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A case study of motion data-driven biomechanical assessment for identifying and evaluating ergonomic interventions in reinforced-concrete work

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ABSTRACT

Physical ergonomic intervention (e.g., use of tools) is adopted to improve working postures in the reinforced-concrete trade. However, evaluating its effectiveness often focuses on a specific body part mostly concerned although posture modification in one part may physically affect another. This paper presents a case study to comprehensively examine the effectiveness of existing ergonomic interventions. In the experiment, a subject repeated typical motions 15 times, which served as the baseline of biomechanical simulation with the 50th percentile of the anthropometric size of the U.S. population. 3D-motion-capture and biomechanical simulation were then adopted to collect full-body posture data and compute the load exerted on body parts with population strength capability. The results indicated that the disc compressions and joint moments were reduced by 45.41% and 31.86% whereas the effectiveness varied among the body parts (e.g., elbow, shoulder, knee). These results suggest that ergonomic interventions can lessen physical demands by carefully selecting an appropriate intervention for specific tasks and body parts in practice.

1. Introduction

Reinforced-concrete (RC) structures are widely used and constructed for the availability of materials, their stability in responding to various climates and tectonic shifts, and their economic effectiveness with regard to construction and maintenance (James, 2016). Compared with other types of structures (e.g., steel structures), RC structures rely more heavily on a manual workforce to accomplish reinforcement installation, formwork installation, and concrete placement (Cheng et al., 2013). Consequently, RC workers are frequently exposed to excessive workloads involving physically demanding and repetitive tasks (Moran, 2003). Such characteristics of RC work may have resulted in the highest rates and compensation claims of work-related musculoskeletal disorders (WMSDs) for the foundation, structure, and building exterior contractors (in which the RC trades are involved) among construction trades (AbdulHafeez and Smallwood, 2018; Dale et al., 2017). The development of these WMSDs have social and economic consequences, such as body degeneration and eventual injuries, early retirement, and low productivity (Kramer et al., 2010; Welch et al., 2015). Accordingly, mitigating musculoskeletal risks among RC workers is important not only for protecting the health of the workforce and sustaining their employment but also for reducing the economic and social costs of WMSDs.

To reduce the incidence of WMSDs, ergonomics interventions have been proposed and implemented as a tool which the construction industry can utilize to reduce work related injuries on construction sites by focusing on designing equipment, tools, tasks and the working environment for the individual worker (AbdulHafeez and Smallwood, 2018). These ergonomics interventions have been proposed in the form of organizational, administrative, and engineering controls applied through various workplace ergonomics programs (e.g., exercise, rest, workplace rotation, and change of tools); however, their adoption in the construction industry is limited (Dale et al., 2017; Kramer et al., 2010; Welch et al., 2015). This issue may be due to the short-term nature of

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construction projects, which results in the unwillingness of employers to commit to long-term ergonomic intervention strategies and systematic approaches for identifying and analyzing risk factors (Dong et al., 2004). Along with such limitations, increased costs, uncertainty in return on investment, and lack of adequate information cause employers to be hesitant to adopt the strategies (Dale et al., 2016). For example, Nnaji and Karakhan (2020) and Qi et al. (2021) pointed out that the doubts over the reliability and unknown effectiveness of safety and health technology may be one of the reasons for the reluctance to adopt such technologies. To facilitate the adoption of ergonomic intervention strategies, the commitment of stakeholders who are to initiate the intervention (e.g., contractors) and those who are to apply it (i.e., workers) is thus essential (Welch et al., 2015). Their commitment may be encouraged if suggested ergonomic intervention strategies can be demonstrated to reduce the physical workload and their advantages are thus evident. However, previous studies examined the effectiveness of ergonomic intervention strategies by adopting methods such as qualitative assessment (Dale et al., 2017), questionnaire surveys (de Jong and Vink, 2002), and reviews of case studies (Lowe et al., 2020). As these studies were based on the assessment criteria obtained via interviews, observations, and Likert scale questionnaires, the effectiveness evaluation of those ergonomic strategies could be dependent on the subjective judgment as personal interpretation was possibly involved. This can be limited in identifying the degree to which ergonomic intervention strategies can physically reduce the workload from an ergonomic aspect.

This paper aims to understand the comprehensive effect of ergonomic interventions (e.g., positive and negative impacts) for specific parts of a whole body. To this end, a case study was performed by comprehensively investigating representative postures observed during frequently practiced activities and quantitatively evaluating applicable ergonomic intervention strategies for reducing the physical demand on the human body. Specifically, the frequently practiced activities of RC trade workers and relevant ergonomic intervention strategies applicable to each activity were examined and identified through a quantitative review of the literature. For the postures likely assumed during frequent activities and modified by adopting intervention strategies, the corresponding three-dimensional (3D) motion data of a human body in digital form were collected using a markerless vision-based motion-capture system (e.g., Microsoft Kinect). This markerless system adopted two depth sensors placed at optimal angles and synchronized through calibration, which may minimize self-occlusions and increase the accuracy of the data (Yang et al., 2015). These data were biomechanically analyzed to determine the physical loads at specific body parts (e.g., wrists, elbows, shoulders, hips, discs, knees, and ankles). The simulation results were compared with the results of previous surveys on commonly injured body parts (Bhattacharya et al., 1997; Chaiklieng et al., 2020; Holmström and Engholm, 2003) to determine the relationship between possible workloads and actual injuries and identify the difference between applying and not applying ergonomic intervention strategies to evaluate the effect of interventions quantitatively. The findings are anticipated to provide postural education on worker safety and insight into the adoption of ergonomic intervention strategies in practice and to support the creation of an ergonomically safe working environment in the construction field.

2. Literature review

The construction of RC buildings requires large workforces responsible for (1) reinforcement installation (shaping the concrete skeleton); (2) formwork installation (installing frames before concrete pouring); and (3) concrete placement (concrete pouring and finishing) (Burfdorf et al., 1991; Forde and Buchholz, 2004). This section focuses on reviewing the ergonomic posture assessment methods that can be used to identify the WMSDs risk factor involved in the three types of RC construction tasks, and discussing what challenges can potentially be posed when directly applied to onsite investigation. Then, the potential limitations of scrutinizing the ergonomic intervention strategies are discussed to find the need for further research.

2.1. Onsite ergonomic assessment tools and methods

Musculoskeletal risks during occupational tasks are associated with three WMSD risk factors: awkward postures, forceful exertion, and the frequency and duration of manual activities (Chen et al., 2017; Jaffar et al., 2011). Among these factors, awkward postures (i.e., the significant deviation of the body from the neutral position during physical activities (Karwowski and Marras, 2003) have been reported to be the leading cause of WMSDs (Chen et al., 2017; Jaffar et al., 2011). Thus, posture assessment methods have widely been used to evaluate the degree of risk in epidemiological studies.

One of the widely used approaches is observational posture assessment, e.g., Posture, Activity, Tools, and Handling (PATH) (Buchholz et al., 1996); Rapid Upper Limb Assessment (McAtamney and Nigel Corlett, 1993); Rapid Entire Body Assessment (REBA) (Hignett and McAtamney, 2000); Ovako Working Postures Analyzing System (OWAS) (Karhu et al., 1977); and Washing Ergonomic Rule (L&I, 2000). The assessment procedure generally involves the evaluation of worker postures and tasks through work sampling (e.g., recording activities or direct observation in the field). A score sheet is employed for rating the posture risk (e.g., degree of flexion) of major body joints (e.g., neck, trunk, upper and lower arms, and wrist), handled loads (e.g., 0, <5, and 5–10 kg), and motions (e.g., lifting, lowering, and carrying). Then, the result can be used to identify postures and tasks that are associated with high musculoskeletal risk and require immediate intervention. Examples of the applications include the OWAS analysis of 13 common awkward postures in the RC trade (Li and Lee, 1999), a work sampling-based PATH assessment for reinforcement operations (Forde and Buchholz, 2004), and the use of the Washington Ergonomic Rule for concrete pouring tasks (Spielholz et al., 2006). These studies show that observational methods are suitable for the initial screening of risky tasks in a field setting. However, the result generally describes only the awkwardness (e.g., low, medium, high) in a certain hazardous posture. Furthermore, the accuracy of measurements relies heavily on an observer's judgment and experience. Consequently, it is pointed out that these techniques can be time-consuming and possibly prone to errors in the field (Chiasson et al., 2012; Golabchi et al., 2016).

