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WAISTBAND ENABLED CONSTRUCTION WORKERS LOW BACK HEALTH MONITORING SYSTEM

RESEARCH SUMMARY

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Waistband Enabled Construction Workers Low Back Health Monitoring System

Research Summary

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FOREWORD

The total number of industrial accidents in Hong Kong construction industry rose from 2,755 in 2009 to 3,467 in 2014. One of the possible reason of this increase was physical pains, which caused by high-level of physical demands in workers' daily works. While studies on the health of construction workers found that the most frequency painful spot was lower back, the Construction Industry Council (CIC) initiated the research by engaging a research team from The Hong Kong Polytechnic University to develop a wearable sensor for measuring the workers' movements and alerting the workers if the positions are inappropriate.

The research team led by Prof. Heng LI has conducted extensive investigation and tests. A wearable inertial measurement unit based realtime motion warning system was successfully developed. The threshold values in the system is personalized instead of the recommendations from international standards. The research team has proposed a method to capture an individual's postural response to tasks and workplace when performing construction work. Field study verifies the effectiveness of the proposed system.

The research work presented in this report was funded by the CIC Research Fund, which was set up in September 2012 to provide financial support to research institutes/construction industry organizations to undertake research projects which can benefit the Hong Kong construction industry through practical application of the research outcomes. CIC believes that research and innovation are of great importance to the sustainable development of the Hong Kong construction industry. Hence, CIC is committed to working closely with industry stakeholders to drive innovation and initiate practical research projects.

The project cannot succeed without the dedicated effort of the research team. I would like to thank to all who took part in this valuable work.

Ir Albert CHENG
Executive Director of Construction Industry Council

PREFACE

Occupational health and safety (OHS) is an important concern to the construction industry. In particular, lower back pains (LBP) and fall accidents (FA) which are two common disorders suffered by Hong Kong construction rebar workers. We are pleased to note that the research team, led by Professor Heng Li, has conducted a series of studies to investigate the causes and potential preventive measures of these disorders. Specifically, the research team has firstly compared typical postures adopted by rebar workers. The results of the posture-comparison study 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. Then, the team has designed a lightweight, cheap, auto-foldable and wearable stool as an intervention. Thirdly, based on a posture-comparison study, the research team developed a wearable inertial measurement unit (WIMU) based real-time motion warning system to enable construction workers to self-manage risk factors leading to work related musculoskeletal disorders (WMSDs) around lower back and neck without disturbing their operations. Fourth, the research team developed a machine learning system to predict and prevent falls based on foot plantar pressure distribution from insoles.

The research team is surely grateful to the Construction Industry Council for the funding support. The Faculty and Department are looking forward to more collaboration with the Construction Industry Council.

Prof. Albert CHAN
Head of Department of Building and Real Estate
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RESEARCH HIGHLIGHTS

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. Construction workers are highly susceptible to lower-back disorders (LBDs) given the physically demanding nature of their work (repetitive works in prolonged static and awkward postures). The first objective of the research is 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 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 was known to be a risk factor for LBD development. Collectively, the results from this study may help explain the high prevalence of LBDs in rebar workers.

Based on the above findings, the second objective of the research is to develop a real-time motion warning personal protective equipment (PPE) that enables workers' self-awareness and self-management of ergonomically hazardous operational pattern for the prevention of work related musculoskeletal disorders (WMSDs). The system consists of three major components: an upper safety vest and a safety helmet, each was equipped by an inertial measurement unit (IMU) for motion capture; a smartphone application for data processing and motion warning, and a cloud database for data storage. Both motion capture and real-time motion warning algorithms were proposed for automatic risk postures assessment and warning through a connected smartphone application as soon as dangerous patterns were detected. The warning thresholds were set in the system based on an international standard organisation ISO 11226:2000(E). For example, if a detected trunk flexion angle was larger than 60º, the warning module would be activated and sent out alarms until the wearer adjusted the postures that were not recommended in the standard.

We tested the developed motion warning system on a construction site in Hong Kong. We also asked construction union leaders and some experienced workers for their suggestions to improve the motion warning system. After the field tests and meetings, we improved the proposed motion warning system by identifying and solving three problems.

First, the upper vest that was designed to hold the IMU sensor was not comfortable for workers to wear. To tackle this problem, we compared different upper vests in terms of comfort level, portability, and wearability. Then, we improved the upper safety vest by using an easy-to-wear, portable, and comfortable-to-wear reflective vest. Second, the international standard organisation ISO 11226:2000(E) for postural hazard warning was not practical reported by some front-line construction workers, because most of their works require “Not Recommended” postures according to the ergonomic standard, which would disturb the wearers’ manual operation. Third, the ergonomic rule for postural hazard warning did not consider individual differences among different workers. To tackle these two problems, we proposed a data-driven work-centric personalized healthcare strategy of LBDs by providing personalized recommendation of trunk holding time to an individual worker.

To examine whether the proposed data-driven personalized healthcare strategy can reduce an individual’s risk level leading to lower back disorders, a field test was carried out. The field study had three periods. Three paired comparison t-test was used to determine any significant differences in trunk postural ovako working posture analysing system (OWAS) scores during the subject’s working time. The results indicated that the subject’s postural scores significantly decreased in the 2nd period compared with the scores in the 1st period (p=0.02). There was a significant increase of postural scores in the 3rd period comparing with that in the 2nd period (p = 0.02), but there were no significant differences comparing with the scores in the 1st period (0.93). The significant rebound of the postural scores in the 3rd period indicates that without real-time personalized trunk posture recommendations, the postural working patterns of the subject turn to the patterns in the 1st period. This result revealed the positive effectiveness of worker-centric self-management based on personalized postural recommendations in the 2nd period. The field test provided positive support for applying worker-centric self-management based on data-driven personalized healthcare with recommendations on holding time.

CONTENTS

1 INTRODUCTION

1.1 Background

The construction industry has always been prone to be afflicted by work related musculoskeletal disorders (WMSDs). According to the illustrations found in Bureau of Labor Statistics, 2014 and Wang *et al.*, 2015, amongst 15 typical work tasks in construction, 7 tasks, namely flooring, roofing, framing, plumbing, masonry, concrete pouring and drywall installing hold a WMSDs incidence rate of more than 50%, with a nearly 80% prevalence in flooring. In addition, amongst these typical construction tasks, the prevalence of back pain is far higher than that in other parts of body. Furthermore, though the prevalence of neck pain is less than that in the back, the statistical median days away from work are almost equal to those of prevalence in the trunk. Lower back and neck pain have received considerable attention in occupational health issue (Briggs *et al.,* 2009) and are representative precursors of WMSDs amongst construction workers. Thus, the WMSDs around lower back and neck are prioritized in this paper accordingly.

In general, work-related physical postures and holding time have been proven to be statistically significant risk factors for WMSDs, especially regarding lower back pain (Burdorf & Sorock, 1997; Hoogendoorn *et al.,* 2000; O'Sullivan *et al.,* 2006). Compared to other industries, heavy manual operations in the construction domain are universal and inevitable, exposing workers in various trades to danger at work, regardless of different individuals, environments or countries. Spielholz *et al.* (2006) evaluated major risk factors regarding body postures, holding time, and force requirements for trades like roofing, floor installation, carpentry, reinforcing, etc. Repetitive or awkward postures like stooping, squatting and kneeling, frequently confronted by operational workers, can cause overexertion in the spine and the muscle of the back and neck. Maintaining similar working postures for a long period of time is another common cause of WMSDs around lower back and neck. Both ergonomically hazardous postures and insecure holding time are major risk factors for construction workers, and should be taken as major concerns in WMSDs prevention.

Both researches and practices showed potentials to assess and prevent WMSDs based on motion data. Early representative studies that have proposed posture analysis techniques to assess WMSDs hazards include “Rapid Upper Limb Assessment” (RULA) (McAtamney & Corlett, 1993), and "Ovako Working Posture Analyzing System" (OWAS) (Kant *et al.,* 1990) for identifying and evaluating operational postures. Although limited by the posture data capture technology available at the time when these classical evaluation techniques and methods were developed, they provided valuable insights for ergonomic posture analysis and description of physical demands. Current researches on ergonomic hazard assessment suggest both vision-based methods (e.g. Kinect and Stereo Camera System) and wearable sensor systems (e.g., joint angle measurement systems and Inertial Measurement Units (IMUs)) to be effective on-site ergonomic assessment tools (Wang *et al.,* 2015). As markerless-based assessment methods, vision-based techniques rely on the selection of appropriate camera positions and may suffer from occlusion and view variances (Seo *et al.,* 2015). Recently, Inertial Measurement Units (IMUs) have begun to see an increase of attempts in the construction industry. Previous applications of IMUs in injury risk assessment indicate they help reconstruct human postures and record holding time in a more precise and reliable way (Chen *et al.,* 2014; Jebelli *et al.,* 2016; Yang *et al.,* 2016) as well as addressing the limitations of vision-based methods. The IMU sensors also had a great potential in the ergonomic domain. Not only were the wearable IMUs capable of automatically capturing posture data in a more reliable way, they also helped to assess potential operational hazards using the captured posture data without disrupting jobsite manual operations because of the portability. Previous applications of IMUs in health care and ergonomic assessment were also inspiring. For example, Bastani *et al.* (2016) have developed a task classification algorithm for monitoring and evaluation of manual material handling (MMH) activities using whole-body kinematics captured by IMUs as the inputs of the algorithms. Schelldorfer *et al.* (2015) used IMUs and Wii balance board to investigate differences in postural control adaptations of the spine, hip and the center of pressure between people who suffer from non-specific low back pain and asymptomatic control. The body movement output of IMUs was also used in physical rehabilitation (Olugbade *et al.,* 2014) and ergonomic assessment of manual tasks in the industrial environment (Vignais *et al.,* 2013). An activity tracking system based on IMUs for postural hazards assessment was also proposed for WMSDs assessments (Valero *et al.,* 2016). However, on-site real-time alarms feature was not developed in previous researches and only summary feedbacks can be provided, which was not adequate for real-time WMSDs prevention on construction site. A move from assessment to real-time prevention of WMSDs around lower back and neck should be addressed. More practical and effective wearable sensor based personalized healthcare solutions for workers' WMSDs prevention remain to be developed in the construction industry.

