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Wearable IMU-based real-time motion warning system for construction workers' musculoskeletal disorders prevention

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ABSTRACT

The prevalent work-related musculoskeletal disorders (WMSDs) around lower back and neck amongst construction workers are precursors of operational injury in the construction industry. As a significant risk factor of WMSDs, time spent in insecure operational postures should be proactively prevented. This study developed 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 WMSDs based on wearable Inertial Measurement Units (WIMUs). Data processing and real-time warning algorithms are proposed for automatically risk postures assessment and warning through a connected smartphone application as soon as dangerous operational patterns are detected. The system was tested and validated with robust clinical motion data output and effective alarm ringing in both laboratory and field experiments on a construction site in Hong Kong. The proposed PPE provides an alternative to help construction workers prevent WMSDs without disturbance and distraction in operations.

1. Introduction

Notwithstanding technological advances, on-site construction continues to be a labor-intensive and heavy manual industry [1,2]. The physical condition and health status of laborers remain to be a significant determinant of project performance [3]. However, a large percentage of work-related injuries remains to be a major concern and work-related musculoskeletal disorders (WMSDs) are amongst the most frequently reported causes of lost and restrictions in the construction industry [4], with general incidence rate of more than 30% according to the report of Bureau of Labor Statistics in the U.S. [5]. A survey by Forde, et al. [6] found WMSDs to be especially severe for rebar ironworkers that are predominantly concerned placing and tying reinforcing bars in in-situ concrete work. In particular, the prevalence of self-reported lower back pain is high as 56% amongst rebar ironworkers in this survey. Many manual operations on construction site like rebar ironwork require workers to maintain non-neutral trunk postures such as stooping, squatting and kneeling for long working hours during workdays, which significantly increases the risk of lower back injuries [7,8]. Thus, it is of great importance to provide practical cost-effective solutions for on-site construction workers against postural hazards that significantly contribute to WMSDs.

Driven by the severe situation regarding to WMSDs around lower back and neck amongst front-line construction workers, practices for postures and body movement evaluations in the workplace have been conducted to assess postural hazards of WMSDs [9–11]. Nowadays, the development of Inertial Measurement Units (IMUs) enables a precise measurement of postures and body movements for safety management in the construction industry [12–14]. Inertial sensor has been improved to be effective for the measurement of trunk inclination [15]. An activity tracking system based on IMUs for postural hazards assessment was also proposed for musculoskeletal disorders assessments [16]. However, on-site real-time alarms feature was not developed in previous researches. As a result, ergonomic assessment or evaluation can only be provided to workers after their operations, in which ergonomic hazards may already cause negative consequences before the assessment. The workers cannot make timely adjustments to protect themselves from ergonomic risks, which is not sufficient for real-time WMSDs prevention on site. Real-time ergonomic assessment would be more effective for workers to understand what types of manual operations are ergonomically hazardous and how can they make adjustment and improvement to reduce the occurrence of them. In the context of on-site safety management against WMSDs in the construction industry, to prevent is always better than to cure [17]. In some cases, on-site workers, especially young workers who temporarily do not percept musculoskeletal disorders pain, would relatively underestimate the invisible and cumulative chronic disorders stemming from ergonomically hazardous operational postures and holding time

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comparing with obvious traumatic or fatal injury. Such situation requires a move towards both self-awareness and self-management of the potential disorders with proper ergonomic disciplines and portable protective equipment to effectively prevent WMSDs in advance [18], rather than post hoc assessments and post-rehabilitation that should consider multifactorial pathophysiology including physical, psychosocial and organizational elements [19], which is unfit and not cost-effective for safety management on construction site. In addition, previous IMU-based interventions did not consider adequate recovery time following the holding time based on endurance data for a certain captured body movement, as is emphasized in the Technical Report ISO 11226:2000 [20] for WMSDs prevention. Thus, contribution that can solve the aforementioned problems should be made for real-time construction workers' WMSDs prevention in a practical way.

This paper has improved and validated the IMU sensor technology, turning it into wearable sensor-based real-time motion warning personal protective equipment (PPE) that is capable of automatically assessing ergonomically hazardous postures and warning the wearer with chosen alarms through a connected smartphone application as soon as ergonomically hazardous operational postures and holding time leading to lower back and neck pain are detected. Such dangerous behavior and holding time thresholds are preset into the IMUs sensor-based system according to the ISO 11226:2000 [20]. The standard is a landmark in musculoskeletal disorders prevention and control [21], specifying recommended limits and acceptable body kinestate in terms of body angles and time frame for operational postures. A smartphone application is attached for dangerous motion assessment and alarm delivery using received data. Several types of alarms are carefully chosen for practical concern. Individual wearers can choose their preferred type of alarm, which can gently remind individuals whether their real-time operational postures are ergonomically hazardous, without interferences to their proper operations. Construction workers will benefit from the self-awareness of risk postures that may lead to lower back and neck pain: they will be able to timely adjust head, neck or trunk postures to more acceptable manners [20] in order to decrease WMSDs risks in advance. Also, the system may help construction workers better understand the ergonomic hazard level of their actions by the frequency of individual alarms.