In contrast, biomechanical assessment techniques investigate human movements from a mechanical perspective by considering the body as a structure with joints and calculating the reactive moment at each joint to maintain posture (Robertson, 1997). By estimating internal forces (e.g., joint moments) via the measurement of joint angles and external forces (Chaffin et al., 2006)—generally exerted by the hands—, this method thus provides an understanding of how certain tasks can lead to WMSDs in specific body parts and produces a precise posture assessment result rather than a perception-based evaluation (Marras et al., 2009). To measure the biomechanical status of posture, two approaches are mainly employed for the field applications: (i) direct measurement (e.g., using a biometric sensor that estimates muscle force) and (ii) computer-based simulations (e.g., modeling a series of 3D motions to be calculated according to body mechanics). As an example of direct measurement, the surface electromyography (sEMG) sensor is attached to body parts to measure sEMG activity. By measuring the increase and decrease in the sEMG signals, the load transfer within the muscle and tissue is determined, identifying the risk of a specific body part where the sensor is attached. In a previous study, Colim et al. (2021) used sEMG to examine the muscular impact of vertical manual material handling tasks on the upper extremities (i.e., spine, shoulder, and arm) of industrial workstation workers, considering two different conditions: with and without the restraint of a barrier while lifting the material with different weights (i.e., 5, 10, and 15 kg). For construction work, Umer et al. (2017a) conducted a postural assessment of typically observed awkward postures (i.e., squatting while installing reinforcements) and intervention tools by measuring the muscle activity and neuromuscular fatigue of the trunk using sEMG. Jebelli and Lee (2019) measured the upper limb (i.e., elbow and shoulder) movements with a wearable sEMG device while simulating the motion of concrete block lifting. For simulation-based biomechanical assessment, a series of human postures with x–y–z rotation angles with tracked velocities and directions can be acquired via two sensing approaches: body markers and visual sensors (Guo et al., 2018; Han and Lee, 2013). These motion-sensing approaches allow the detection of subtle angle changes in posture in the 3D motion data for the evaluation of a specific internal load (in Newtons) against an external force, even if postures visually appear similar (Granata et al., 1997). For the biomechanical evaluation, simulation tools, such as 3D Static Strength Prediction Program (3D Static Strength Prediction Program, 2005), and OpenSim (Delp et al., 2007),have been introduced to obtain sufficient details on human kinematics using 3D angular data of human joints (Seo et al., 2015). For example, Alwasel et al. (2017) collected motion data using body markers (e.g., inertial measurement units, IMU) and used 3D SSPP to compare the motions of expert and unskilled masonry workers in joint angle and moment units. Similarly, Colim et al. (2021) examined real-world motion data using eleven IMU sensors on the upper body to assess the musculoskeletal risk of tasks required in novel assembly workstation with RULA. Subedi and Pradhananga (Pradhananga et al., 2021) proposed an approach to identify the theoretical maximum attainable level of safety by measuring the postures using a RGB-D sensor (e.g., Microsoft Kinect) and simulating the acquired posture data in OpenSim. Recently, Yu et al. (2019) and Chu et al. (2020) used vision-based motion capture, which extracts 3D human skeletal data from a two-dimensional video via deep-learning algorithms, to assess body joints using an ergonomic tool (i.e., REBA). Despite its advantages, however the biomechanical assessment approach may have the following limitations for the field applications. The use of wearable sensors (e.g., biometric sensors, marker-based motion capture) may only be feasible under certain operational conditions owing to equipment requirements (e.g., sensor attachments and the onsite sensor network) and for a short period on a construction site owing to tracking errors that accumulate over time (Golabchi et al., 2016; Chu et al.). Furthermore, vision-based approaches remain limited in areas where research is ongoing for field applications. For example, they are prone to errors due to camera occlusions caused by other objects or self-occlusion (e.g., squatting) and extreme weather conditions (e.g., fog, rain, and intense illumination) (Guo et al.; Fang et al., 2020).

2.2. Effectiveness of ergonomic intervention strategies

Body pains resulting from an awkward posture may persist even after work and lead to injuries. Therefore, the process of identifying and eliminating discomfort due to awkward postures, i.e., ergonomic intervention, is suggested. Ergonomic intervention includes organizational and administrative control (e.g., physical exercise, sessions with a physiotherapist, postural training, and breaks), engineering control (e.g., adjusting the workload and redesigning the workplace), and the modification of tools/equipment (e.g., applying extension tools and modify the tool design) (Lowe et al., 2020). Therein, the organizational and administrative control are administrative interventions that can only be implemented by management such as controlling the muscle relaxation time, work schedule and work pace, and postural training (AbdulHafeez and Smallwood, 2018). Meanwhile, with the application of engineering control and modification of tools/equipment, the positional interface of the handgrip and overall body structure are modified, which directly change the components of internal force (i.e., magnitude and direction) (Cacha, 1999). Thus, engineering control and modification of tools/equipment are considered fundamental in the prevention of overexertion injury.

Among ergonomic intervention strategies, modification of tool/equipment can reduce physical work demands particularly when workers are directly involved, researchers have assessed the effectiveness of intervention strategies by biomechanically scrutinizing postures with and without the implementation of the strategies. For example, for reinforcement installation, Albers and Hudock (2007), Vi (2003), and Lingard et al. (2019) evaluated the feasibility of using an extension bar for reinforcing rebars in comparison with the use of a conventional rebar twisting tool, pincer–cutter tool, or basic rebar tying gun, which requires a worker to stoop forward. The findings of those studies include that the utilization of ergonomic intervention tools (e.g., rebar tying gun with extension) reduced the flexion/bending and stress of wrists and discs by half compared with the posture involved in the conventional method. Umer et al. (2017b) reported that the intervention strategy that workers sit on a small stool during the installation of horizontal reinforcement could be effective to prevent severe flexing. For formwork construction, Mirka et al. (2003) demonstrated that the use of mechanical and hoist lifts for frame handling reduced trunk compression by more than one-third when comparing the resulting disc compression with and without the intervention. Regarding the concrete-placement trade, through the 3D pose estimation approach, Hess et al. (2004) demonstrated improvements in the angle and moment of the disc with the use of a concrete skid compared with manual handling; the concrete skid enables moving a hose filled with concrete with the aid of an extended handle. For concrete finishing tasks, the use of various concrete screeds, such as vibratory, roller, and laser screeds, instead of manual screeding (which causes severe flexion of a worker's disc during leveling of a floor), was introduced and demonstrated to be effective via the PATH and Washington Ergonomic Rule methods (Albers et al., 2004).

Previous studies have focused on evaluating the effectiveness of the selected tools to improve a certain type of awkward posture commonly observed in construction, such as stooping (Albers and Hudock, 2007; Vi, 2003), half squatting (Hess et al., 2004), full squatting (Umer et al., 2017a), and lifting (Mirka et al., 2003). However, RC workers are involved in various activities requiring postures with different positions of the legs and hands (Moir et al., 2003). Thus, it is still questionable whether all of the physically demanding postures involved in RC activities are known. Besides, previous studies often evaluated the effectiveness of the selected tools at only certain body parts, such as the disc (Umer et al., 2017a; Mirka et al., 2003; Hess et al., 2004) or upper extremities (Albers and Hudock, 2007; Lingard et al., 2019; Albers et al., 2004). However, RC workers suffer WMSDs over a wide range of body parts (e.g., wrists, elbows, shoulders, hips, discs, knees, and ankles), as indicated by WMSD statistics (Howard and Adams, 2018). Notably, the biomechanical chain reaction (a.k.a. the full-chain effect of human motion) also may not be neglectable as posture modification in one body part may physically affect another (Chang, 2019). In other words, the effects of adopting a specific intervention may be positive in reducing the stresses of some body parts to prevent WMSDs risks, whereas such effects may possibly be negative, which increases the risks at other parts in certain conditions(Umer et al., 2017a; Lingard et al., 2019). For example, Lingard et al. (2019) reported that compared with the conventional pincer-cutter in steel-tying, the use of a long-handled stapler tool significantly reduces the amount of trunk inclination when working above the hip level, which prevents the risk of back and wrist injury; however, the amount of trunk inclination excessively increased when a worker had to work from ankle to knee height or from knee to hip height, which was classified as a musculoskeletal risk. In this regard, a comprehensive assessment of a wide range of postures involved in all types of RC work and the effectiveness of ergonomic interventions for various body parts are required to understand and identify ergonomically awkward postures among conventional ones performed during each RC activity, as well as determining an appropriate intervention strategy to reduce relevant physical stresses. This information may provide the guideline of what ergonomic intervention can be adopted to mitigate musculoskeletal risk for a certain RC activity and further support in understanding the potential risk at different parts of a whole body when adopting a specific ergonomic intervention.

3. Research methodology

This study aims to comprehensively identify awkward postures among conventional ones performed during each RC activity and biomechanically evaluate the posture modified by ergonomic intervention for specific parts of a whole body. Particularly, the scope of this study focuses on work methods for ergonomic improvements (ergonomic intervention strategies in this paper) such as posture change using intervention tools and workload adjustment by workers performing together for ergonomic modification. The motivation is to provide knowledge of a wide range of awkward postures of RC trades and the effect of ergonomic interventions (e.g., positive and negative impacts) at specific parts of body. To achieve these objectives, biomechanical simulation using motion capture data is performed to identify (i) how relevant awkward postures are to the occurrence of WMSDs, (ii) what postures may arouse high physical loads exceeding the acceptable stress capacity at specific body parts, and (iii) how much the bodily stresses are reduced at specific body parts by applying work methods for ergonomic improvements. This comprehensive assessment includes both conventional and awkward postures as well as postures with and without intervention.

The procedure of this study consists of three phases: (1) posture selection, (2) motion capture and biomechanical simulation, and (3) assessment (Fig. 1). First, throughout a literature review, the sequences of RC trades are determined and classified into activity units with frequency. Then, the activities with a high frequency are selected to determine the postures to be evaluated, and ergonomic intervention strategies, including postures associated with the selected ones, are reviewed and collated. To verify the effectiveness of ergonomic intervention strategies, the conventional (pre-intervention) and non-neutral (post-intervention) postures of the selected activities are also collected for comparison. Second, a laboratory experiment is carried out to collect reliable motion capture data of the selected postures using a vision-based approach. The motion data collected by mimicking postures in front of visual sensors are then transformed into 3D computational skeletal data to be used as the model input for a biomechanical simulation. In the simulation, external forces (e.g., the weight of a tool typically supported by hands) and human factors (i.e., gender, height, and weight) are also considered to estimate the internal force according to the anthropometric distribution. Third, the relationship between the selected conventional postures and actual body pains experienced by construction workers is investigated. To accomplish this, the biomechanical simulation results of the selected conventional postures (strength capabilities, %) for seven body parts are compared with the prevalence of body pains (%) based on the WMSD survey for each reinforcement, formwork, and concrete placement trade. Then, the biomechanical simulation results of conventional postures in the forms of joint moment (N•m) and compression (N) are compared with those of the ergonomic intervention strategy postures. In the comparison, the results of both the conventional work and intervention postures are categorized into activity units to determine the extent to which physical stresses decrease or increase through the application of intervention strategies. Thus, the effectiveness of ergonomic intervention strategies may be evaluated according to the stress reduction that can be achieved by implementing them in practice.