1.2 Aims and Objectives

I. To compare the differences in lumbar biomechanics during three typical rebar tying postures: stooping, one-legged kneeling, and squatting;

II. To develop a wearable sensor-based real-time motion capture system for measuring ergonomic movements of workers while they are performing construction tasks;

III. To design ergonomic motion capturing and warning algorithms to alert workers when their trunk inclination angles or holding time are beyond acceptable thresholds;

IV. To improve the proposed motion warning system based on a field test and front-line practitioners' suggestions;

V. To develop a data-driven method for personalized recommendation of trunk holding time, and examine the effect of the method in a field test.

1.3 Scope

1st period covered:

a) To compare the differences in lumbar biomechanics during three typical rebar tying postures: stooping, one-legged kneeling, and squatting;

b) Development of a wearable sensor-based real-time motion capture system;

c) Designing ergonomic motion capturing and warning algorithms to alert workers.

2nd period covered:

a) Development of a wearable sensor-based real-time motion warning system;

b) Algorithms designing;

c) Improvement of the proposed system based on a field test and front-line practitioners' suggestions;

d) Development of a quantitative method for data-driven work-centric personalized healthcare, and test of the method on a construction site in Hong Kong.

3rd period covered:

a) Improvement of the proposed system;

b) Development of a quantitative method for data-driven work-centric personalized healthcare, and test of the method on a construction site in Hong Kong.

2 RESEARCH METHODOLOGY

2.1 Comparing the Differences in Lumbar Biomechanics during Three Typical Rebar Tying Postures

Ten healthy male participants performed a simulated rebar tying task in each of the three postures in a laboratory setting. The participants had to complete two sets of rebar tying in the front three rows of the simulation setup while keeping their feet within a defined area (40 by 50 cm), as shown in Figure 1. The same procedure was repeated for each of the three postures. 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. The MyoMotion system was used to capture the spinal motions in three dimensions (Figure 2). A 16-channel wireless TeleMyo surface electromyography (sEMG) system (Noraxon USA, Scottsdale, Arizona) was used to record the muscle activities of the rebar workers. The technical data acquired in the experiment was summarized in Table 1.

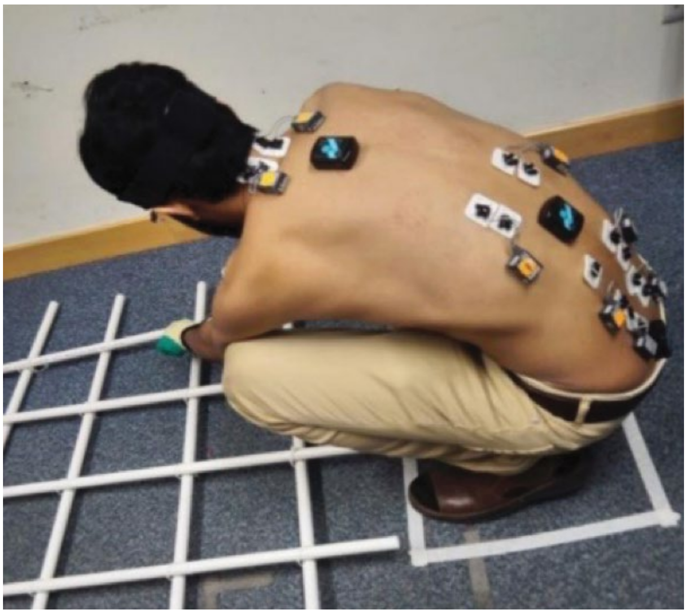


Figure 1 Rebar tying simulation setup (Umer *et al.*, 2016)

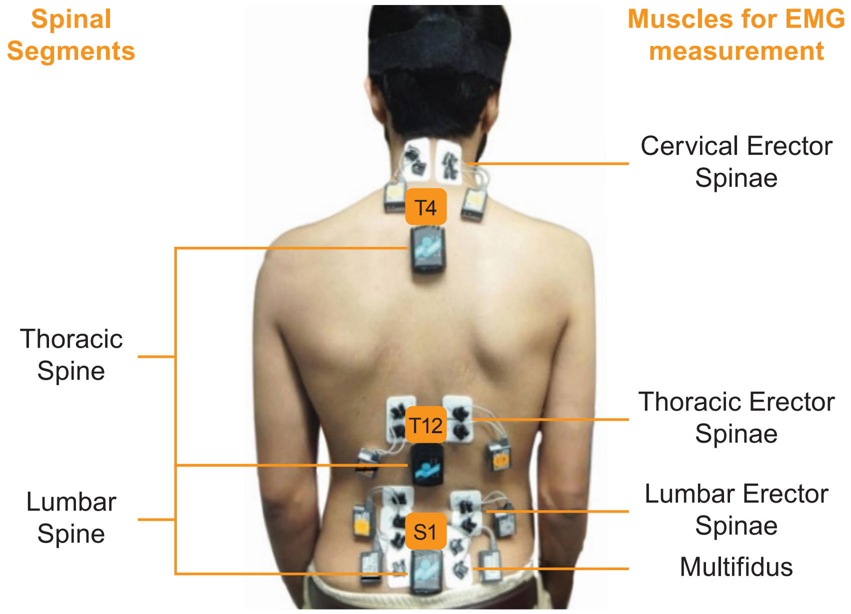


Figure 2 Spinal segments, surface EMG electrodes, and motion sensor placement (Umer *et al.*, 2016)

Table 1 Summary of Data Acquired in the Experiment (Umer *et al.*, 2016).

Data collected	Measurement method	Equipment Used	Sampling frequency	Accuracy	Sensor size / weight	Sensor range
Muscle activity	Wireless surface electromyography sensors	Noraxon wireless TeleMyo sEMG system	1500Hz	EMG signals are collected with noise < 1 uV RMS	3.4 x 2.4 x 1.4 cm / 14g	30m
Flexion / extension, lateral bending and axial rotation angles of the thoracic and lumbar spine	Wireless motion sensors	Noraxon MyoMotion	100Hz	1 degree in the sagittal and frontal planes and 2 degrees in lumbar the transverse spine plane	3.8 x 5.2 x 1.8 cm / 34g	30m
Subjective pre and post rebar tying pain score	11-point numeric pain rating scale	N/A	N/A	N/A	N/A	N/A

The directions of kinematics data were defined, as shown in Figure 3. Repeated measures analysis 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 amplitude probability distribution function (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/lower-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 was used for all of the statistical analysis.

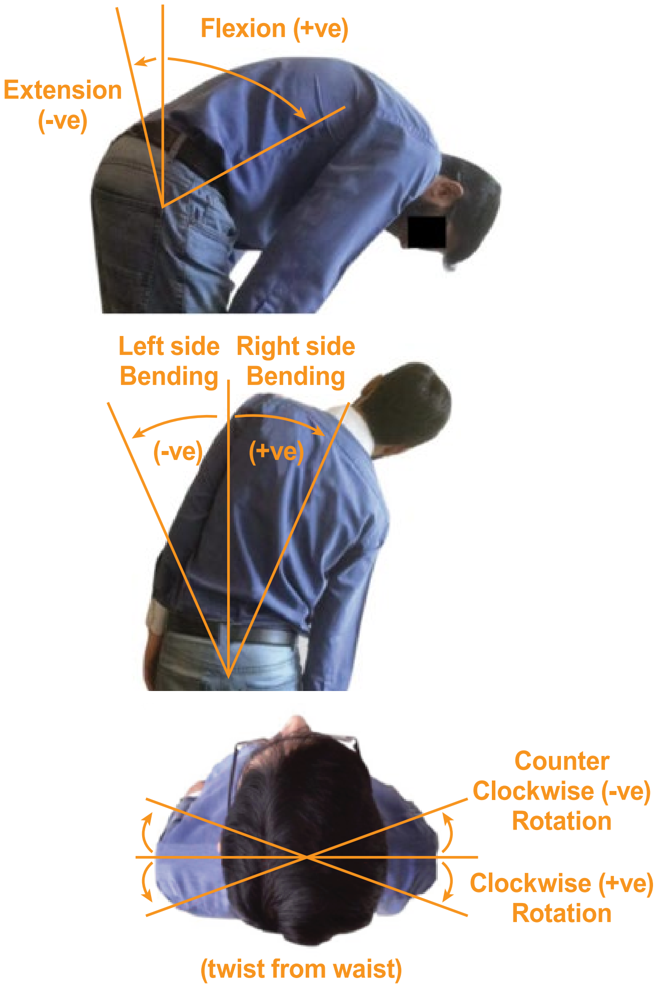
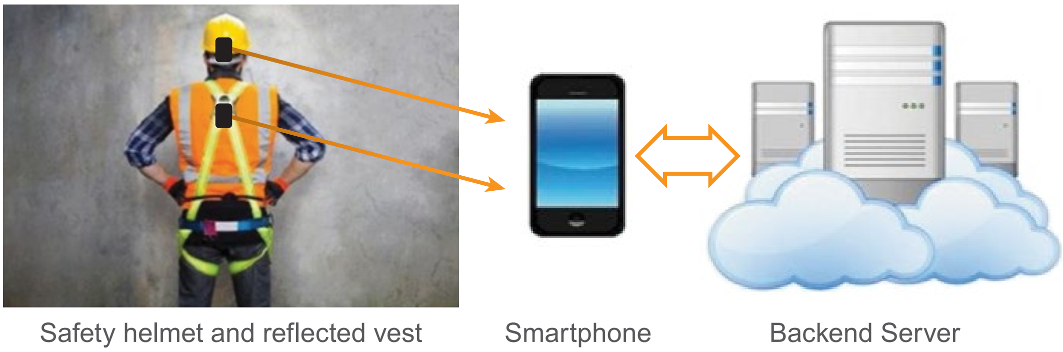