The following sections of this paper outline the literature review of this research logically sorted by WMSDs risk factors assessment, posture analysis techniques in ergonomic hazards assessment, and indications of self-management and self-awareness strategy for effective WMSDs prevention. The paper then provides the motion data capturing and processing methods used in the PPE. Both laboratory experiment and field experiment, which was conducted on a construction site in Hong Kong, are described to demonstrate the validity of the proposed wearable IMU-based motion warning system. Finally, the discussion summarized from the results, the limitations of the current research and future work are presented.

2. Research background

Unfortunately, the construction industry has always been prone to be afflicted by WMSDs. According to the illustrations found in [22,23], 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 [24] and are representative precursors of WMSDs amongst construction workers. Thus, WMSDs around lower back and neck are prioritized in this paper accordingly.

2.1. Risk factors of lower back and neck pain in the construction industry

Risk factors are ergonomic hazards with significant causal relationships to WMSDs, and should be carefully evaluated in its specific context rather than in isolation [25,26]. Current risk factors of WMSDs around lower back and neck amongst operational workers in the construction industry are generally divided into three categories: physical (biomechanical) exposure as a primary factor, psychosocial stressors, and individual factors amongst different tasks. Individual factors include workers' age, gender, and operational habitus. Psychosocial stressors have been shown to mainly derive from frequent tiredness or pressures and were reported to have a relatively strong association to neck pain [27]. Another survey indicated that psychosocial factors were not significant to lower back pain [28]. Further investigations remain to be conducted with larger samples. Both of the aforementioned two risk factors vary amongst different individuals, projects and regions, resulting in complex issues to be controlled from a perspective of cost-effective on-site safety management.

In general, comparing with the aforementioned individual factors and psychosocial stressors, work-related physical postures and holding time have been proven to be statistically significant risk factors for WMSDs, especially with regard to lower back pain [29–31]. 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. [32] 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 operational 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 are taken as major concerns in the proposed system for real-time warning for WMSDs prevention. The human body is a precise dynamic system capable of comprehensive feedbacks for the risk factors of WMSDs. In order to fully recover from WMSDs, multifactorial treatments should be developed clinically that consider individual differences. However, such endeavors may have low outcomes with high costs in the construction industry. From a perspective of practical on-site safety management, it is more efficient and cost-effective to prevent WMSDs amongst detectable and containable hazards exposed by in-situ operational workers in advance rather than when it is too late to mend.

2.2. Posture analysis techniques in ergonomic assessment

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 the “Rapid Entire Body Analysis” (REBA) [9] for the whole body posture analysis; “Posture, Activity, Tools and Handling” (PATH) [10], an ergonomic analysis of non-repetitive work using a sampling approach; “Portable Ergonomic Observation” (PEO) [33], a computerized posture data collection and analysis method; “Rapid Upper Limb Assessment” (RULA) [11], a method focusing on upper limbs; and “Ovako Working Posture Analyzing System” (OWAS) [34] 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, the resulting research patterns provided valuable insights for the present posture analysis and description of physical demands.

Current researches into 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 [22]. As markerless-based assessment methods, vision-based techniques rely on the selection of appropriate camera positions and may suffer from occlusion. The obstacles of using this method include the dynamic conditions of construction sites and the diverse viewpoints of comprehensive image datasets [35]. 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 [12,13,36] as well as addressing the limitations of vision-based methods. The IMU sensors also have a great potential in the ergonomic domain. Not only are the wearable IMUs capable of automatically capturing posture data in a more reliable way, they also help 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 are also inspiring. For example, Bastani et al. [37] 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. [38] 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 lower back pain and asymptomatic control. The body movement output of IMUs was also used in physical rehabilitation [39] and ergonomic assessment of manual tasks [16] and operations in the industrial environment [40]. However, on-site real-time alarms feature was not developed in previous researches. Ergonomic assessment can only be provided to workers after their manual operations, in which ergonomic hazards may already cause negative consequences before the assessment. As a result, the workers cannot make timely adjustments to protect themselves from ergonomic risks, nor can they understand what types of manual operations are ergonomically hazardous and how can they make adjustment and improvement to reduce the occurrence of them, which is not adequate for real-time WMSDs prevention on construction site. A move from post hoc ergonomic assessment to real-time prevention of WMSDs around lower back and neck should be made concerning the unique conditions in the construction industry. More practical and effective solutions for construction workers' WMSDs prevention remain to be developed.

2.3. Self-awareness and self-management for effective WMSDs prevention

WMSDs prevention and their pain managing are not only medical matter; it is about construction workers managing their feelings and reactions to potential conditions in which pain may influence the ways of body movement and the ability to work. Equipment that can enable individual workers to have the right disciplines of WMSDs prevention will allow them to stay in control of their potential risks to musculoskeletal disorders rather than letting the disorders accumulate and allowing the disorders to control them [18]. Considering the high prevalence of WMSDs around lower back and neck and their costly work-loss and healthcare expenditure in the construction industry, as well as the harsh and complex on-site environment, early awareness and management of potential lower back and neck pain is the best approach to preventing the disorders [41]. A move towards self-awareness and self-management is central to health care strategy around lower back and neck pain [18,42], which can support construction workers by pro-active independent self-prevention against WMSDs.

