudock 2007), can be introduced as a technical intervention to allow the workers to perform rebar tying in a neutral standing posture. Further, the rebar tying task can be scheduled in between other less physically demanding activities (e.g. bending and cutting of steel bars) so as to minimize back and leg muscles fatigue secondary to prolonged postures.

Conclusions

This is a first experimental study to objectively quantify biomechanical characteristics of the spine during three common rebar tying postures. Specifically, all postures require the participants to maintain their trunk inclination at an angle exceeding the ISO11226 standard recommended trunk flexion angle for static working posture. Stooping causes the largest decrease in sEMG activity of lumbar muscles as compared to the other examined postures. These decreass in sEMG activity indicates a transfer of load from back muscles to passive spinal tissues that can increase the risk of LBDs. Further, working in one-legged kneeling involves asymmetrical lumbar posture and pressure on the kneeling knee, which can increase the risk of back and knee pain in rebar workers. Importantly, the current study highlights that construction/project managers can play a crucial role in enhancing the health and productivity of rebar workers. By understanding the influences of different rebar tying postures on the muscle activitiy and kinematics of the trunk, construction/project managers can redesign the work schedule to ensure that workers regularly change their tasks in order to avoid working in a prolonged static posture. The managers can also introduce remedial measures (e.g. educational pamplets on the importance of postural variation and occupational safety, on-site stretching/exercise program, and ergonomic equipment) to reduce biomechanical risk factors for worked-related musculoskeletal disorders and to improve the productivity of rebar workers.

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Fig. 1. Three postures of rebar tying

Fig. 2. Rebar tying simulation setup. Participants performed the task while keeping their legs within the assigned area

Fig. 3. Spinal segments, surface EMG electrodes and motion sensors placement

Fig. 4. Trunk movements in the three Cartesian planes

Fig. 5. Range of movements of joint segments in three Cartesian planes at the lumbar and thoracic region during the performance of rebar tying in three postures

Note: Lumbar lateral = lumbar lateral bending; lumbar axial = lumbar axial rotation; thoracic lateral = thoracic lateral bending; thoracic axial = thoracic axial rotation;* $p < 0.05$; the error bar indicates standard deviation

Fig. 6. Comparison of median muscle activity (50^{th} %APDF) in spinal muscles

Note: * indicates $p < 0.05$; ^ indicates $p = 0.06$; # indicates $p = 0.07$; MVC= maximum voluntarily contraction; ES= erector spinae; MF= multifidus; bars indicate standard deviation

Table 1. Muscle Action and Electrode Placement

Muscle	Electrodes Location	Muscle`s action
Cervical Erector Spinae	2cm laterally from C5 level	Extension of the neck
Thoracic Erector Spinae	5cm laterally from T9 level	Extend /Maintain thoracic lumbar against gravity or applied load
Lumbar Erector Spinae	5cm laterally from L3 level	Extend /Maintain lower back against gravity or applied load
Multifidus	2cm laterally from L4 level	Maintain lumbar spine segmental stability

Table 2. Summary of Data Acquired in the Experiment

Types of data collected	Measurement method
1. Muscle activity from bilateral cervical erector spinae, thoracic erector spinae, lumbar erector and multifidus muscles	Wireless surface electromyography sensors
2. Flexion/extension, lateral bending and axial rotation angles of the thoracic and lumbar spine	Wireless motion sensors
3. Subjective pre and post rebar tying pain score	11-point numeric pain rating scale

Table 3. Median Angles and Standard Deviations for Rebar Tying in Three Postures (± SD)

Angles (Degrees)	Lumbar Region			Thoracic Region		
	Flexion	Lateral bending	Axial rotation	Flexion	Lateral bending	Axial rotation
Stooping						
10% APDF	54.45	-8.67	-0.45	3.24	-6.58	-6.23
	(8.31)	(9.24)	(4.43)	(6.14)	(2.97)	(4.11)
50% APDF	58.41*	-2.77	1.56	7.91	-3.04	-2.65
	(8.88)	(9.54)	(4.47)	(6.51)	(3.26)	(4.88)
90% APDF	60.92	3.34	3.44	11.33	0.32	0.79
	(9.21)	(10.26)	(4.33)	(6.54)	(3.49)	(5.56)
Range of movements	6.47	12.02	3.89	8.08	6.90	7.02
	(3.52)	(4.36)	(1.12)	(2.05)	(1.52)	(2.47)
One-legged kneeling						
10% APDF	44.29	-12.44	-2.54	3.48	-7.72	-6.94
	(14.43)	(10.40)	(4.44)	(5.20)	(2.29)	(4.56)
50% APDF	54.21*	-4.13	0.84	7.45	-2.77	-1.23
	(8.85)	(10.39)	(4.34)	(5.11)	(2.81)	(3.83)
90% APDF	58.23	4.89	4.28	10.47	2.74	5.18
	(8.65)	(10.09)	(4.60)	(5.53)	(3.34)	(4.54)
Range of movements	13.34	17.21	7.01	7.15	10.64	12.84
	(10.37)	(5.94)	(2.24)	(1.78)	(1.79)	(4.80)
Squatting						
10% APDF	50.74	-9.76	-5.78	4.87	-7.46	-7.30
	(11.43)	(10.61)	(5.11)	(7.58)	(2.96)	(4.35)
50% APDF	56.23	-2.29	-0.63	8.61	-2.64	-2.24
	(9.53)	(11.05)	(4.57)	(6.70)	(3.43)	(4.02)
90% APDF	60.34	4.26	4.69	11.17	2.19	3.16
	(8.87)	(12.69)	(4.82)	(6.32)	(4.15)	(5.34)
Range of movements	9.60	14.02	10.47	6.30	9.66	10.46
	(4.91)	(7.78)	(4.37)	(2.46)	(2.79)	(3.37)

Note: Positive values indicate flexion, rightwards lateral bending and clockwise rotation. Negative values indicate leftwards lateral bending and anti-clockwise rotation. APDF = Amplitude Probability Distribution Function,(* indicates that there was a significance difference between stooping and one-legged kneeling at $p<0.05$)

Table 4. The 10th, 50th And 90th Percentile of Normalized Muscle Activity at the Cervical, Thoracic and Lumbar Regions during Rebar Tying in Three Different Postures (± SD within Each Percentile)

Muscles	**Stooping**			**One-legged kneeling**			**Squatting**		
	10% APDF	**50% APDF**	**90% APDF**	**10% APDF**	**50% APDF**	**90% APDF**	**10% APDF**	**50% APDF**	**90% APDF**
Cervical ES	8.42	13.75	22.70	8.59	14.37	23.29	8.98	15.01	25.16
	(2.38)	(4.26)	(7.39)	(3.37)	(4.89)	(7.25)	(2.97)	(4.68)	(7.66)
Thoracic ES	2.60	8.03	21.74	3.60	9.60	22.8	3.43	8.41	18.79
	(2.52)	(6.50)	(15.60)	(3.47)	(7.24)	(16.24)	(3.95)	(6.40)	(10.85)
Lumbar ES	0.26	1.48	8.99	1.04	6.54	21.09	0.93	4.42	14.06
	(0.42)	(0.76)	(5.12)	(1.81)	(6.83)	(13.37)	(1.77)	(4.38)	(9.78)
Multifidus	0.57	1.75	7.09	1.47	5.67	19.16	1.15	4.34	12.55
	(1.22)	(1.77)	(4.38)	(2.37)	(6.88)	(12.2)	(1.95)	(4.67)	(10.47)

Note: ES = Erector Spinae; APDF = Amplitude Probability Distribution Function