3.1. Selection of postures and intervention strategies

For a comprehensive analysis and comparison of biomechanical simulation results, RC activities were reviewed and categorized into each of the three RC trades (i.e., reinforcement, formwork, and concrete placement). For each activity, work-related conventional postures that

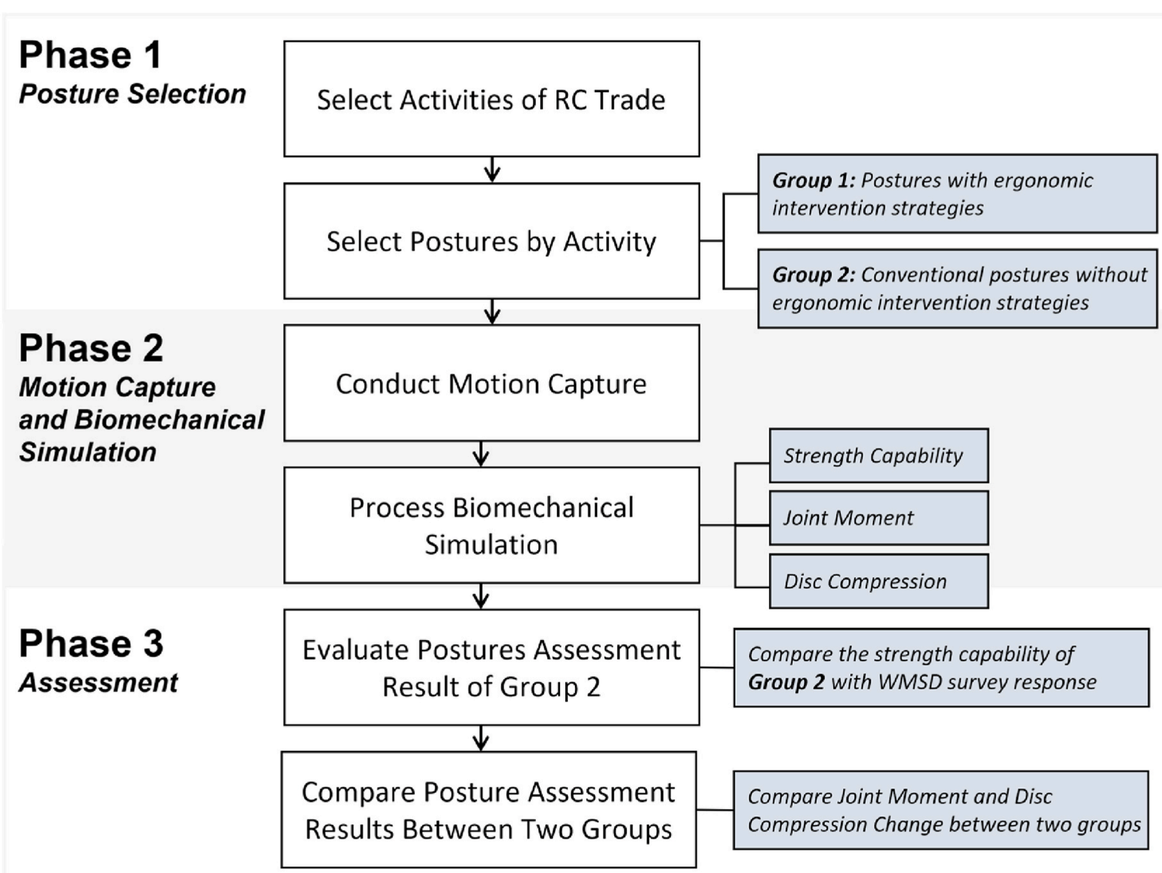

Fig. 1. Conceptual framework of the experiment.

had high musculoskeletal risk and were frequently observed on a site as well as postures resulting from the adoption of potentially applicable ergonomic intervention strategies were then selected according to the work characteristics and frequency, as reported in the relevant literature.

Specifically, for the activity selection, assembly (i.e., moving steel bars and guiding cranes to set the bars) and horizontal and vertical reinforcement (i.e., tying rod bars at the subbase surface and walls) were found to be the typical activities involved in the reinforcement trade, as indicated by their high frequency of implementation (Tak et al., 2011; Buchholz et al., 2003). For the formwork trade, the activities of assembly (i.e., manually moving panels or forms), erecting and lowering (i.e., holding an extended bar support to lower the form from a crane or holding a form while it is being connected), connecting (i.e., nailing and screwing of forms with a hammer), and bracing (i.e., setting brackets supporting the form from the base) forms were selected (Spielholz et al., 2006; Hallowell and Gambatese, 2009; Schneider and Susi, 1994). For the concrete-placement trade, the activities of hose holding (i.e., holding and lifting hoses filled with concrete), screeding (i.e., spreading concrete using a hand rake), and vibrating (i.e., inserting a vibrator into freshly poured concrete to eliminate air bubbles) were selected (Goldsheyder et al., 2004; Love, 1973; Hajaghazadeh et al., 2019).

Unlike other construction operations with the inconsistency of posture patterns, RC construction work generally has a standardized work sequence defining the predictable pattern of work-related postures for each activity. This is possibly because RC construction involves distinct and repetitive work processes (i.e., reinforcement installation, form installation, and concrete placement) regardless of the purpose, shape, and size of the RC structures (e.g., bridges and buildings) (Ching, 2018). In this regard, typical work-related postures involved in RC activities were selected through a thorough review of literature, including ones identified by experts (i.e., ergonomic experts and construction managers) based on site observations under different conditions (i.e., time period, regions, and weather). In total, the selected work-related postures included 36 conventional non-neutral postures that were frequently observed on construction sites. Specifically, 8 postures were selected for the reinforcement trade, 18 for the formwork trade, and 10 for the concrete-placement trade, as summarized and described in

Table 1
Selected conventional postures.

Trade	Activity	Posture	Description	Reference
Reinforcement	Assembly	R1	Carrying rod bundles on one shoulder with one hand	(Dababneh and Waters, 2000; Drisya et al., 2018)
		R2	Only on the shoulder	
		R3	With both hands at the waist level	
		R4	With both hands above the shoulder	
	Horizontal reinforcement	R5	Rebar tying with conventional rebar twister while kneeling	(Li and Lee, 1999; Umer et al., 2017a, 2017bAlbers and Hudock, 2007; Lingard et al., 2019; Drisya et al., 2018; Saari and Wickström, 1978)
		R6	While squatting	
		R7	While stooping	
		R8	While stooping but slightly stretching one foot	
Formwork	Assembly	F1	Transporting a form while holding its sides at the waist level	(Dababneh and Waters, 2000; Pan and Chiou, 1999)
		F2	Above the shoulder level	
		F3	Below the waist level	
		F4	Diagonally at the chest level	
		F5	Diagonally at the chest level but leaning back	
	Erecting/lowering	F6	Supporting a form or holding an extended handle to position the form with both hands above the shoulder	(Bhattacharya et al., 1997; Choi and Yuan, 2016; Sahu et al., 2010)
		F7	At the waist level	
		F8	Pressing the form with both hands with the trunk twisted	
		F9	Supporting a form or holding an extended handle to position the form with both hands at the head level	
		F10	Toward the ceiling	
	Horizontal and vertical hammering	F11	Horizontal hammering with 1 kg of hammer while one knee bent at the floor level	(Bhattacharya et al., 1997; Mattila et al., 1993)
		F12	While kneeling	
		F13	While torso and one knee bent	
		F14	While torso bent forward	
		F15	Vertical hammering by swinging the hammer at the head level	
		F16	Below the shoulder level while standing on a ladder	
		F17	At the shoulder level, upright while standing on the ladder	
		F18	At the shoulder level, slightly leaning back while standing on the ladder	
Concrete placement	Hose holding	C1	Holding a concrete hose full of concrete with both hands at the chest level	(Lop et al., 2019; Rwamamara, 2005; Rwamamara et al., 2010)
		C2	With one hand at the waist level	
		C3	With both hands while a leg is bent	
		C4	With both hands while partially squatting	
	Screeding	C5	Pushing screeder while a half prone position is maintained	(Albers et al., 2004)
	Vibrating	C6	Holding the concrete vibrating hose with both hands at the waist level with the torso bent	(Lop et al. 2019; Rwamamara et al., 2010; Rwamamara and Simonsson, 2012)
		C7	At the shoulder level with the torso straight	
		C8	At the shoulder level with the torso bent	
		C9	At the waist level with the torso bent	
		C10	At the head level	

Table 1. These postures when using work-related specific tools are illustrated in Fig. 2 (where R#, F#, and C# denote reinforcement, formwork, and concrete placement, respectively).