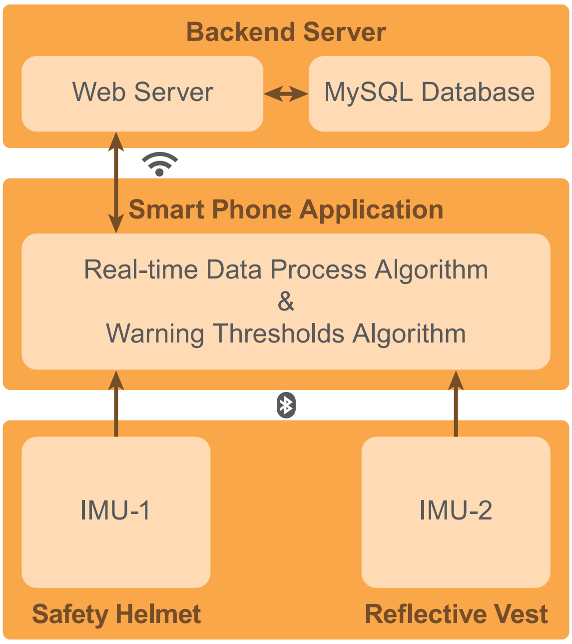
Figure 3 Trunk movements in the three Cartesian planes (Umer *et al.,* 2016)

2.2 Development of a Wearable Sensor-based Real-time Motion Capture System

The wearable IMU-based motion warning PPE has three components (Figure 4): an upper safety vest and a safety helmet that were equipped with sensors for motion capture; a smart phone application for receiving, processing motion data captured by IMU sensors via Bluetooth technology, and sending motion warnings; and cloud database for motion data storage.



(a) System architecture



(b) System components

Figure 4 The wearable IMU-based real-time motion warning system architecture and components (Yan *et al.*, 2017)

The kinestate of the upper sensor (IMU-1) approaches to the motion of the head that is deemed a rigid segment. The inclination of the lower sensor (IMU-2) approximately equals that of the solid line T1-T2 (Figure 5). The measurement of neck movement is represented by the relative position of the head and trunk captured by the two IMUs with the approximate measured length of head and trunk:

$$V_{neck} = l_{head} \cdot v_{head} + l_{trunk} \cdot v_{trunk} \tag{1}$$

Where v_{head} denotes the vector outputted by the IMU attached on the helmet. v_{trunk} denotes the vector outputted by the IMU attached on the upper vest. l_{head} and l_{trunk} denote the length of head and trunk. V_{neck} denotes the vector of neck calculated by the output vectors of the IMUs attached on head and back. The output of each sensor is the following normalized quaternion with an output frequency of 50 frames per second,

$$q = [w, ai, bk, ck] \tag{2}$$

Where $\|q\| = 1$. According to the definition of quaternions, $i^2 = j^2 = k^2 = -1$ are the fundamental quaternion units; w, a, b, c are real numbers that are captured by the IMU to describe spatial rotations. Taking IMU-2 as an example for illustration, the sensor's initial calibration state in default reference coordinate is shown in Figure 6(a). Two initial unit vectors are utilized to represent the calibrated state of the sensor for convenience. One is a positive unit vector in a quaternion format with w = 0 along the Y-axis denoted p_1 to determine spine segment's tilt (ϕ) and tilt azimuth (θ) angles; the other is a negative unit vector in the same quaternion format along the Z-axis denoted p_2 to calculate twist (τ) angles, as shown in Figure 6(b). A clockwise inclination revolving around an axis indicates a negative value and vice versa. According to the multiplication formula of quaternions,

$$p' = qpq^{-1} \tag{3}$$

Where q^{-1} is the inverse vector of real-time quaternion q generated by IMUs. Thus, the coordinates after rotation of both p_1 and p_2 in quaternion formats can be represented as:

$$p_1' = [0,(-2w_1 \cdot z_1 + 2x_1 \cdot y_1)i,(w_1^2 - x_1^2 + y_1^2 - z_1^2)j,(2w_1 \cdot x_1 + 2y_1 \cdot z_1)k] \tag{4}$$

$$p_2' = [0,(-2w_2 \cdot y_2 - 2x_2 \cdot z_2)i,(2w_2 - x_2 + 2y_2 - z_2)j,(-w_2^2 + x_2^2 + y_2^2 - z_2^2)k] \tag{5}$$

Where $w_n, x_n, y_n, z_n, n = 1,2$ are the quaternion parameters outputted by the IMU to calculate the position and orientation of p_1 and p_2. Tilt angle can be determined by using the projection of unit vector p_1' onto the Y-axis (see Figure 6 (b)) with the use of the following arccosine function:

$$\varphi = \arccos(w_1^2 - x_1^2 + y_1^2 - z_1^2) \tag{6}$$

Where, the denominator in the arc cosine formulation equals to 1 because of the unit vector. The measured ranges of tilt angle are 0-180° during flexion movements forward from the initial position and -180°-0 during extension backward from the initial position. The tilt azimuth angle can be determined by the projection of the same unit vector onto the X-Z plate using the arctangent function:

$$\theta = \arctan\left(\frac{2w_1 \cdot z_1 - 2x_1 \cdot y_1}{-2w_1 \cdot x_1 + 2y_1 \cdot z_1}\right) \tag{7}$$

Where the angle is measured with respect to the negative Z-axis with a clockwise range to -180° and a counter clockwise range to 180°. Thereby, clinical flexion-extension and lateral bending angles can be calculated respectively using tilt (ϕ) angle and tilt azimuth (θ) angle:

$$F = \varphi \cdot \cos(\theta) \tag{8}$$

$$L = \varphi \cdot \sin(\theta) \tag{9}$$

Where L is positive while left lateral bending (counter clockwise). Meanwhile, the real-time rotation angle can be represented by the twist (τ) angle obtained from the current value of the unit vector p_2' as follows:

$$R = \tau = \arctan\left(\frac{2w_2 \cdot y_2 + 2x_2 \cdot z_2}{-2w_2 \cdot x_2 - 2y_2 \cdot z_2}\right) \tag{10}$$

Where the range of twist (τ) angle is same as tilt azimuth (θ) angle from the midsagittal line. The three clinically meaningful parameters flexion-extension (*F*), lateral bending (*L*) and rotation (*R*) are used to calculate the angular motion of the trunk. The processed outcomes are then compared with the predefined insecure thresholds for WMSDs prevention. The clinical parameters for head and neck can be determined in the same way.

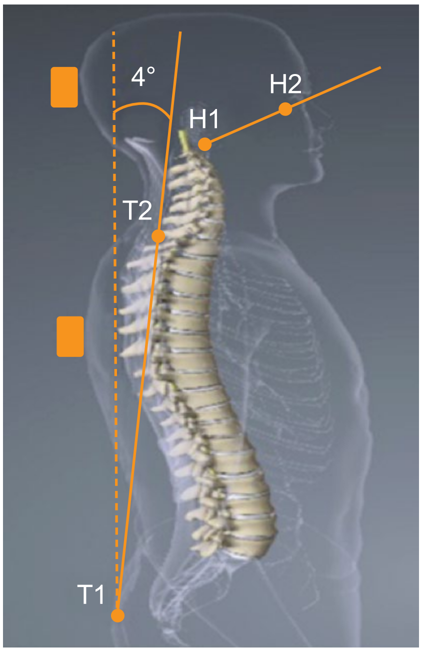


Figure 5 Determination of head and trunk inclination (Yan *et al.,* 2017)

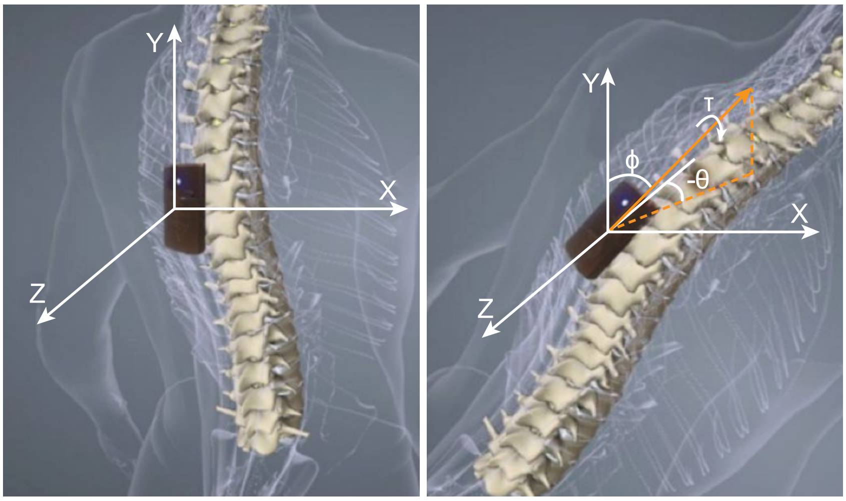


Figure 6 (a) Trunk IMU sensor calibration in reference coordinate;
(b) Trunk inclination tilt, tilt azimuth and twist angles (Yan *et al.,* 2017)

The real-time warning threshold algorithm for the prevention of WMSDs in the construction worker population is developed to translate the clinically meaningful real-time data into warning triggers when postural risk factors are detected. Taking trunk inclination for an example, the according maximum acceptable holding time and insecure angle of inclination are shown in Figure 7 (ISO, 2000).