Several healthcare system empowering patients in self-management provide insights for the proposed motion warning system for construction workers' WMSDs prevention. For example, Chang, et al. [43] introduced a valid and economical self-management and self-awareness model enabling effective osteoporosis prevention for women at risk. Rovini, et al. [44] proposed a cooperative Information and Communication Technologies (ICT) system with the use of two wearable inertial sensors that enable self-management of Parkinson's disease. These approaches have indicated the effectiveness of the move towards self-awareness and self-management of potential musculoskeletal disorders in health care strategy and safety management in the construction industry. However, such move towards self-awareness and self-management of WMSDs prevention in the safety management of the construction industry remains to be a gap that urges practical and cost-effective solutions based on both identified risk factors of lower back and neck pain and adaptable WMSDs intervention technologies. It should be noted that the effectiveness of self-management and self-awareness of WMSDs may varies in different context [45]. Considering the importance of WMSDs prevention and the unique situation of the construction industry, in which on-site workers are usually exposed to heavy manual tasks, portable devices that can warn workers for their ergonomically hazardous operational actions could help them better self-aware and self-manage their operational patterns.

This paper proposed a WIMU-based real-time motion warning system for construction workers' WMSDs prevention by comparing captured operational postures (in a clinically meaningful way) and holding time with preset ergonomic risk thresholds using specific algorithms preset in an attached smartphone application. Such system makes workers self-aware of their operational risk status precursory to WMSDs around lower back and neck, by which proper adjustments [20] can be made according to different working conditions. The system may also help construction workers better understand the ergonomic hazard level of their actions by the frequency of individual alarms so that they could gradually make a habitus of more proper and less ergonomically hazardous operational pattern.

3. Overall design of the PPE

Based on the above review and discussion, this section shows an illustration of the system framework, algorithm development of the WIMU-based system and how the developed design guarantees for on-site self-awareness and self-management of risk factors leading to lower back and neck pain.

3.1. Framework of the WIMU-based real-time warning system

Figs. 1 and 2 depict the system framework and components of the WIMU-based (YEI 3-Space Sensor™ Bluetooth) real-time motion warning system. Final orientation of outputted quaternion translated from angular motion, acceleration due to gravity, and magnetic direction, which are generated by 3-axis accelerometer, 3-axis rate gyro, and 3-axis compass respectively, is adjusted to be more accurate and reliable by the preset Kalman filter after calibration of the sensors. The Kalman filter mode has its own set of trust values ranging from 0 to 1 to balance between the smoothness of the motion and drift. Meanwhile, for better reliability, two IMU sensors were mounted firmly on the back of a safety helmet with Velcro tape and middle-upper part of the wearer's back by a strap and rubber sleeve holding the sensor under a safety reflective vest. This can avoid rotational noise caused by unstable adherence. It should be noted that when providing practical devices for on-site operational workers to prevent WMSDs using real-time captured data, compromise between theoretical accuracy and practical utility is inevitable, due to the harsh conditions and in-situ environment around workers. Through careful balancing, two sensors were equipped in the wearable system, which can guarantee the reliability and accuracy based on the head, neck and trunk inclination calculation methods provided in ISO 11226:2000 (E), while also giving consideration to operational convenience for practical utility in the construction industry. Detailed algorithms are illustrated in the following sections. The locations of the two IMU sensors were also selected carefully according to the anatomical landmarks [15,46], because the location of the sensors also influence the accuracy of captured data [47]. The arrangement of these IMU sensors in the wearable PPE was validated by practitioners to be convenient during repetitive operational tasks in a construction site in Hong Kong.

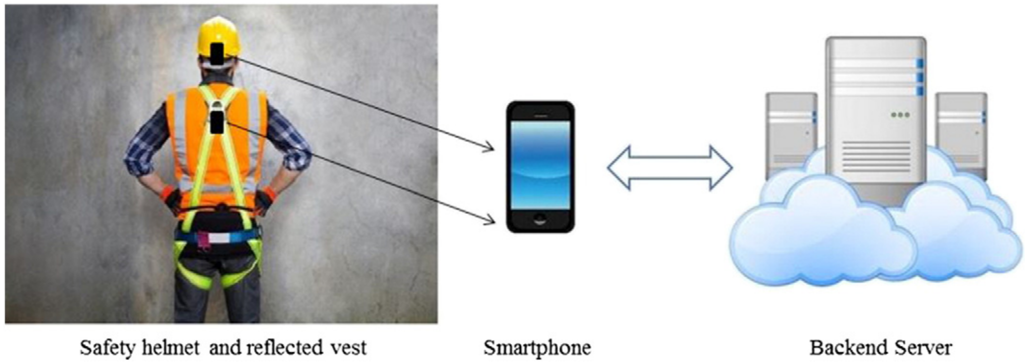

Fig. 1. The WIMU-based real-time motion warning system framework.

Additionally, a smartphone application was developed to receive and process motion data captured by WIMU sensors via Bluetooth technology. Real-time sensor output is transferred to the attached application for data processing. Raw unit quaternion vectors generated by IMU sensors depicting the kinestate of body segments are translated into clinically meaningful parameters in term of flexion-extension, lateral bending and axial rotation of relevant body segment including head, neck and trunk, with respect to calibrated reference coordinates [48] achieved by a real-time data processing algorithm. These clinical outputs will simultaneously join an evaluation procedure that leads to 'acceptable' or 'not recommended' judgements according to ISO 11226: 2000 (E), and will be compared with predefined insecure angle thresholds of head, neck and trunk inclination. If the value of real-time operational angle becomes larger than the angle threshold of a treated part of body, the alarm system of the application will be activated by the warning thresholds algorithm to send out alarm sounds, warning workers that their current operational posture has a high risk leading to WMSDs if not being paid attention to and adjusted according to the standard. On the contrary, if the values of a real-time operational angles are less than the predefined insecure thresholds yet still larger than the acceptable thresholds, the algorithm will start to estimate their according accumulated holding time based on the linear relationship between static inclination angles of body segments and maximum holding time (MHT). Once the accumulated holding time is larger than the accumulated maximum holding time of a set of operational postures whose angles of inclination lie between the acceptable and insecure thresholds, the application alarm system will send out a different alarm sound, suggesting adjustments of current operational posture or an available pause for respite from the mentioned postures.