Potential applicable ergonomic intervention strategies were then identified for the selected activities of concrete work, as summarized in Table 2 and illustrated in Fig. 3 (EI: Ergonomic Intervention Strategy; #: number). Overall, for most of the postures, the trunk is straight, and the core of the body is not tilted in any direction. These postures can mostly be maintained with the use of assistive tools to support the tasks. Specifically, posture EI1 for the reinforcement trade is that two workers hold a heavy bundle of bars together rather than carrying the bars alone (conventional posture R1). This strategy may impose a smaller load on the body than posture R1 because the load can be shared by another worker. As a substitute of conventional rebar twisting tool, the use of an extended handle attached to the rebar tying tool (EI2) enables straightening the trunk of a worker for the installation of horizontal reinforcement while the head is slightly bent forward to the floor. The posture associated with the installation of horizontal reinforcement while sitting on a small mobile stool (10–15 cm high) (EI3) involves less trunk bending than the conventional posture with the legs fully supporting the entire body. For the formwork trade, postures involving manual handling of objects with arms stretched above the head may cause significant strain on the body. In this case, the physical stresses can be reduced by using a vacuum lift that a suction pump at the end of an extended arm enables gripping (EI4), a pneumatic wall lift that assists in lifting a form vertically (EI5), and a lifting machine that allows for less trunk flexion (EI6). For the concrete-placement trade, instead of holding concrete hose as conventional method (Yiheng, 2022), the intervention strategies include the use of a 60-cm-diameter metal disk with a fixture in the middle (where a hose for concrete pouring can be placed) and an extension handle at the end (skid plate) for concrete pouring (EI7). Also, instead of manual screening (Cacha, 1999), a fuel-powered vibrating screed with a blade or plow for concrete spreading (EI8), a seamless piped machine powered by a motor (roller screed) operated by pulling the handle toward the body of the worker (EI9), a two-wheeled engine-based machine with an attached plow (laser screed) (EI10). In addition, a vibrating hose, which could be substitute of manual vibrating hose that worker must carry (High Frequency Concrete Vibrator) with a portable engine in backpack form (backpack vibrator) that can facilitate the vibration of freshly poured concrete (EI11). These tools and devices may generally allow the postures to lessen trunk bending.

3.2. Biomechanical analysis using motion-capture data

For the 47 postures, a biomechanical simulation was conducted using motion-capture data to identify potentially risky postures, as shown in Fig. 4. Two commercial RGB-D sensors (Microsoft Kinect v2) were selected and connected to each other to accurately capture the motion of the entire body (Yang et al., 2015) (*experiment setting* in Fig. 4) and collect reliable kinetic data under laboratory conditions (*motion capture*). In this experiment, a participant repeated the work motion 15 times while handling the same weight and shape of the tool for each posture. The motion data from the physical simulation of postures were then converted into 3D human skeletal data (*data conversion*). Specifically, the 3D motion data consisted of a series of joint segment movements in the form of the Euler rotation angle, whereas 3D SSPP (3D Static Strength Prediction Program, 2005) adopted for the biomechanical analysis required posture data in the form of the horizontal and vertical joint angles in a global coordinate system. Thus, the data format was further converted into a batch file input into 3D SSPP as described in Seo et al. (2015). Using the 3D SSPP, the biomechanical analysis of posture was conducted by simulating posture data, force parameters, and anthropometry on the job (*biomechanical simulation*). The mean anthropometric size of the 50th percentile of the male population (i.e., a height of 175.4 cm, and a weight of 87.4 kg) was considered as a baseline of the biomechanical simulation (National Center for Health Statistics, 2021). This population included all races including Hispanic-origin groups with the age of 20 and over, the body size of which was measured from 18,061 of the U.S. population in 2015–2018 by the National Center for Health Statistics. As a result, internal forces at each joint unit under an applied external load were estimated in the forms of the joint moments of 6 major body parts (e.g., wrist, elbow, shoulder, hip, knee, and ankle) and disc compressions (i.e., L5/S1 and L4/L5). The strength capability—the percentage of the population capable of generating a moment greater than the resultant moment (3D Static Strength Prediction Program, 2005)—was also obtained and used for comparison with the actual WMSDs.

In this process, an external load applied to the body while performing work is critical in biomechanically assessing the posture. To account for the biomechanical load distribution on the human body, an external load was applied to the support/action point in a direction opposite to the hand that supported the object, as lifting or pushing an object requires a force greater than its weight. When lifting an object perpendicular to the ground, the force is applied to the hand or body parts that have direct contact with the material in a downward direction toward the ground. Conversely, when pushing an object in the opposite direction of the human body, force is applied to the hand towards the body. To incorporate these external loads into the 3DSSPP system, the code was revised during the conversion of the raw 3D human skeletal file (.bvh) to the input file (.tsk), following the method outlined by Seo et al. (2015). Accordingly, in the simulation, an external load was applied to each posture considering various work situations, e.g., the use of different equipment and materials. In particular, three magnitudes of the external force loaded on specific body parts, i.e., the maximum weight handled by the worker and 2/3 and 1/3 of the maximum weight, were analyzed in this experiment (Table 3). The maximum external force was determined by reviewing the literature (e.g., papers, brochures, and books) discussing the typical materials handled by workers, including the weight of rod bundles (e.g., 5 bars) that workers typically carry (R1–R4) (Schneider and Susi, 1994), the type of tool used for rebar twisting and its weight (R5–R8) (Saari and Wickström, 1978), and the typical weight of wooden concrete forms (F1–F10) (Schneider and Susi, 1994). The weight of a hose full of concrete for pouring (C1–C4) (Yiheng, 2022), the magnitude of friction during concrete screeding using a wooden stick (C5) (Cacha, 1999), and the weight of a vibrating hose (C6–C10) (High Frequency Concrete Vibrator) were also obtained for analysis. Meanwhile, the load sustained by both hands during hammering (F11–F18) was manually acquired using a gripper and weight sensor by simulating the hammering task using a 1 kg hammer (Balendra and Langenderfer, 2017).

Similarly, three types of external loads were applied to each of the ergonomic-intervention postures for considering the variation in the tool types and weights (e.g., loads resulting from the manual handling of materials), as presented in Table 4. The maximum force was obtained from relevant studies. For example, a load was applied to postures EI2 (Albers and Hudock, 2007; Vi, 2003), EI4 (Waters et al., 1993), EI5 (Mirka et al., 2003), EI7 (Hess et al., 2004), EI8, EI9, EI10 (Albers et al., 2004), and EI11 (CPWR, 2008)). For these postures, the ergonomic intervention strategy included the use of new hand tools with the aim of safely adjusting the postures. The use of new tools resulted in external forces (e.g., weight and directions) being loaded onto the body parts that differed from the forces exerted by the commonly used hand tools. For the other postures, the intervention strategies included providing supportive tools, such as a chair (EI3) and a ridable machine that adjusted the working height (EI6). Because these tools supported the conventional hand tools used for construction tasks, the resulting postures were more neutral (e.g., less trunk bending) than the postures without the support of these tools. However, because the hand tools for task completion were the same before and after applying the support tools, the external loads applied to the body were identical in the experiment for EI3. Meanwhile, for the IE6 posture, despite using the same tool (i.e., a 1 kg hammer), less load was applied to the worker compared with

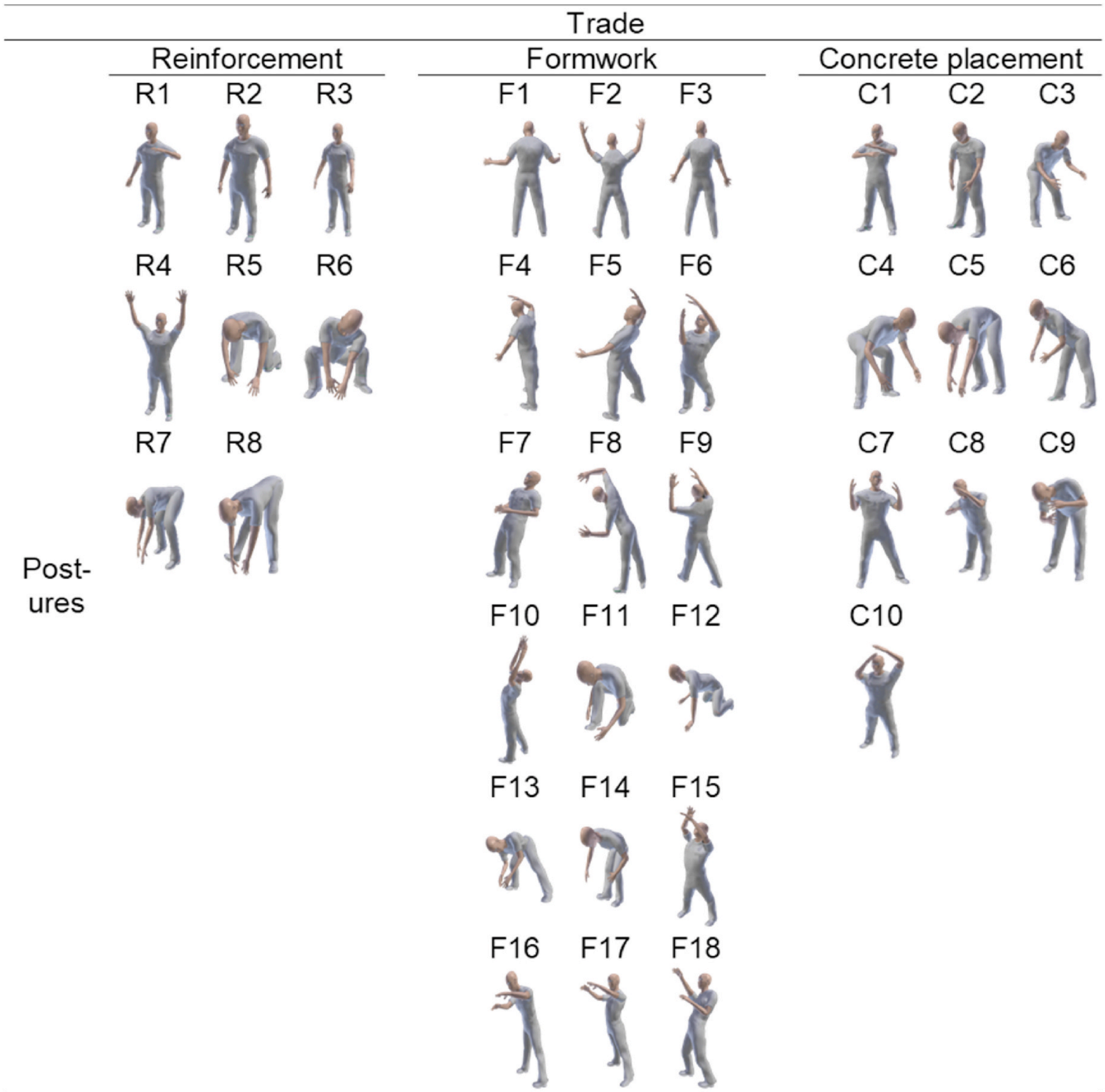

Fig. 2. 36 commonly observed postures in the reinforced-concrete trade.