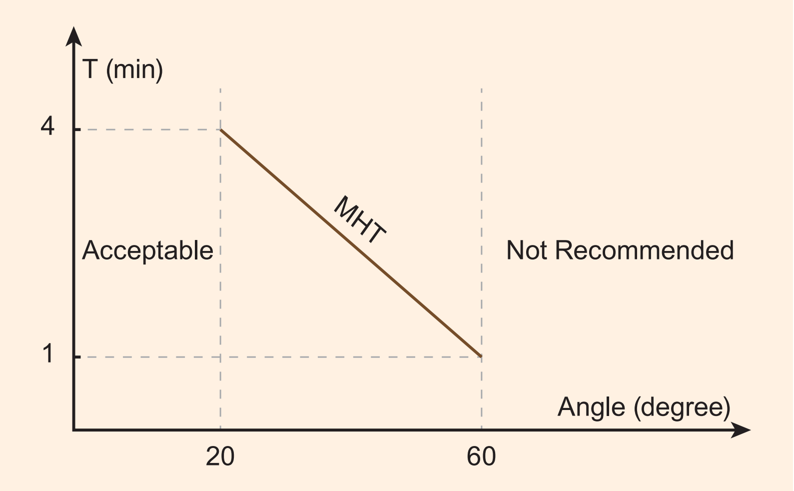


Figure 7 Maximum holding time vs. trunk inclination (Yan *et al.,* 2017)

Between the ‘Acceptable’ and the ‘Not Recommended’ zone, a function indicating the quantitative relationship between holding time (min) and static angle (degree) of trunk inclination is indicated,

$$MHT\ (A) = -3\ /\ 40 \text{ x } A + 11\ /2 \tag{11}$$

Where A denotes the degree of an angle. According to Eq. (11), the thresholds of maximum holding time of operational postures can be determined. The basic procedure of the algorithm is to accumulate the entire individual maximum holding time of each real-time angle emerging in each frame to compare with the actual period of operational postures. The real-time accumulating individual maximum holding time (MHT) at time t (s) and nth frame with an output frequency $f = 1\ /\ T$ can be approximately calculated as follows,

$$MHT_n = MHT\left(\sum_{i=1}^{i=f\cdot t} A_i \cdot T\ /\ t\right) \tag{12}$$

where A_i denotes the inclination angle in frame i, T is the output cycle of the IMU. Previous research has revealed that dynamic movement results in longer endurance times than that in static tasks (Law *et al.,* 2010) so that current conservative functions indicating the quantitative relationship between holding time and static angle can guarantee the purpose of preventing lower back and neck pain for workers in both static and dynamic operational postures.

3 RESEARCH FINDINGS AND DISCUSSION

3.1 Comparing the Differences in Lumbar Biomechanics during Three Typical Rebar Tying Postures

Table 2 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 2). 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.

Table 2 The 10th, 50th And 90th Percentile of Thoracic and Lumbar Regions during Rebar Tying in Three Different Postures (± SD within Each Percentile).

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

Notes:
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 $p < 0.05$)

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 2). 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% confidence interval (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 (Figure 8) 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 (Figure 8). 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.

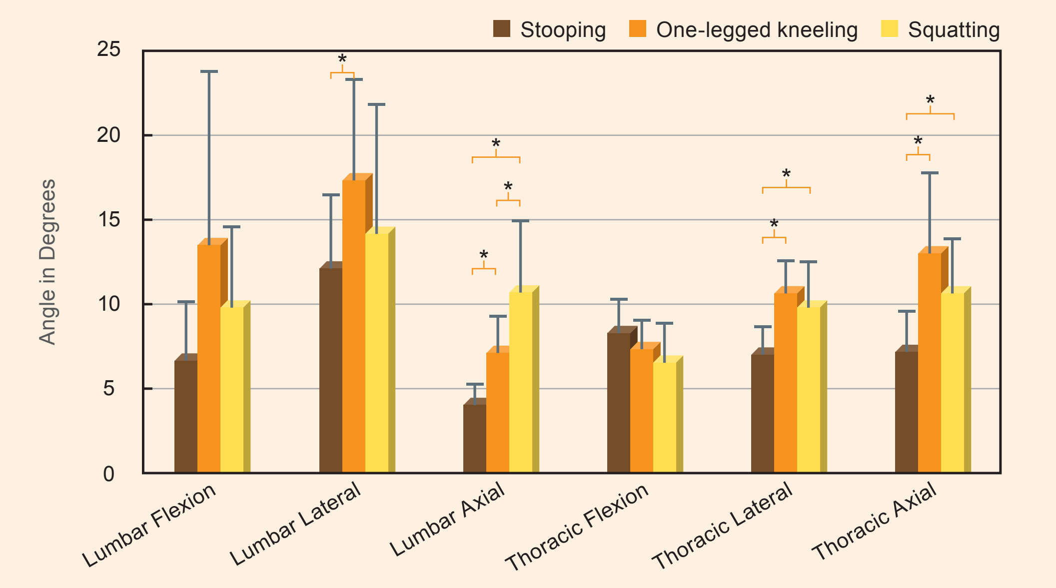


Figure 8 Range of movements of joint segments in three Cartesian planes at the lumbar and thoracic region during the performance of rebar tying in three postures (Umer *et al.,* 2016)

Notes:
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

Table 3 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] (Figure 9). 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.

Table 3 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 (2.38)	13.75 (4.26)	22.70 (7.39)	8.59 (3.37)	14.37 (4.89)	23.29 (7.25)	8.98 (2.97)	15.01 (4.68)	25.16 (7.66)
Thoracic ES	2.60 (2.52)	8.03 (6.50)	21.74 (15.60)	3.60 (3.47)	9.60 (7.24)	22.8 (16.24)	3.43 (3.95)	8.41 (6.40)	18.79 (10.85)
Lumbar ES	0.26 (0.42)	1.48 (0.76)	8.99 (5.12)	1.04 (1.81)	6.54 (6.83)	21.09 (13.37)	0.93 (1.77)	4.42 (4.38)	14.06 (9.78)
Multifidus	0.57 (1.22)	1.75 (1.77)	7.09 (4.38)	1.47 (2.37)	5.67 (6.88)	19.16 (12.2)	1.15 (1.95)	4.34 (4.67)	12.55 (10.47)

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

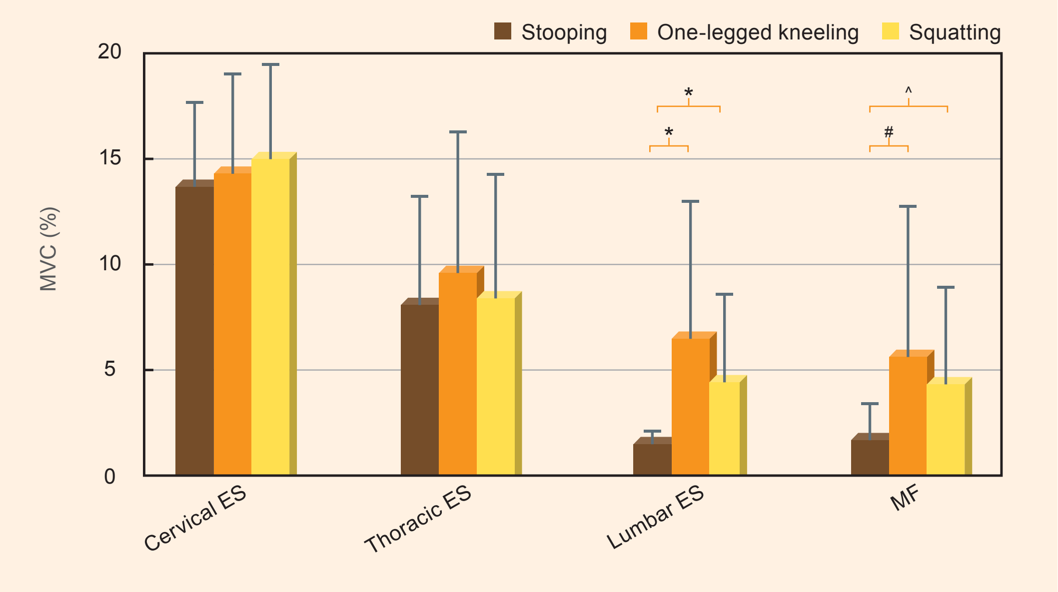


Figure 9 Comparison of median muscle activity (50th % APDF) in spinal muscles (Umer *et al.,* 2016)

Notes:
* 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

The results of the current study, 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 & 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. The 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.