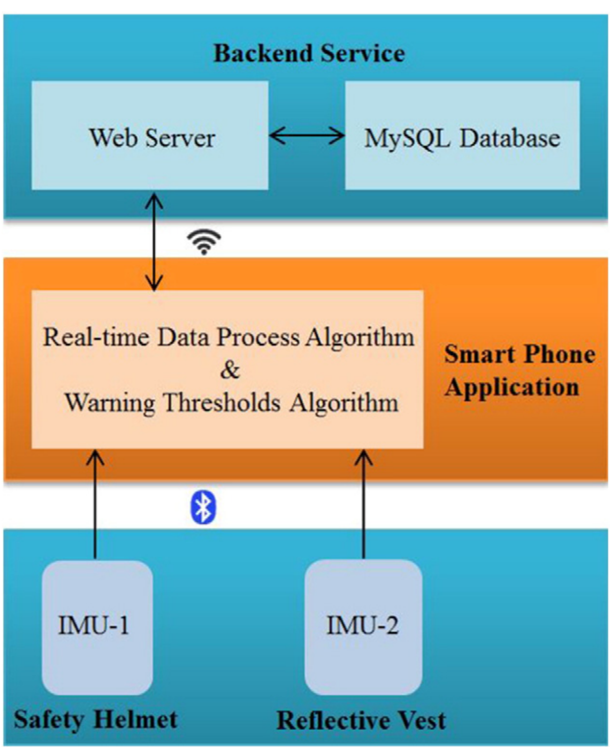

Fig. 2. The system components.

Furthermore, all operational motion posture data received and processed will be transferred to our safety management database in the backend server through site Wi-Fi. A large quantity of on-site practical operational motion data would enable us to accurately assess individual ergonomic hazard level, which will contribute significantly to on-site safety management and individual ergonomic training.

3.2. Motion data collecting and processing

The head and trunk are defined as two straight lines perpendicular to the plane of symmetry of the segment from the side view when a user looks straight ahead. The description and capture of the inclination illustrated in the standard are adjusted without losing reliability for convenient and practical purposes. As Fig. 3 shows, the procedure begins with marking two points on both the trunk and the head segments denoted by T1-T2 and H1-H2, respectively. The angle between the vertical broken line and the solid line T1-T2 in the standard is 4°. H1 and H2 are located closely to the lobe of the ear and the lateral corner of the eye respectively. Next, based on the aforementioned arrangements, the inclination angles of head and trunk are defined as the relative displacement angle of H1–H2 and T1–T2 around point H1 and T1 respectively. The two IMU sensors are then located rigidly on the back of the safety helmet and the middle-upper part of the back. 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 the movements of the solid line T1–T2. 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:

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

The normalized vector $N(V_{neck})$ can then be translated into the kinestate of neck through the following algorithms.

Based on the aforementioned locations and arrangements, the real-time data captured by both IMU-1 and IMU-2 is comparable with the recommended references in the ergonomic standard, which are predefined in the smartphone application for insecure operational posture and holding time monitoring as well as dangerous state alarming.

The tilt/twist method [49] is referred and adjusted for the algorithms in the system framework. The real-time motion parameters of the three

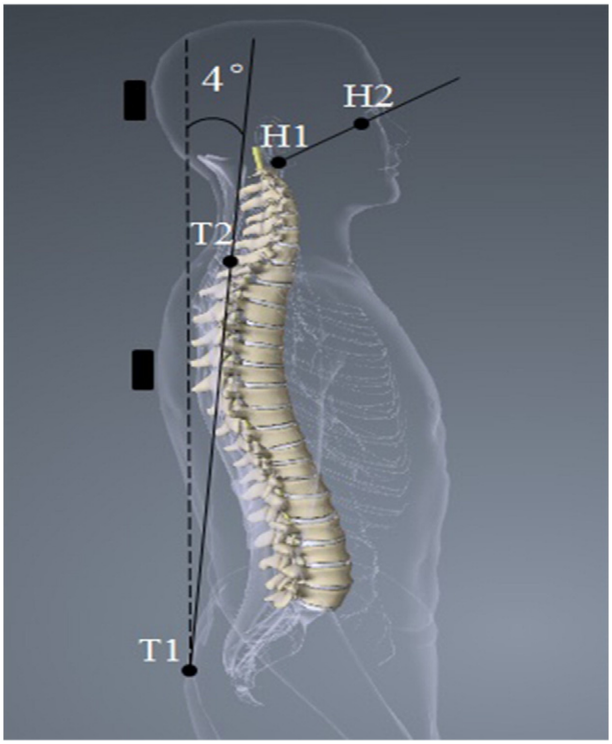

Fig. 3. Determination of head and trunk inclination.

body segments captured by the two IMU sensors can be transferred into the clinically intuitive format of flexion-extension, lateral bending and rotation [48] through the postural data processing algorithm. Real-time angles of postures can be reflected on the attached smartphone screen for posture monitoring purpose. The output of each sensor is the following normalized quaternion.