F11-18 postures. This reduction in load is due to the ergonomic intervention that reduces the supporting force of the left hand as the trunk straightens up and brings the work area closer, thereby decreasing the range of motion of the right hand. In the EI1 strategy, two workers (instead of one worker) handled a bundle of bars (i.e., a conventional method); hence, half of the external load of R3–R4 was applied to the same body part. To reflect the various weight of construction site, maximum load applied to each posture, 2/3 and 1/3 of the maximum load were considered as well.

3.3. Assessment of intervention strategies

In this assessment phase, the results of the biomechanical simulation were analyzed at (i) trade level, (ii) posture level, and (ii) activity level. First, the mean strength capability (%) of conventional postures in each trade was compared with the result (%) of a WMSD survey to validate whether selected conventional postures may well represent the typical awkward postures observed on RC construction sites. This survey showed the prevalence of WMSDs among RC workers in each trade, with responses indicating multiple body parts where they experienced WMSDs (e.g., Goldsheyder et al., 2004; Forde et al., 2005; Spielholz et al., 1998); that is, the number in Table 5 represents how many respondents spending at least 6,000 h in various fields of RC, such as reinforcement (Forde et al., 2005), formwork (Spielholz et al., 1998), and concrete placement (Goldsheyder et al., 2004) suffer musculoskeletal pains at each body part. The survey on musculoskeletal pains provides direct inputs from workers indicating the ergonomic pains they suffer, thus allowing for an understanding of how the physical stresses exerted on specific body parts have led to injuries. For the comparison, three studies on construction (Table 5) were selected according to the following criteria; (1) A survey includes responses regarding the WMSD pains experienced by workers on seven body parts (i.e., wrist, elbow, shoulder, hip, knee, ankle, and disc); (2) The number of survey responses is relatively larger than those of other studies; and (3) the responses are expressed in percentile form for comparison. Specifically, the strength capabilities corresponding to conventional postures were compared with the typical pains reflected by the survey on musculoskeletal disorders through a Pearson correlation analysis (Benesty et al., 2009).

Because the biomechanical simulation did not provide results on disc capability, the disc compression due to posture was converted into the strength capability for a fair comparison. This conversion was achieved

Table 2
Selected ergonomic intervention strategies.

Trade	Activity	Posture	Description	Reference
Reinforcement	Assembly	EI1	Hold together	(OSHA, 2000)
	Horizontal reinforcement	EI2	Extension handle	(Albers and Hudock, 2007; Vi, 2003; Lingard et al., 2019)
		EI3	Stool	(Umer et al. 2017b)
Formwork	Assembly	EI4	Vacuum lift	(Albers and Jim, 2007; Waters et al., 1993)
	Erecting/lowering	EI5	Pneumatic wall lift	(Mirka et al., 2003; Waters et al., 1993)
	Horizontal and vertical hammering	EI6	Hydraulic lift	Albers and Jim, 2007
Concrete placement	Hose holding	EI7	Skid plate	(Hess et al. 2004)
	Screeding	EI8	Vibratory screed	(Albers et al. 2004)
		EI9	Roller screed	(Albers et al. 2004)
		EI10	Laser screed	(Albers et al. 2004)
	Vibrating	EI11	Vibratory backpack	(CPWR, 2008)

Note: EI: Ergonomic Intervention Strategy; #: posture number.

via linear interpolation, as follows:

$$Y = y_1 + (x - x_1)\,\frac{y_2 - y_1}{x_1 - x_2} \tag{1}$$

The maximum magnitude of compression permitted on the human disc is specified as 6400 N (x_1) (NIOSH, 1981), which is equal to 25% of the strength-capability value given by the biomechanical simulation. When 0-N (x_2) compression is concurrently loaded on the disc, its strength capability may reach 100% (y_2) because it does not sustain any pressure from the load. Consequently, using the sustained disc compression (x), calculation of the strength capability (y) in percentile form is analytically possible. As an input value (x), the disc compression of L4/L5 is applied because it is more likely to be generated than L5/S1 (Marcum and Adams, 2017).

Second, to further determine whether these selected conventional postures are ergonomically hazardous and ascertain the body parts at high risk of injury, this study evaluated the stresses of body parts for each conventional posture. Particularly, the joint moments and disc compressions of seven body parts (i.e., wrist, elbow, shoulder, hip, knee, ankle, and disc) of 36 conventional postures were identified and evaluated whether they exceed the acceptable capacity. These results may allow for identifying what posture may cause excessive bodily stresses.

Lastly, the joint-moment, disc-compression, and strength-capability of the conventional and intervention-applied postures were classified by activity and compared to determine the quantitative difference between the cases with and without ergonomic intervention strategies at the activity level. An activity-level comparison was adopted as various intervention strategies can be applied to the same activity (e.g., vibratory screed (EI8), roller screed (EI9), and laser screed (EI10) for screeding activity). From this analysis, thus one can figure out which activity may possibly be improved by adopting an ergonomic intervention strategy and which activity is highly exposed to musculoskeletal risk by understanding its effectiveness.

4. Experimental results

In this section, biomechanical assessment results are presented to identify ergonomically awkward postures among conventional ones performed during each RC activity and biomechanically evaluate the posture modified by ergonomic intervention for specific parts of a whole body. In particular, to validate whether selected conventional postures may well represent the typical awkward postures observed on RC construction sites, this study compared the strength capabilities caused by these postures and WMSD survey results. Then, a biomechanical simulation result of conventional postures was analyzed to ascertain the body parts at high risk of injury and further evaluate whether these postures exceed the acceptable stress (e.g., compression) capacity. Lastly, a biomechanical simulation assessment of postures with ergonomic

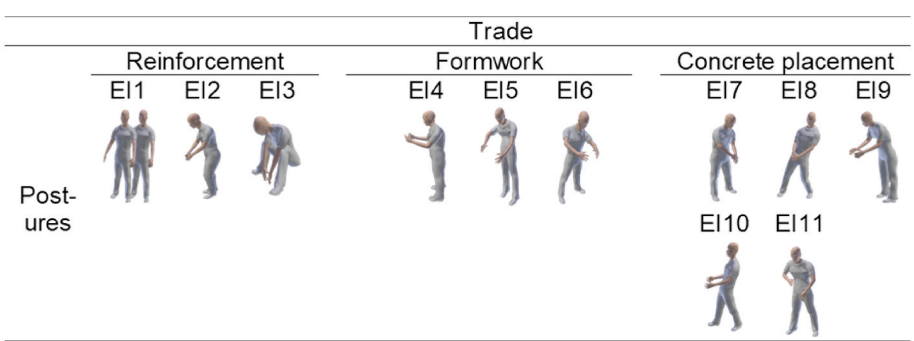

Fig. 3. Postures acquired for ergonomic intervention tool.

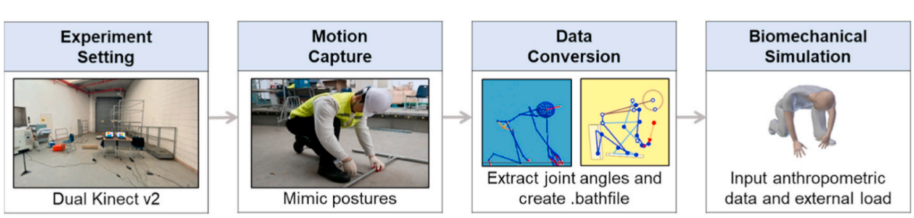

Fig. 4. Process of motion capture and biomechanical simulation.

Table 3
External force applied to specific body parts for each conventional posture.

Trade	Activity	Posture	Body part	Load 1 (N)	Load 2 (N)	Load 3 (N)
Reinforcement	Assembly	R1	Right shoulder	268.05	178.7	89.35
			Right hand	134.02	89.34	44.67
			Total load	402.07	268.04	134.02
		R2	Right shoulder	402.07	268.05	134.02
		R3–R4	Both hands	201.03	178.7	89.35
			Total load	402.07	268.04	134.02
	Horizontal reinforcement	R5–R8	Right hand	16.90	11.27	5.63
Formwork	Assembly	F1–F5	Both hands	133.45	88.96	44.48
			Total load	266.9	177.92	88.96
	Erecting/lowering	F6–F10	Both hands	111.21	74.14	37.07
			Total load	222.42	148.28	74.14
	Hammering	F11–18	Both hands	88.96	59.31	29.65
			Total load	177.92	118.62	59.3
Concrete placement	Hose holding	C1, C3–C4	Both hands	68.65	45.76	22.88
			Total load	137.29	91.53	45.76
		C2	Right hand	137.29	91.53	45.76
	Screeding	C5	Both hands	78.45	52.30	26.15
			Total load	156.9	104.6	52.3
	Vibrating	C6–C10	Both hands	29.42	19.61	9.81
			Total load	58.84	39.22	19.62

Table 4
External force applied to specific body parts for each posture of ergonomic intervention strategies.