The current 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).

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.

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 & 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 & 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 the authors` pilot observational visits have 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 (Figure 8). 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, the authors' 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 & Deluca, 1985).

3.2 Development of a Wearable Sensor-based Real-time Motion Capture System

A laboratory experiment was first carried out to validate the proposed WIMU-based real-time motion warning system with a data capture rate 10 times per second. The system stability and energy efficiency were tested for long-term service in the following experiments. After IMU sensors calibration, the laboratory experimental subject started doing some basic movement in sequence in terms of flexion, extension, right lateral bending, left lateral bending, right rotation, and left rotation in head and trunk respectively. These are shown in Figure 10 as an intercepted part of the obtained motion data from our safety management database in the backend server. The brown solid line indicates the flexion-extension mode, the orange solid line indicates the lateral bending mode, and the brown dotted line indicates the rotation mode. The real-time kinestate of head, neck and trunk captured in the experiment are shown in three figures respectively. The real-time angles of both head and neck are calculated relative to the movement of trunk. After frame 150, the experimental subject only moved his trunk in flexion, right lateral bending, left lateral bending, right rotation, and left rotation. As a result, the trajectories of real-time angles of both head and neck were relatively smooth with minor changes. From Figure 10, the distinct trajectories of real-time angles in flexion-extension, lateral bending, and rotation mode validate the motion data collecting and processing algorithms predefined in the proposed personal protected equipment.

After the initial test of the motion warning system, the laboratory experimental subject started to imitate typical operations of construction workers. Taking imitated brick lifting and rebar tying as examples for illustration. Figure 11 (a) and (b) illustrate two intercepted parts of the captured motion data in the laboratory experiment. As shown in Figure 9, the smartphone application attached to the motion warning systems enable wearers to connect their wearable equipment to the smartphone via Bluetooth and calibrate the IMU sensors.

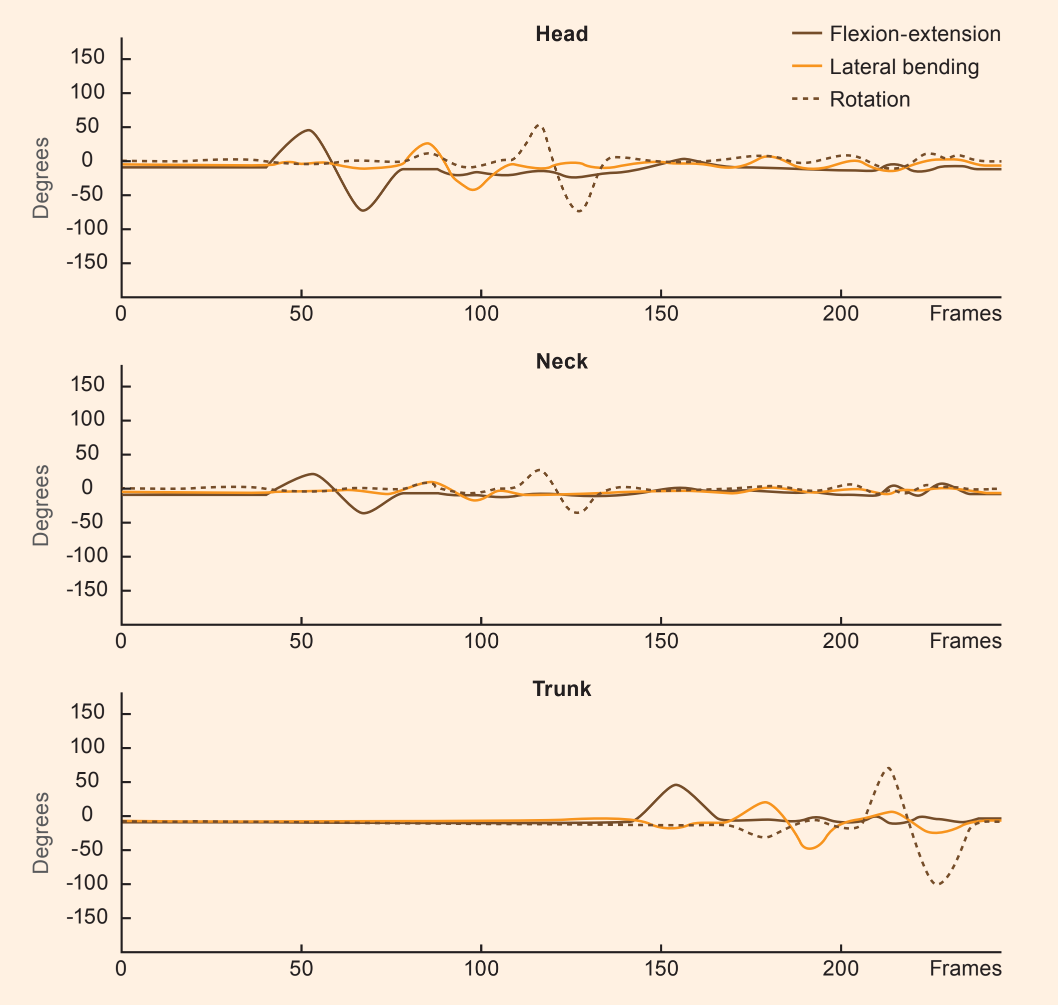
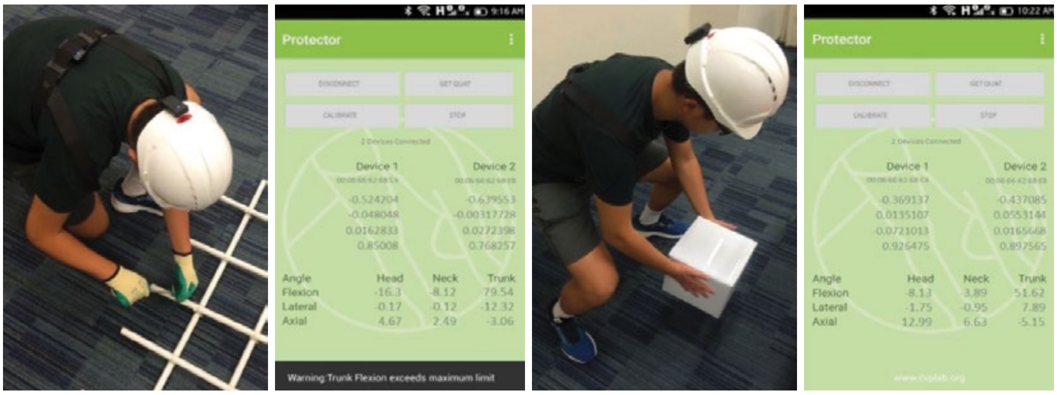


Figure 10 Maximum holding time vs. trunk inclination (Yan *et al.,* 2017)



Device 1	Device 2
-0.524204	-0.639553
-0.048048	-0.00317728
0.0162833	0.0272398
0.85008	0.768257

Angle	Head	Neck	Trunk
Flexion	-16.3	-8.12	79.54
Lateral	-0.17	-0.12	-12.32
Axial	4.67	2.49	-3.06

Warning:Trunk Flexion exceeds maximum limit

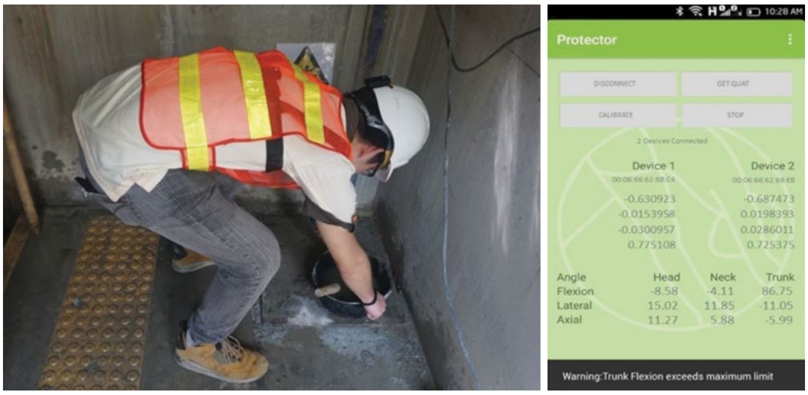
Device 1	Device 2
-0.369137	-0.437085
0.0135107	0.0553144
-0.0721013	0.0165668
0.926475	0.897565

Angle	Head	Neck	Trunk
Flexion	-8.13	-3.89	51.62
Lateral	-1.75	-0.95	7.89
Axial	12.99	6.63	-5.15

Figure 11 (a) Laboratory experiment-imitated rebar tying;
(b) Laboratory experiment-imitated brick lifting (Yan *et al.,* 2017)

The identifiers of the IMU sensors, real-time quaternions captured by the IMU sensors and clinically meaningful motion data translated from the quaternions are displayed in the application. Once ergonomically hazardous operational postures are detected by the predefined real-time warning threshold algorithm, alarm will be sent out to warn individual wearers adjust their current operational postures or pause for a respite from current postures. Meanwhile, a warning message will also be displayed on the bottom of the smartphone screen. In addition, users can change alarm type, enable vibration, and set the frequency of IMU sampling rate by pressing the ‘Setting’ button on the upper right part of the screen. The laboratory experiment validates the functionality and capabilities of the proposed real-time motion warning equipment.