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

where $\|q\| = 1$. Taking IMU-2 as an example for illustration, the sensor's initial calibration state in default reference coordinate is shown in Fig. 4(a). Two initial unit vectors are utilized to represent the calibrated state of each 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 Fig. 4 (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 that is generated by IMUs. Thus, the coordinates after rotation of both p_1 and $p_2$in quaternion formats can be represented as:

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

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

Tilt angle can be determined by using the projection of unit vector p_1' onto the Y-axis (see Fig. 4 (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 counterclockwise range to 180°.

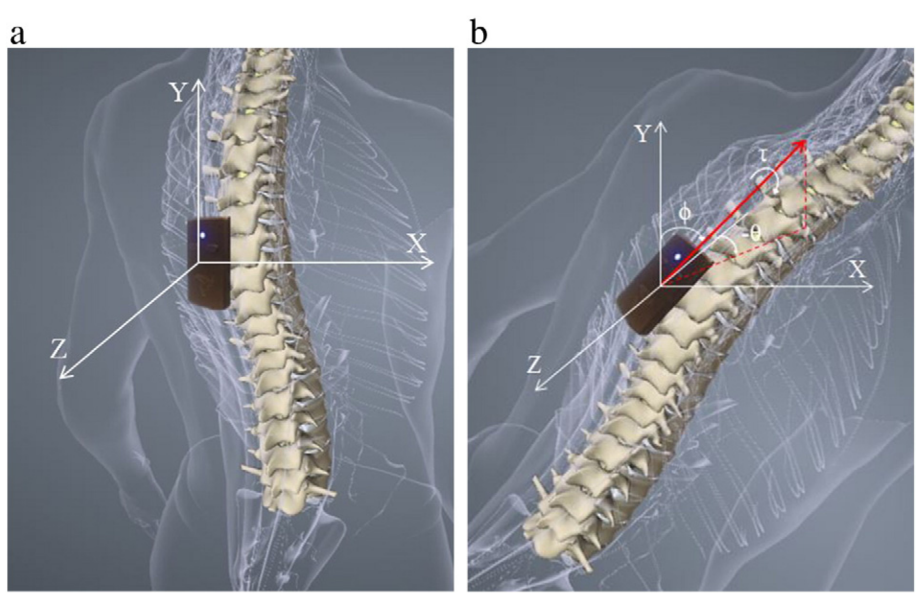

Fig. 4. (a). Trunk IMU sensor calibration in reference coordinate, (b). Trunk inclination tilt (ϕ), tilt azimuth (θ) and twist (τ) angles.

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 (counterclockwise). 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. It should be noted that the motion angles of both head and neck are relative to the trunk. As a result, the motion angles of both head and neck are determined by their real-time angles relative to the calibration position minus the motion angles of trunk.

3.3. Real-time warning threshold algorithm

The real-time warning threshold algorithm in the WIMU-based motion warning system 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 Fig. 5 [20].

The 'Acceptable' zone indicates that a worker's angle of trunk inclination during operation is ergonomically safe. The 'Not Recommended' zone represents a high risk of lower back pains once the angle of trunk inclination is over 60° during manual operations. 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 suggested,

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

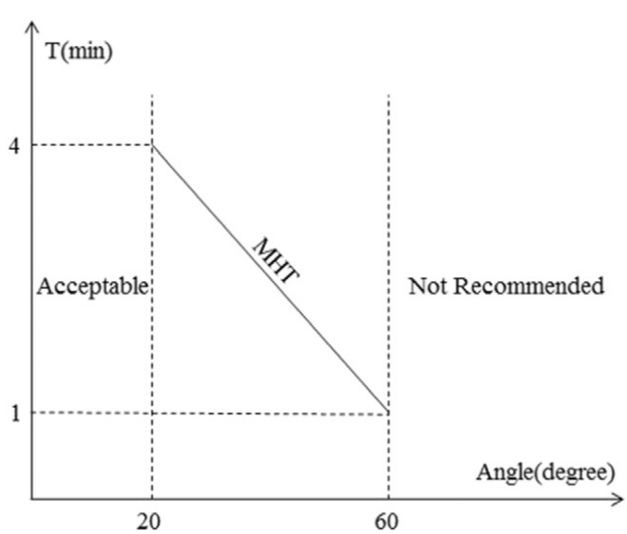

Fig. 5. Maximum holding time vs. trunk inclination.

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,

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

Previous research has revealed that dynamic movement results in longer endurance times than that in static tasks [50] 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. The actual period of time in which insecure postures are detected by the algorithm is determined by $\Delta t = \Delta n/f$ (unit of Δt: s). Once the actual period Δt is larger than the accumulated maximum holding time, the smartphone application will send out an alarm warning, indicating that the current angle of trunk inclination between the 'Acceptable' and the 'Not Recommended' zones has lasted for a period that can significantly increase the risk of WMSDs around lower back pain.