Trade	Activity	Posture	Body part	Load 1 (N)	Load 2 (N)	Load 3 (N)
Reinforcement	Assembly	EI1	Both hands	61.29	40.86	20.43
			Total load	122.58	81.72	40.86
	Horizontal reinforcement	EI2	Both hands	42.26	28.17	14.09
			Total load	84.52	56.34	28.18
	Horizontal reinforcement	EI3	Right hand	16.90	11.27	5.63
Formwork	Assembly	EI4	Both hands	58.84	39.23	19.61
			Total load	117.68	78.46	39.22
	Erecting/lowering	EI5	Both hands	49.03	32.69	16.34
			Total load	98.06	65.38	32.68
	Hammering	EI6	Both hands	49.03	32.69	16.34
			Total load	98.06	65.38	32.68
Concrete placement	Hose holding	EI7	Both hands	68.65	45.76	22.88
			Total load	137.3	91.52	45.76
	Screeding	EI8	Both hands	88.26	58.84	29.42
			Total load	176.52	117.68	58.84
		EI9	Both hands	58.84	39.23	19.61
			Total load	117.68	78.46	39.22
		EI10	Both hands	58.84	39.23	19.61
			Total load	117.68	78.46	39.22
	Vibrating	EI11	Both hands	23.54	15.69	7.85
			Both shoulders	39.23	26.15	13.08
			Total load	125.54	83.68	41.86

Table 5
Survey of musculoskeletal pains experienced by workers in the RC trade.

Trade	Author	Size	Method	Body parts (%)						
				Wrist	Elbo-w	Shou-lder	Disc	Hip	Knee	Ankl-e
Reinforc-ement	(Forde et al., 2005)	249	Q	47.8	24.1	34.1	52.2	19.7	36.9	26.9
Formwork	(Spielholz et al., 1998)	82	Q/V	37	33	32	47	21	2	9
Concrete placement	(Goldsheyder et al., 2004)	110	Q	37	26	47	66	23	38	29

Note: Q = questionnaire; V = videotape.

intervention strategies was performed to provide a deep understanding of how much loads are reduced and what specific parts of body may be biomechanically affected with these intervention strategies.

4.1. Physical stress caused by postures compared with WMSD survey results

To validate whether selected conventional postures may well represent the typical awkward postures observed on RC construction sites, the physical stress caused by these postures were compared with WMSD survey results. Fig. 5 presents the averaged strength capabilities of each body part of postures by trade unit (bar graph) and the WMSD survey responses (line graph). For the readability, the survey responses representing the body pains of workers were subtracted from 100% to make them compatible with the strength capabilities. Thus, in Fig. 5, bars and lines close to 0% indicate that the body stress experienced by a worker is high and frequent. Overall, the strength capabilities obtained from the survey and experiment visually exhibited similar patterns for the three trades. For reinforcement, as shown in Fig. 5, the body parts exhibiting the lowest strength capabilities values in the survey (disc = 47%, wrist = 52%, and knee = 63%) also had the lowest values in the experiment (disc = 79%, wrist = 88%, and knee = 91%). For formwork, the lowest values were observed for the same body parts, such as the disc and wrist, in the survey and experiment. For example, the strength capabilities of the disc and wrist in the survey were 54% and 63%, respectively, and those in the experiment were 67% and 75%, respectively. For concrete placement, the strength capabilities of the wrist and knee were similar between the survey and the experiment (survey: 63% and 77% for the wrist and knee, respectively; experiment: 83.4% and 85.5% for the wrist and knee, respectively). These results were similar to those for the hip and ankle (survey: 62% for both the hip and ankle; experiments: 86.7% and 86.7% for the hip and ankle, respectively). As shown in the figure, owing to the similarities between the two groups, the correlation coefficients were large, i.e., 0.86, 0.63, and 0.77 for the reinforcement, formwork, and concrete placement, respectively. These results imply that the selected postures for the experiment and those observed on the construction site leading to WMSDs are similar. Hence, the conventional postures that were selected and analyzed in the experiment may well represent the typical awkward postures observed on RC construction sites.

4.2. *Biomechanical simulation result of conventional postures*

To ascertain the body parts at high risk of injury in selected conventional postures and further evaluate whether these postures exceed the acceptable stress (e.g., compression) capacity, the biomechanical simulation results of the 36 conventional postures for three magnitudes of external forces were computed (Table 6). The joint moments of the wrist, elbow, shoulder, hip, knee, and ankle as well as the compressions of two types of discs (L5/S1 and L4/L5) were classified according to the posture, activity, and trade. In particular, the joint with a higher moment between two body parts (wrists, elbows, shoulders, hips, knees, and ankles on the left and right sides) was presented because a higher-magnitude joint moment has a higher probability of reaching a threshold, leading to WMSDs.

The results presented in Table 6 indicate that for most of the postures, a severe body reaction occurs in the lower extremities and discs. The average moments at the wrist, elbow, and shoulder, i.e., 4.18, 17.77, and 26.03 N m, respectively, were lower than those at the hip, knee, and ankle (101.59, 62.79, and 65.51 N m, respectively). The average disc compressions were in the range of 2106.17–2111.80 N. In contrast, the disc compressions of several postures exceeded the NIOSH Action Limit (AL) (AL = 3400 N), which is the maximum force that a person is allowed to exert without exceeding the threshold specified by the Work Practice Guide for Manual Lifting (Balendra and Langenderfer, 2017). In particular, posture R5 associated with the horizontal reinforcement activity, postures F11–F14 associated with the horizontal hammering activity, and postures C3 and C4 associated with the concrete hose-holding activity result in severe disc compressions exceeding or approaching the NIOSH AL.

4.3. *Biomechanical simulation assessment of postures with ergonomic intervention strategy*

To provide a deep understanding of how much loads are reduced and what specific parts of body may be biomechanically affected with intervention strategies, the biomechanical simulation results of the seven body parts in the postures relevant to each ergonomic intervention strategy were compared with those of the conventional postures (without interventions) in terms of joint moment and disc compression. For a fair comparison, the simulation results of the conventional postures were grouped in the same activity unit as the ergonomic-intervention postures. This is because each strategy is designed to alleviate the risk involved in a set of diverse postures with the same task purpose in an activity rather than in a specific posture. An ergonomic intervention strategy is typically applied by considering activity (task)-specific characteristics (Boatman et al., 2015). For example, for horizontal rebar tying, an extended rebar tying tool is applied as an ergonomic intervention tool to reduce disc bending, which typically occurs in conventional rebar tying postures, such as kneeling, squatting, and stooping, leading to severe back bending (Lingard et al., 2019; Umer et al., 2017b).

Table 7 presents the average values of the biomechanical simulation results for the three loads applied to the body parts. Overall, by adopting ergonomic intervention strategies, the body reaction rarely exceeded 100 N m at each joint and the NIOSH AL (3400 N) on each disc, compared to that of conventional postures. The results also indicate that the joint moments at the lower extremities exceeded those at the upper extremities for the three loads considered. For example, the average moments at the wrist, elbow, and shoulder, i.e., 2.50, 11.56, and 19.99 N m, respectively, were lower than those at the hip, knee, and ankle (57.57, 38.47, and 31.97 N m, respectively). The average disc

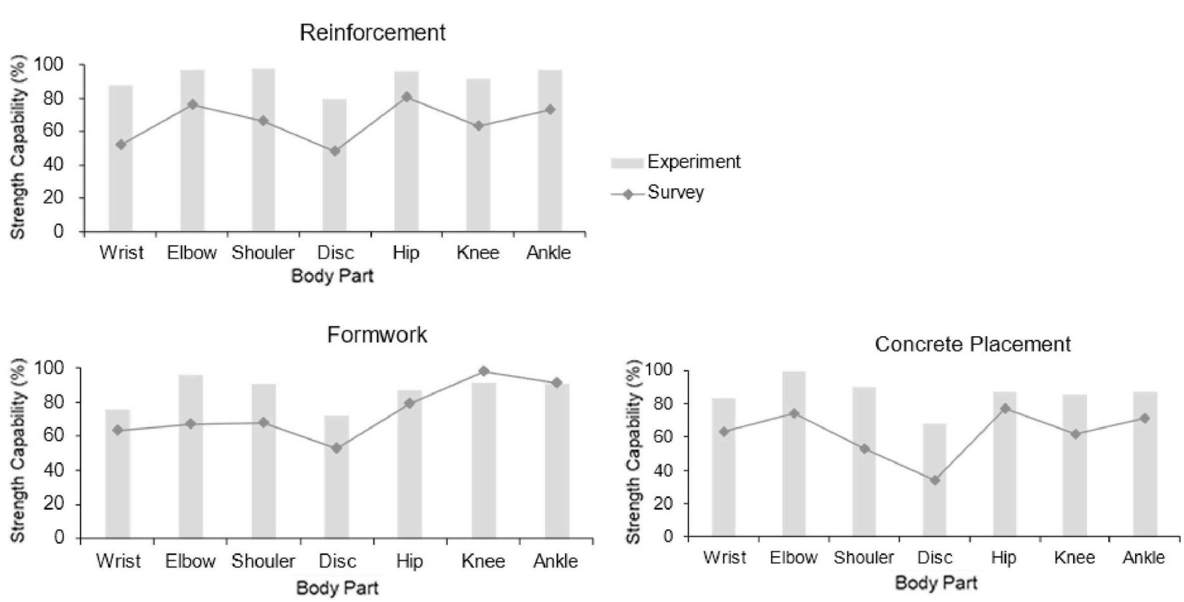

Fig. 5. Comparison of strength capabilities of body parts between the experiment and the survey.