To validate the practical utility and reliability of the proposed WIMU-based motion warning system, field experiments on a construction site in Hong Kong were conducted. Two scenarios were shown in Figure 12(a) and (b). It was reported by the on-site workers that the proposed personal protective equipment could help them recognize hazardous postures without disturbing their operations. Some of them can gradually change previous ergonomically hazardous operational patterns by interacting with the real-time warning system. As shown in Figure 12(a), the tester used to stoop while lifting, which is highly ergonomically hazardous for lower back. After a nearly one-day break-in period for the tester, improvement was made in his operations (Figure 12(b)), which indicated the effectiveness of the self-awareness and self-management strategy based on the proposed WIMU-based motion warning system for lower back and neck pain prevention.



```
2 Devices Connected

        Device 1              Device 2
   00:06:66:62:68:C4     00:06:66:62:68:EB
       -0.630923             -0.687473
      -0.0153958             0.0198393
      -0.0300957             0.0286011
        0.775108              0.725375

Angle        Head    Neck    Trunk
Flexion     -8.58   -4.11    86.75
Lateral     15.02   11.85   -11.05
Axial       11.27    5.88    -5.99

Warning:Trunk Flexion exceeds maximum limit
```

Figure 12 (a) Break-in period for one tester wearing the PPE in the field experiment (Yan *et al.,* 2017)

```
2 Devices Connected

        Device 1              Device 2
   00:06:66:62:68:C4     00:06:66:62:68:EB
       -0.327658             -0.230077
      -0.0513576          -0.000906251
        0.128053             0.0235261
        0.934669              0.972888

Angle        Head    Neck    Trunk
Flexion     12.52    6.32    26.61
Lateral    -12.18   -5.75    -0.81
Axial      -10.17   -5.01    -2.70
```

Figure 12 (b) Adjustment made by the tester according to the warnings from the PPE (Yan *et al.,* 2017)

To further improve the developed motion warning system so that it would be applied in real-world outdoor construction sites, we also held meetings with some construction union leaders and front-line construction workers in Hong Kong. During the meetings, we presented our works to the union leaders and front-line construction workers and collected their suggestions for the proposed motion warning system. Based on both the field test and the meetings with construction practitioners, we improved the proposed motion warning system by identifying and solving three problems. First, the upper vest that was designed to hold the IMU sensor is not comfortable for workers to wear. To tackle this problem, we compared different upper vests in terms of comfort level, portability, and wearability. Then, we improved the upper safety vest by using an easy-to-wear, portable, and comfortable-to-wear reflective vest, as shown in Figure 13. The IMU sensor is designed to be embedded into the reflective safety vest (the orange circled area) so that potential sensor damages can be prevented.

Figure 13 Improved upper reflective safety vest

Second, the ergonomic rule for postural hazard warning is not practical reported by some front-line construction workers. In the first stage of the project, a real-time motion warning personal protective equipment was proposed for ergonomically hazardous trunk inclination and holding time detection and warning. The warning thresholds are pre-set in the system based on an international ergonomic standard ISO 11226:2000(E). For example, if the detected trunk flexion angle is larger than 60º, the warning module will be activated and send out alarms until the wearer adjusts the postures that are not recommended in the standard. However, this threshold is not practical because most construction workers should use the “Not Recommended” postures to do their job. In that case, the real-time motion warning system would continuously send out alarms, which would disturb the wearers’ manual operation.

Third, the ergonomic rule for postural hazard warning does not consider individual differences among different workers. In the first research stage, we designed the motion warning algorithm based on an international standard ISO 11226:2000(E), which specifies the relationship between trunk inclination angle and corresponding maximum acceptable holding time (MAHT) defined as 20% of maximum holding time. According to the standard, neutralizing an awkward posture before its holding time exceeds the MAHT is one of the most effective approaches to prevent lower back pain (LBP). However, this international standard was developed based on a statistical average of a large population. It may not be effective for individual worker due to individual differences in terms of physical abilities, experiences, skills, and knowledges. Thus, the values specified in this international standard must be personalized to reflect individual postural pattern.

To tackle these two problems, we proposed to provide personalized recommendation of trunk holding time to an individual worker. To capture an individual's postural response to tasks and workplace when performing construction work, a Gaussian-like probability density function $f(x) \sim N(\mu,\sigma^2)$ is used to describe the range of holding time values around an interval of trunk inclination angles in a worker's performance. μ and σ^2 are the mean value and variance respectively. An individual response to workplace cannot be pre-measured in an experimental environment because it is a comprehensive outcome effected by both real-world task demand and individual capability, as shown in Figure 14.

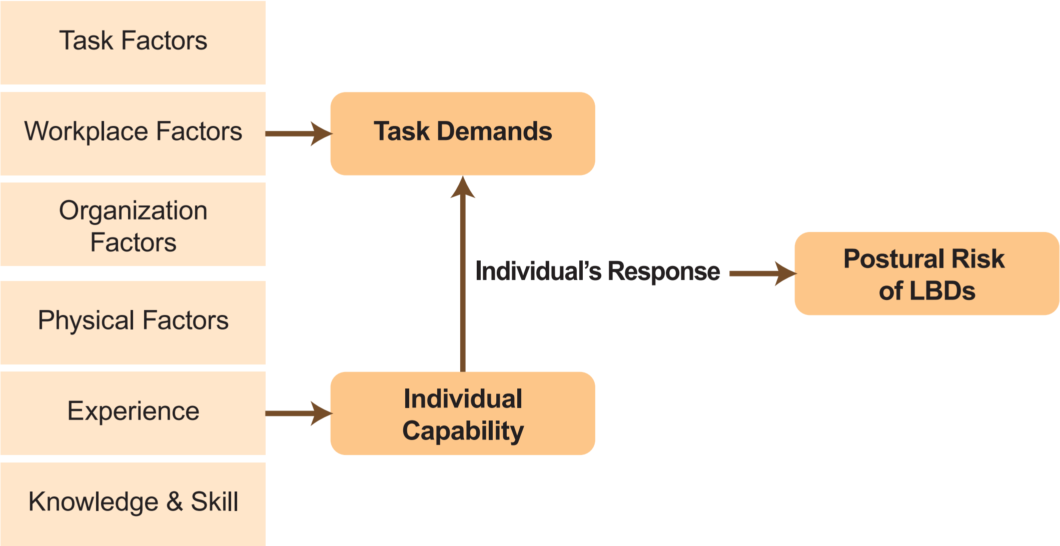


Figure 14 Individual's postural response model

Thus, to reveal an individual's postural response with implementing of worker-centric self-management, a prolonged period of trunk motion captured on a real-world construction site is required, which is used as a representative sample of individual's postural response. As both individual capability and task demand evolve with project progress, the parameters of Gaussian-like probability density function to assess individual's postural response are updated by new captured records. According to the procedure of updating individual sensor values, given the holding time values $\{T_i\}_{i=1}^{n}$ and the learned probability density function $f(x) = e^{-\frac{(x-\mu)^2}{2\sigma^2}}$, when a new holding time T_{n+1} of an inclination angle interval arrives, the updated functions for the new parameter values μ_{new} and σ^2_{new} are defined by Eq. (13) and Eq. (14).

$$\mu_{new} = \frac{n}{n+1}\mu + \frac{T_{n+1}}{n+1} \tag{13}$$

$$\sigma_{new}^2 = \frac{n}{n+1}(\mu^2 + \sigma^2) + \frac{T_{n+1}^2}{n+1} - \mu_{new}^2 \tag{14}$$

We separate the holding time values into normal ones and far from normal ones. The range of normal values for holding time is within $T = [\mu - 2\sigma, \mu + 2\sigma]$, in which unstable holding time values is excluded. After each updating, the holding time at $T = \mu + 2\sigma$ would be set as holding time warning threshold in the smart phone application. When the worker is in an abnormal status compared with historical status distribution, the warning system would be activated by the threshold. The duration of the alarm sound is around 0.5s so that it would not disturb an individual's normal performance. By providing data-driven personalized postural information and warnings based on individual historical working pattern, activeness of an individual worker is motivated in preventing LBDs and improving self-manage for ergonomic hazards. The proposed personalized healthcare method was tested on a construction site, as shown in Figure 15.