The pattern of the alarm system took consideration of both the thresholds provided in [20] and practical concerns. Previous study revealed that safety warnings received on a discriminating alarm that requires positive feedback is more effective than warnings from a conventional backup alarm, which could not only let the wearer find out the source of hazards, but also significantly reduce the rate of accidents [51]. Here, the alarm sent out by the attached smartphone will be silenced when the wearer adjust the improper posture to acceptable one defined by the ISO mentioned above. Such positive feedback is expected to change the wearer's reaction to alarms with an active response, which has the potential to improve the wearer's operational patterns. In addition, previous experimental research revealed that workers may response to alarm warnings actively, but differently across the selected building trades [52]. Thus, the time span and types of the alarm warnings in the proposed equipment can be set by individual workers according to their trades and preference of operational habitus. From a perspective of on-site safety management, a system like the one proposed in this paper should neither disturb workers' normal operations, nor distract them in the first place. As a result, the alarm sounds are chosen to be gentle bells without hoarseness when risky postures are detected.

4. Experiment and validation

A laboratory experiment was first carried out to validate the proposed WIMU-based real-time motion warning system with a data capturing rate 10 times per second, which is tested in the following experiments to be detailed enough, stable and energy efficiency for long-term service. After IMU sensors calibration, the laboratory experimental subject started to do some basic movement in sequence in terms of flexion, extension, right lateral bending, left lateral bending, right rotation, and left rotation in head. These are shown in Fig. 6 as an intercepted part of the obtained motion data from our safety management database in the backend server. The red solid line indicates the flexion-extension mode, the green dotted line indicates the lateral bending mode, and the black chain 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 move his trunk

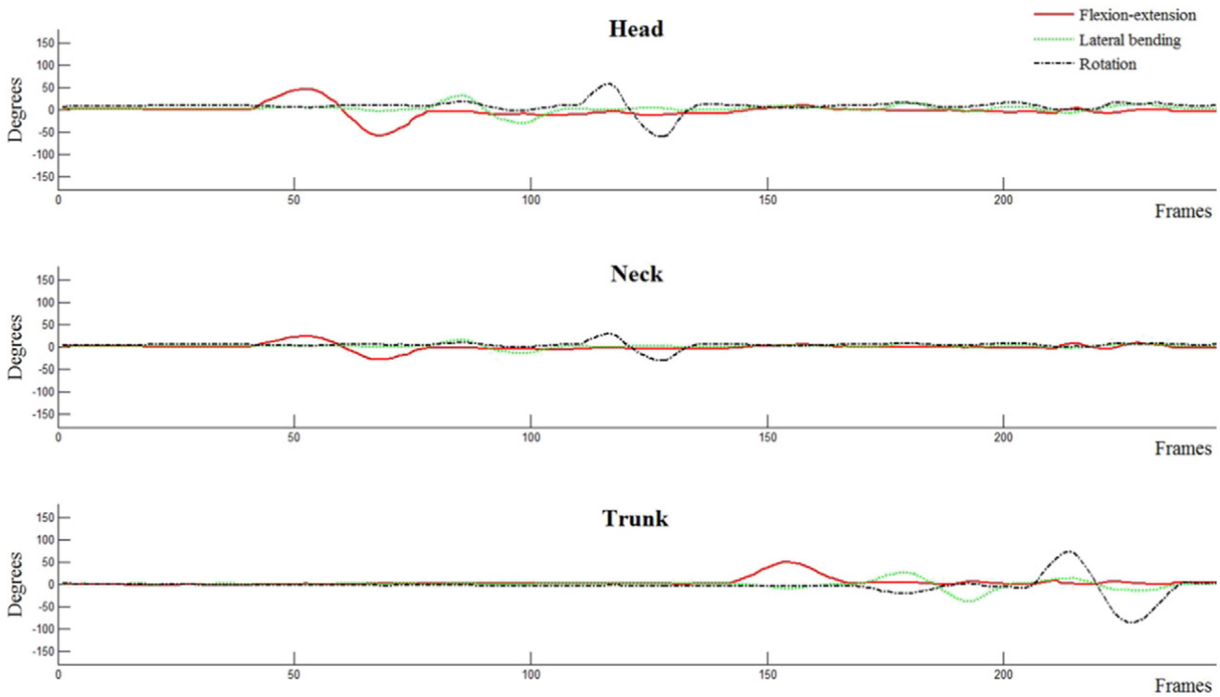

Fig. 6. Real-time motion data captured by the system.

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 are relatively smooth with minor changes. From Fig. 6, 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 PPE system.

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. Fig. 7(a) and Fig. 7(b) illustrate two intercepted parts of the captured motion data in the laboratory experiment. As shown in Fig. 7, the smartphone application attached to the motion warning system enable individual wearer connect their wearable equipment to the smartphone via Bluetooth and calibrate the IMU sensors. 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 on the smartphone screen. Once ergonomically hazardous operational postures are detected by the predefined real-time warning threshold algorithm, alarm will be sent out to warn individual wearers to 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 press 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 system.

To further validate the practical utility and reliability of the proposed WIMU-based motion warning system, field experiment on a construction site in Hong Kong was conducted. Two scenarios are shown in Fig. 8(a) and Fig. 8(b). It was reported by the on-site workers involved in the experiment that the proposed personal protective equipment can help them recognize hazardous postures without disturbing their operations. Some of them, especially workers under age of 35, can gradually change previous ergonomically hazardous operational patterns by interacting with the real-time warning system. As shown in Fig. 8(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 wearing the proposed PPE, improvement has been made in his operations (Fig. 8(b)), which indicates 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.