Table 6
Biomechanical simulation results of conventional postures.

Trade	Activity	Pos-ture	Joint moment (N•m)						Compression (N)	
			Wr-ist	Elb-ow	Shou-lder	Hip	Knee	Ankle	L5/S1	L4/L5
Reinforce-ment	Assembly	R1	8.34	28.66	33.57	67.46	61.02	58.44	1225.83	1196.00
		R2	0.11	0.99	2.85	47.24	46.05	52.82	1088.63	1036.94
		R3	7.24	30.73	24.17	66.41	55.96	45.53	1685.41	1758.54
		R4	4.51	17.45	18.12	67.73	62.83	64.00	1071.01	892.73
	Horizontal reinforcement	R5	1.24	6.69	2.72	132.80	71.34	67.99	3230.33	3232.02
		R6	1.26	4.96	10.55	112.96	91.54	67.36	2302.07	2413.41
		R7	1.09	2.57	4.50	90.66	18.50	23.89	1556.46	1726.39
		R8	1.32	3.84	3.90	133.19	76.27	27.65	2381.74	2526.10
Formwork	Assembly	F1	8.17	34.78	37.22	109.77	43.89	79.10	2011.43	2143.09
		F2	4.41	18.77	32.54	105.93	90.22	79.58	2198.15	2337.96
		F3	5.23	22.28	31.91	64.65	39.19	64.21	1809.76	1817.39
		F4	7.13	30.35	41.14	121.20	62.62	116.13	2271.95	2314.04
		F5	8.17	34.80	54.46	77.59	55.05	19.30	1527.70	1190.26
	Erecting/lowering	F6	4.69	20.16	35.32	73.17	75.73	59.30	1443.36	1321.03
		F7	6.35	27.34	38.08	83.69	66.89	46.85	1468.06	1515.48
		F8	6.47	26.21	39.48	57.43	77.69	89.93	2659.82	589.02
		F9	4.83	20.79	32.32	86.75	46.58	15.81	924.58	837.59
		F10	2.60	11.22	30.19	70.05	67.77	35.15	1495.32	1585.88
	Horizontal hammering	F11	4.67	20.41	22.85	288.32	60.37	177.79	4394.23	4619.07
		F12	4.42	19.33	32.40	154.55	29.19	181.08	4747.25	4968.37
		F13	4.18	18.27	12.05	188.87	91.95	72.32	3197.98	3502.58
		F14	3.56	15.61	10.41	127.06	26.59	76.17	3340.82	3555.09
	Vertical hammering	F15	3.88	16.94	34.49	57.21	33.53	9.47	842.83	813.24
		F16	5.50	24.04	36.69	67.45	50.42	34.23	2114.45	2198.60
		F17	4.51	19.69	44.55	101.63	56.10	33.46	1660.83	1692.01
		F18	4.65	20.28	41.20	102.14	85.18	32.60	1153.74	1106.57
Concrete placement	Hose holding	C1	4.38	19.55	38.63	59.48	54.70	44.96	2021.12	2123.61
		C2	5.59	23.78	43.42	83.56	71.18	67.13	2389.29	2125.97
		C3	4.17	18.60	29.13	123.94	66.75	89.67	3026.62	3027.56
		C4	3.73	16.63	13.10	145.45	66.59	108.17	3240.28	3466.05
	Screeding	C5	4.60	18.82	37.13	214.45	136.60	110.05	2360.68	2549.72
	Vibrating	C6	1.86	9.20	7.56	106.34	102.61	98.83	2487.67	2673.03
		C7	1.72	7.14	21.75	52.98	39.31	32.11	1020.01	1027.76
		C8	1.86	9.58	17.58	71.43	68.78	66.07	1809.01	1912.85
		C9	2.04	10.12	3.01	103.31	74.57	77.66	2453.33	2606.22
		C10	1.88	9.29	18.23	40.28	35.67	33.72	1412.90	1420.00
Avg.			**4.18**	**17.77**	**26.03**	**101.59**	**62.79**	**65.51**	**2111.80**	**2106.17**

compressions were similar with the values of 1145.74 N and 1167.83 N for L5/S1 and L4/L5, respectively.

In addition, overall, compared with conventional postures, these intervention strategy postures reduced the joint moments and disc compressions at all body parts by 4.64 N m, 33.96 N m, and 952.20 N for upper extremities, lower extremities, and disc compressions, respectively (Table 7). To evaluate more specifically for each ergonomic intervention strategy, the biomechanical simulation results of postures adjusted by these strategies (EI1-EI11) were compared with those of related conventional postures under three external loads (Figs. 6–13). The comparisons were based on the average joint moments (N•m) of the wrist, elbow, shoulder, hip, knee, and ankle (shown as (a) in Figs. 6–13), the disc compressions (N) at the discs (shown as (b) in Figs. 6–13), and the corresponding strength capabilities (%). The x-axis in the figures indicates the body parts, while the y-axis shows the moment and compression in a box plot (left side) and the corresponding strength capabilities in a line chart (right side). Box plots were used to present the strength capability and disc compression data obtained from the three different external loads, and the averaged strength capability was represented by a line graph.

The body reactions in EI1 were compared with those in the conventional postures involved in an assembly activity (Fig. 6). Overall, in EI1, the joint moments of every body part (except for the ankle) were reduced by 24.98%–81.69% compared with those in the conventional postures. In particular, significant moment reductions were observed at the wrist (81.69%) and elbow (78.56%), although comparatively low moments were observed before (5.05 and 19.46 N m, respectively) and after (0.92 and 4.17 N m, respectively) implementing EI1. Similarly, the lowest strength capabilities previously observed for the wrist (83.43%) and elbow (84.42%) increased to approximately 100% after EI1 was applied; that is, almost 100% of the population may have the strength capabilities to generate a moment exceeding the exerted moment. This result implies that although the magnitude of the force (moment) at the wrist and elbow may be low before ergonomic intervention, EI1 may result in postures that are more ergonomically comfortable for workers. In contrast, a slight moment increase was observed at the ankle (14.13%), possibly because of the different walking paces of two workers (EI1) working together. Nevertheless, the strength capability of the ankle was increased by 6.24% after EI1 was adopted, indicating that this body part did not suffer discomfort. Meanwhile, owing to EI1, the disc compressions were reduced by 34.06%–43.24%, and the strength capabilities were increased from 85.14%–85.69% to 90.91%–91.57% (Fig. 6(b)). Overall, these results indicate that the body stress is reduced, and the strength capability is increased when two workers hold the material together (EI1).

The results of EI2 and EI3 were compared with those of the conventional postures in the horizontal reinforcement activity (Fig. 7). In Fig. 7(a), the moments at the wrist, elbow, and shoulder increase when EI2 and EI3 are applied; the changes ranged from 1.23 to 1.90 (EI2), from 4.52 to 6.58 (EI3) and 9.07 (EI2), and from 5.42 to 11.22 (EI3) and 16.94 (EI2) N•m, respectively. Nonetheless, the strength capabilities of these parts remained at approximately 100% with the application of ergonomic interventions. This result implies that the application of EI2 and EI3 is acceptable for the upper extremities because the increased

Table 7
Biomechanical simulation results of conventional postures and postures of ergonomic intervention strategies.

Trade	Activity	Pos-ture	Joint moment (N•m)						Compression (N)	
			Wr-ist	Elb-ow	Shou-lder	Hip	Knee	Ankle	L5/S1	L4/L5
Reinforce-ment	Assembly	Pre-EI[1]	5.05	19.46	19.68	62.21	56.47	55.20	1267.72	1221.05
		EI1	0.92	4.17	12.72	46.68	38.82	63.01	719.08	804.62
	Horizontal reinforcement	Pre-EI[1]	1.23	4.52	5.42	117.40	64.41	46.72	2367.65	2474.48
		EI2	1.90	9.07	16.94	73.37	30.99	9.46	1279.12	1367.6
		EI3	1.21	6.58	11.22	45.06	25.01	31.79	1932.66	1889.93
Formwork	Assembly	Pre-EI[1]	6.62	28.20	39.45	95.83	58.19	71.66	1963.80	1960.55
		EI4	3.81	17.25	23.07	65.78	49.69	49.70	1367.31	1458.93
	Erecting/lowering	Pre-EI[1]	4.99	21.14	35.08	74.22	66.93	49.41	1598.23	1169.80
		EI5	3.17	14.66	15.93	56.98	39.90	20.79	967.98	1049.09
	Horizontal hammering	Pre-EI[1]	4.21	18.41	19.43	189.70	52.03	126.84	3920.07	4161.28
		EI6	3.20	14.81	23.33	31.37	19.84	12.90	615.45	609.71
	Vertical hammering	Pre-EI[1]	4.64	20.24	39.23	82.11	56.31	27.44	1442.96	1452.61
		EI6	3.20	14.81	23.33	31.37	19.84	12.90	615.45	609.71
Concrete placement	Hose holding	Pre-EI[1]	4.47	19.64	31.07	103.11	64.81	77.48	2669.33	2685.80
		EI7	2.80	12.55	20.18	107.16	67.23	42.82	2080.83	2233.44
	Screeding	Pre-EI[1]	4.6	18.82	37.13	214.45	136.6	110.05	2360.68	2549.72
		EI8	4.17	17.91	38.20	74.41	54.70	45.20	927.88	669.64
		EI9	1.36	6.69	21.68	36.83	22.90	41.98	980.94	1044.74
		EI10	2.57	11.65	24.36	80.92	68.97	42.47	1378.31	1429.33
	Vibrating	Pre-EI[1]	1.87	9.07	13.63	74.87	64.19	61.68	1836.58	1927.97
		EI11	1.67	8.60	8.95	40.91	23.78	10.61	883.83	847.27
Mean Pre-EI[2]			4.18	17.77	26.03	101.59	62.79	65.51	2111.80	2106.17
Mean Post-EI[3]			**2.50**	**11.56**	**19.99**	**57.57**	**38.47**	**31.97**	**1145.74**	**1167.83**

Note: Pre-EI[1]: the average results of conventional postures for each activity; Mean Pre-EI[2]: the average results of conventional postures for all trades; Mean Post-EI[3]: the average results of ergonomic intervention strategy postures for all trades.