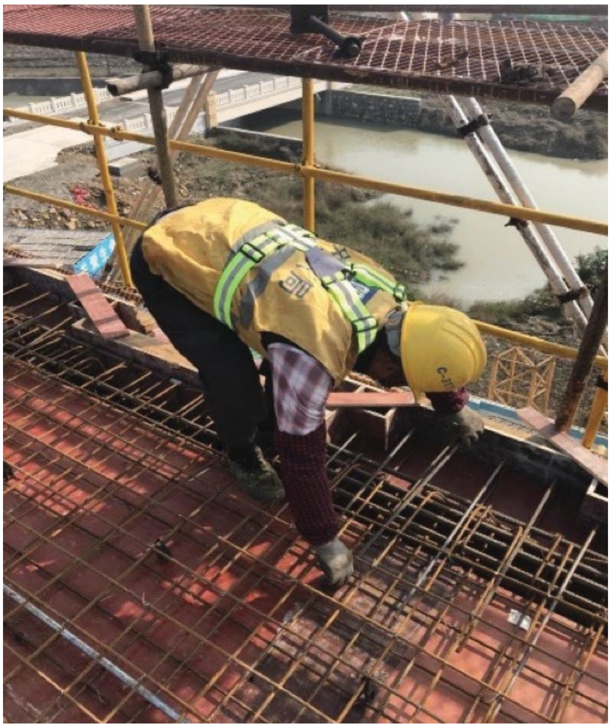


Figure 15 Field test

The field study is designed to contain three periods. In the 1st period, a trunk posture log from the subject was collected for 30 days by the proposed WIMU-based motion capture system. During this period, the alarm function was not activated. The collected trunk motion data are used as the initial sample for the capture of his postural Gaussian-like distribution of holding time, which is regarded as his postural response to the workplace and tasks. The occurred range of trunk flexion angles F are divided by an interval of 20°, as shown in Figure 16. From the captured personalized postural Gaussian-like distribution, it is noted that the holding time patterns are very different from the recommendations provided in the ISO 11226:2000. The holding time of dynamic postures is rarely larger than the “Not Recommended” thresholds in the standard.

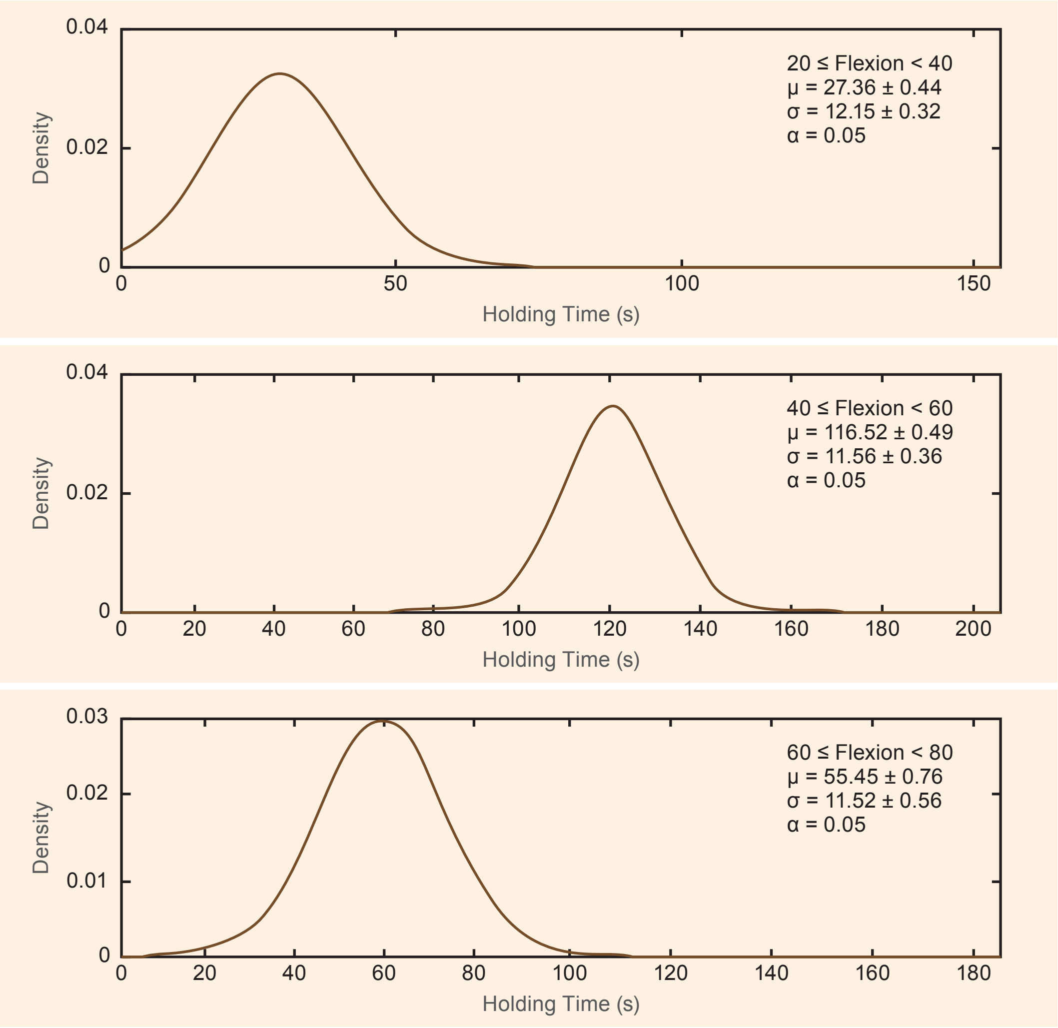


Figure 16 Gaussian-like probability density of holding time in the 1st period

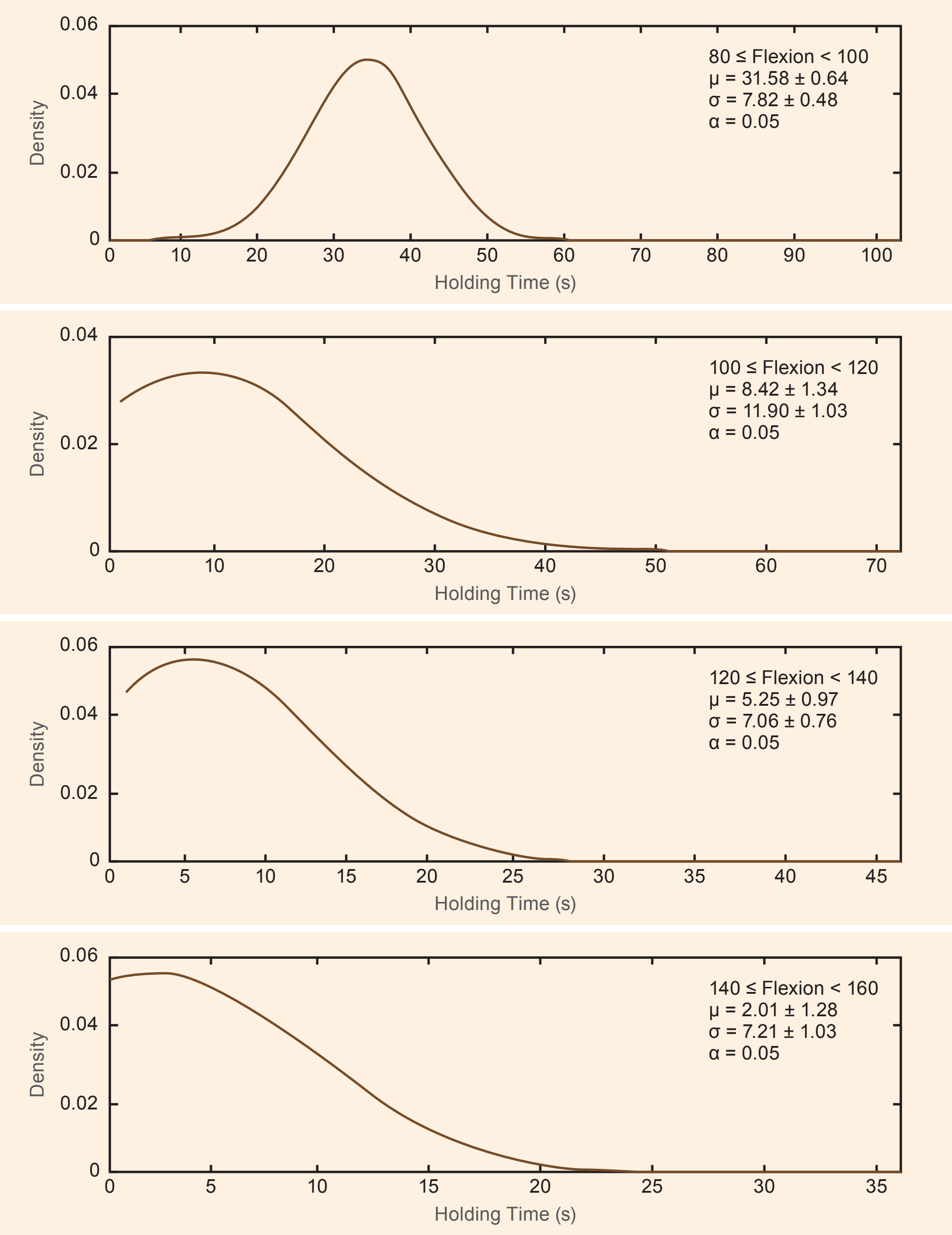


Figure 16 Gaussian-like probability density of holding time in the 1st period

In the 2nd period, the alarm function is activated in the developed smart phone application. Once activated, the alarm sound only lasted for 1 second in case the subject may not want to adjust postures due to task demands. The thresholds of each trunk inclination angle interval were updated by new parameter values μ_{new} and σ_{new}^2 during the subject's performance, which were updated by every new captured holding time. Figure 17 shows μ_{new}, σ_{new}^2, and new threshold in each iteration during a working hour. Based on the personalized alarms, the subject's self-management of ergonomically postural hazards lasted for 30 days. If the postural data have significant changes compared with that in the first period, the third period of field test would be activated.