5. Conclusions

This paper propose a WIMU-based real-time motion warning system that enables construction workers self-aware and self-manage of risk factors precursory to WMSDs around lower back and neck without disturbing their operations. A smartphone application is attached to receive and process real-time motion data captured by the IMU sensors fastened rigidly to the back of a worker's safety helmet and middle-upper part of the wearer's back. Equipped with the proposed system, the worker can operate normally and be aware of postures and holding time that lead to WMSDs around lower back and neck pain. The overall design of the system in terms of sensor arrangement, clinically meaningful motion data collection, and warning mechanism is illustrated in the paper. In order to gather clinically meaningful kinetic motion data, a real-time data process algorithm is developed to transfer quaternion data into real-time angles of flexion-extension, lateral bending and rotation. In addition, a real-time warning threshold algorithm is also indicated and imbedded in the smartphone application for detection and self-prevention purposes. Both laboratory and on-site experimentation of the clinically meaningful kinetic data capturing algorithm and alarming mechanism were conducted to demonstrate and validate the WIMU-based real-time motion warning PPE. The carefully chosen alarm sounds enable construction workers to adjust their postures and time spent in high risky postures. Not only can workers benefit from the proposed PPE, construction project performance can also be improved thanks to healthier workers and lower safety expenses.

In the construction domain, the development of the proposed personal protective equipment could have a wide range of applications in almost every work trade exposed to harsh operational environments and high prevalence of WMSDs. The humanized sensor numbers, locations and carefully chosen alarm sounds make it suitable and practical for site safety management. The smartphone application, together

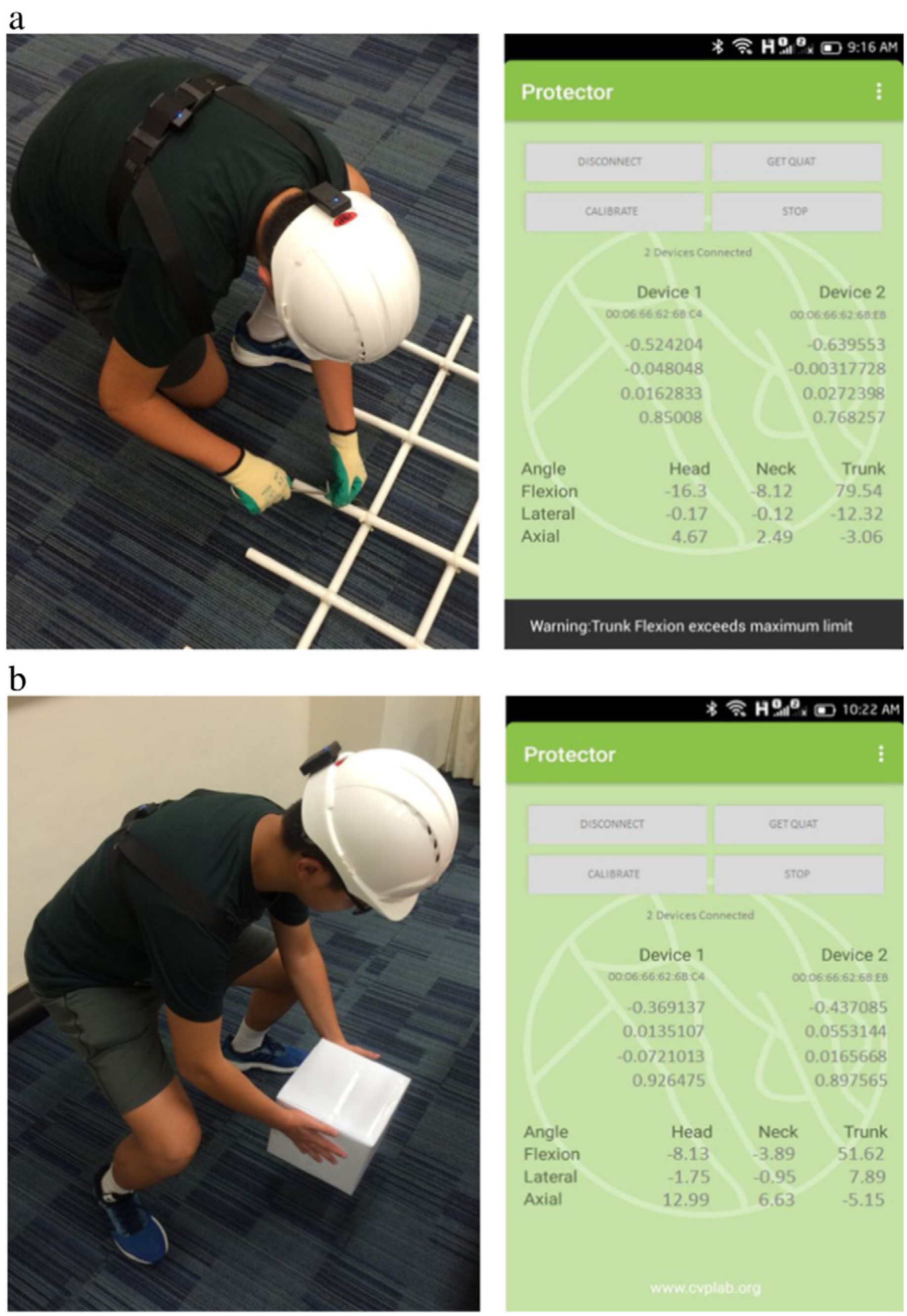

Fig. 7. (a). Laboratory experiment-imitated rebar tying, (b). Laboratory experiment-imitated brick lifting.