Once the 3rd period is activated, the alarm function would be turned off and the system still collects the subject's motion data. The reason for the 3rd period is to examine the behaviour of the subject without personalized interventions. To objectively evaluate the subject's change in trunk posture, the variable status of trunk postures described by OWAS scores within two months are analysed. The OWAS method was designed to deal with the load on the musculoskeletal system caused by poor working postures by scoring the frequency of each posture and time spent in it. Once the frequency value of a recognized posture during a working period exceeds its limit, the corresponding action category will change from lower to higher, indicating the urgency of corrective ergonomic interventions. In each workday, the sum of scores from each defined back postures would be the final scores, which can represent the subject's postural response to ergonomic hazards according to his performance in each workday. We focus on three back postures: A. straight posture, B. back bent slightly, and C. back bent heavily, as listed in Figure 18.

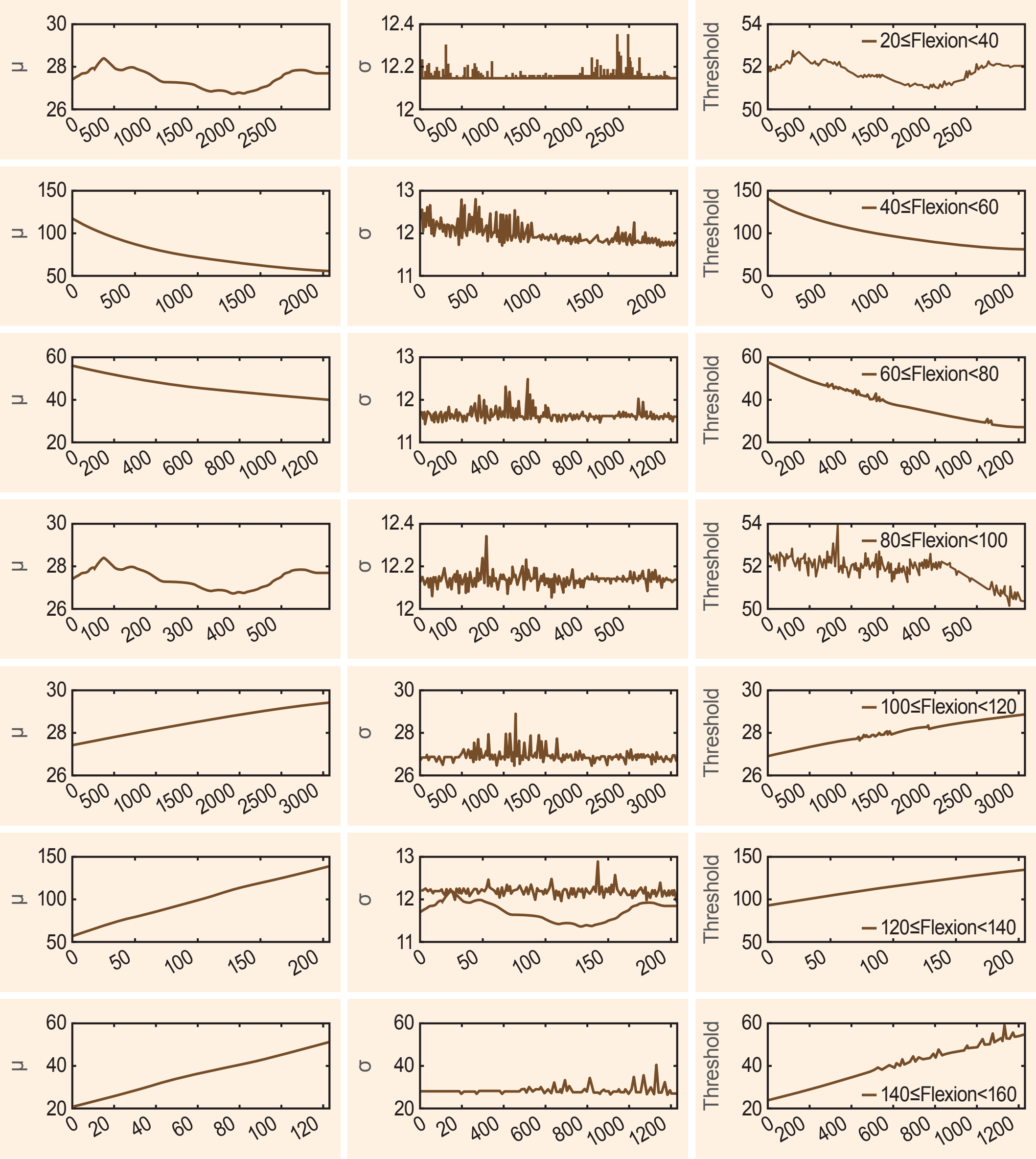
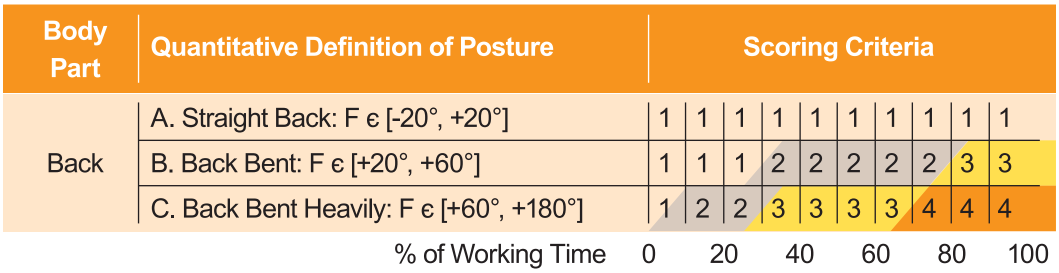


Figure 17 Updated μ_{new}, σ^2_{new}, and new threshold in each iteration.



Body Part	Quantitative Definition of Posture	Scoring Criteria									
Back	A. Straight Back: F є [-20°, +20°]	1	1	1	1	1	1	1	1	1	1
	B. Back Bent: F є [+20°, +60°]	1	1	1	2	2	2	2	2	3	3
	C. Back Bent Heavily: F є [+60°, +180°]	1	2	2	3	3	3	3	4	4	4

% of Working Time 0 20 40 60 80 100

Figure 18 Personalized OWAS-like Trunk Posture Evaluating Criteria.

A paired comparison *t*-test was used to determine any significant differences in trunk postural scores during the subject's working time. Field test results indicate that the subject's postural scores significantly decreased in the 2nd period compared with the scores in the 1st period (see Table 4 for overall mean postural scores in the 1st and 2nd field test period).

Table 4 Comparison of daily overall scores in the 1st and 2nd field test period.

Period	Daily Overall Scores (30 workdays)	Mean	*P-value* (0.05)
1st	6 8 8 7 6 8 5 6 7 5 3 8 6 4 7 7 6 4 5 8 7 7 7 6 4 3 3 8 7 7	6.0667	0.02
2nd	6 8 5 5 8 4 4 5 6 6 4 5 4 4 4 5 4 6 4 5 5 5 8 7 5 4 6 5 4 4	5.1667	

To further test: 1) whether the significant decrease is caused by personalized self-management with recommendation, 2) whether the worker can self-manage his postural responses without any recommendations or interventions, we activated the 3rd period of the field test for another 30 workdays. In the 3rd period, the subject's task was similar to that in the 1st and 2nd periods. The WIMU-based motion warning system was still used to capture and evaluate the subject's posture scores with the alarm functions turned off in the smart phone application. Two paired comparison t-tests are used to analyse significant differences in trunk postural scores, as shown in Table 5. The results indicate that there is an increase of postural scores in the 3rd period comparing with that in the 2nd period, but there are no significant differences comparing with the scores in the 1st period.

Table 5 Comparison of daily overall scores.

Period	Daily Overall Scores (30 workdays)	Mean	*P-value* (0.05)
3rd	4 4 6 7 8 5 7 3 7 7 6 5 4 6 8 7 7 6 5 6 7 8 6 4 8 5 5 6 6 8	6.0333	0.02
2nd	6 8 5 5 8 4 4 5 6 6 4 5 4 4 4 5 4 6 4 5 5 5 8 7 5 4 6 5 4 4	5.1667	
3rd	4 4 6 7 8 5 7 3 7 7 6 5 4 6 8 7 7 6 5 6 7 8 6 4 8 5 5 6 6 8	6.0333	0.93
1st	6 8 8 7 6 8 5 6 7 5 3 8 6 4 7 7 6 4 5 8 7 7 7 6 4 3 3 8 7 7	6.0667	

The significant rebound of the postural scores in the 3rd period indicates that without real-time personalized trunk posture recommendations, the postural working patterns of the subject turn to the patterns in the 1st period. This result reveals the positive effectiveness of worker-centric self-management based on personalized postural recommendations in the 2nd period. The field test provides positive support for applying worker-centric self-management based on data-driven personalized healthcare with recommendations on holding time.

4 RECOMMENDATIONS

Collectively, the results of the posture-comparison study 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.

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 & 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 & 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 & 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.

To alleviate and prevent WMSDs, especially LBDs, construction workers should control their working postures and holding time in trunk based on the proposed motion warning system. Construction project managers should use workers' daily postural scores to identify individuals with high ergonomic risk level, meanwhile improve workplace to reduce environmental ergonomic hazards.

In further research, our team would continue to improve the upper safety vest to be more comfortable-to-wear. In addition, we would improve the motion data capture algorithm to be more accurate. Furthermore, our team would combine computer vision-based ergonomic assessment method with wearable sensor-based ergonomic assessment method. Since computer vision-based method is non-intrusive and applicable in complex work contexts. We hope to explore the potentials of computer vision-based ergonomic interventions for construction workers who cannot wear sensors during operation.

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