with our safety management database can be further developed as an ergonomic hazard monitoring platform for construction safety managers, from which on-site workers' musculoskeletal health status can be captured and monitored. Operational postural data stored in the backend server might also enable safety managers to better analyze the patterns of individuals for more effective ergonomic trainings. The collected clinically meaningful motion data could also be valuable for analyzing the relationships between operational workers' behavior patterns and construction site arrangements. Generally, the proposed WIMU-based real-time motion warning system for WMSDs prevention amongst construction workers has practical values and economic benefits thanks to the small size, cost-effectiveness and particular suitability for construction operations.

There are still challenges to be solved in future research and development. For one thing, as tested in the on-site experiment, current IMU sensors need to recharge after a nearly six-hour service with an output frequency of 10 frames per second. With consideration of energy efficiency, further hardware updating regarding the IMU sensor should consider adding a solar charger into each unit. For another, the accuracy of the captured body segments kinestate by the WIMU sensors may vary upon different people due to different skeletal structures and body sizes. Supplementary studies on WMSDs prevention using WIMU sensors need to be conducted to develop algorithms that refer to more concepts in the clinical domain to improve the accuracy of the system. Additionally, more on-site experiments should be conducted to quantitatively validate the effectiveness of the self-management strategy in WMSDs prevention based on the proposed equipment for its popularization in the construction industry in order to serve and help more on-site construction workers in lower back and neck pain prevention.

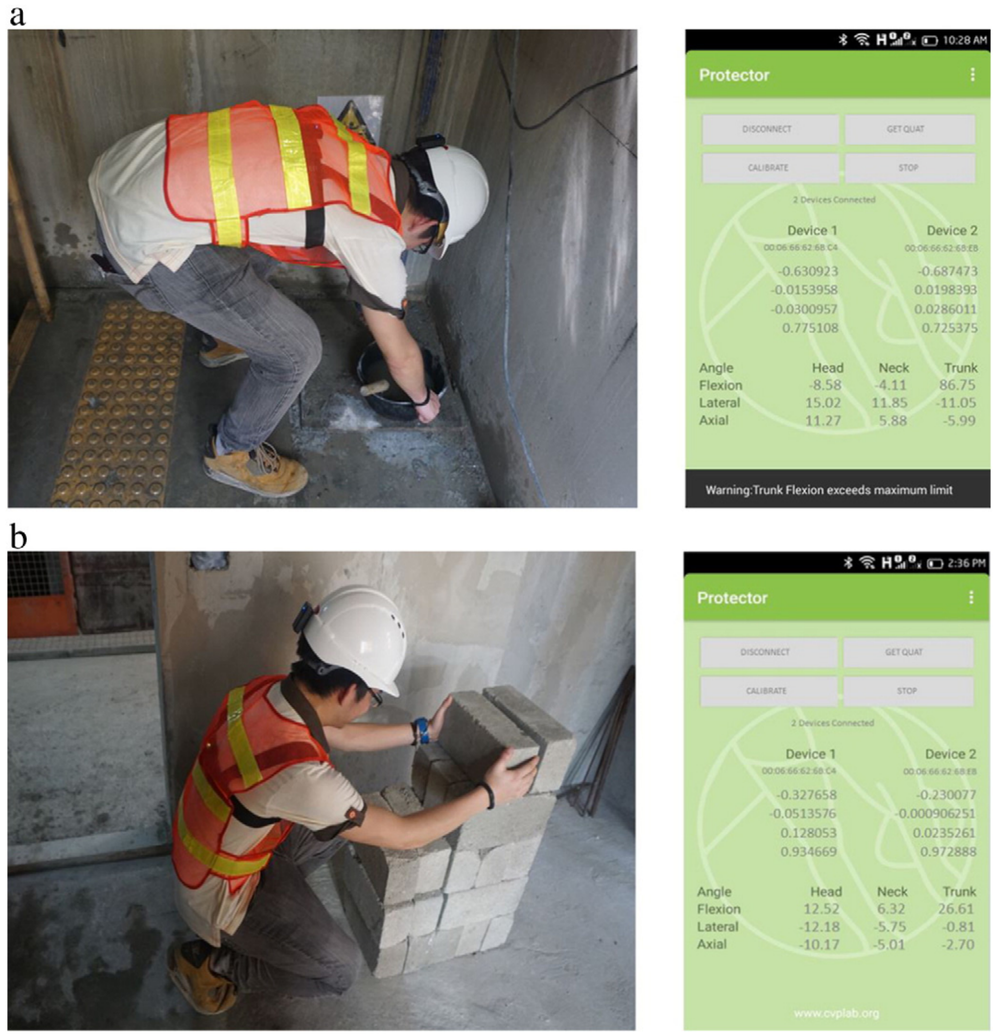

Fig. 8. (a). Break-in period for one tester wearing the PPE in the field experiment, (b). Adjustment made by the tester according to the warnings from the PPE.

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