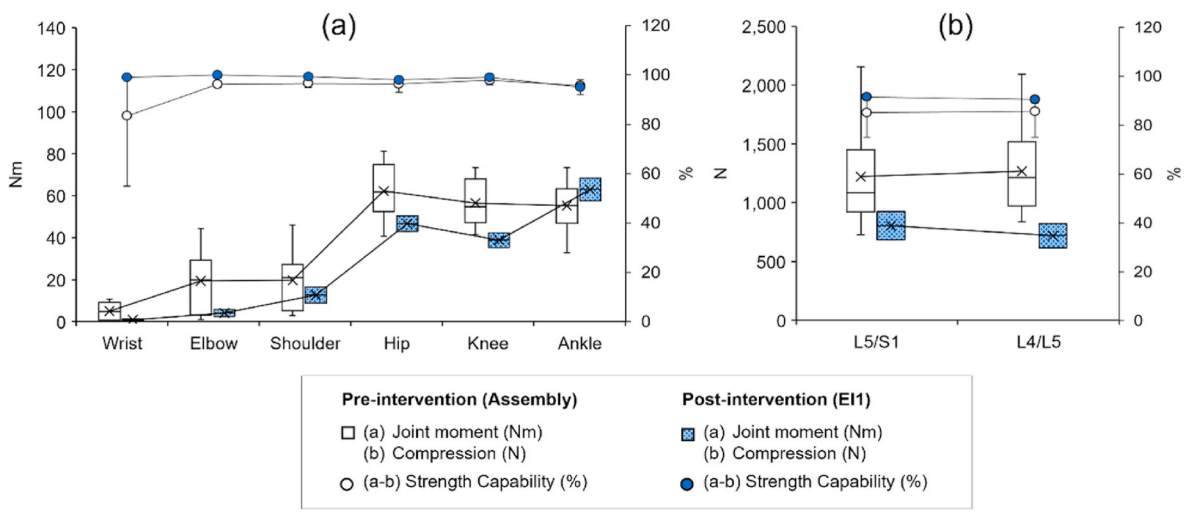

Fig. 6. (a) Joint moments and (b) disc compressions of the postures for the reinforcement assembly activity and EI1, along with the strength capabilities.

moments remain within the allowable range for most of the population. For EI2 and EI3, the joint moments at the lower extremities (hip, knee, and ankle) and disc compressions were reduced by 18.38%–79.79%, and the strength capabilities generally increased, as shown in Fig. 7(a) and (b). However, the strength capability of the knee decreased significantly from 94.75% to 39.33% for EI3, even though the joint moment decreased from 64.41 to 25.00 N m. This is possibly because the center of gravity (weight) shifts to the knee when the upper body tilts forward while the worker sits on a small stool (EI3). This implies that although EI3 can reduce the stress at the target body part (e.g., disc) and modify the posture to one that is neutral, the postural change can cause discomfort to another body part (e.g., knee), depending on the angular rotations of the body parts.

The adoption of EI4 reduced the moments at the wrist, elbow, shoulder, hip, knee, and ankle (Fig. 8(a)) and the disc compressions at L5/S1 and L4/L5 (Fig. 8(b)) by 14.55%–42.51% compared with those of the conventional postures for the assembly activity. The use of a machine in EI4 significantly reduced the external load (Table 4) necessary to hold a form, providing the worker with better control compared with manually handling the form (Table 6). The load applied to the wrist (i.e., contact with the material) was significantly reduced, by an average of 42.45%. Additionally, the strength capability of the wrist increased from 81.53% to 97.33% when the moment decreased from 6.62 to 3.81 N m. In addition, the disc compressions were reduced, and the strength capabilities were increased (Fig. 8(b)) because postures more comfortable than conventional postures affecting the disc (Fig. 2) can be assumed with the use of an extended handle (Fig. 3). In summary, the use of a machine (EI4) in form assembly can reduce the body stress at both the upper and lower extremities by reducing the total weight borne by a worker and straightening the worker's body to a neutral position.

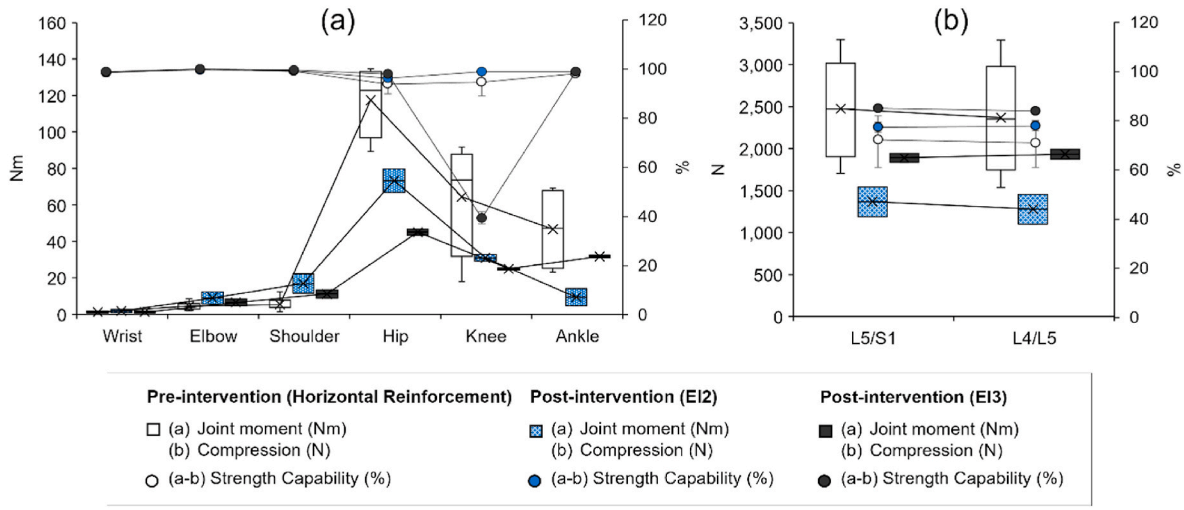

Fig. 7. (a) Joint moments and (b) disc compressions of the postures for the horizontal reinforcement activity, EI2, and EI3, along with strength capabilities.

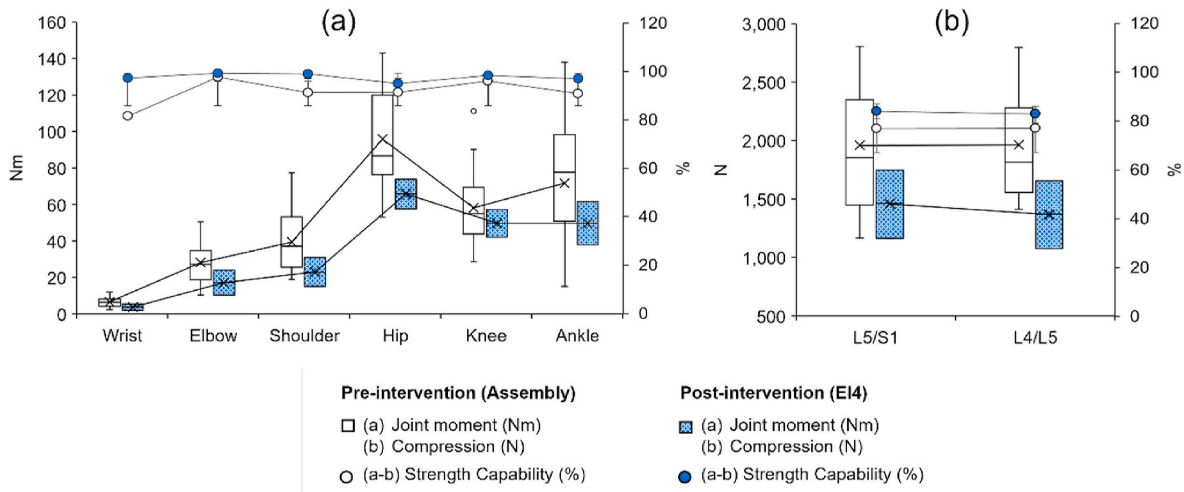

Fig. 8. (a) Joint moments and (b) disc compressions of the postures for the form assembly activity and EI4, along with strength capabilities.

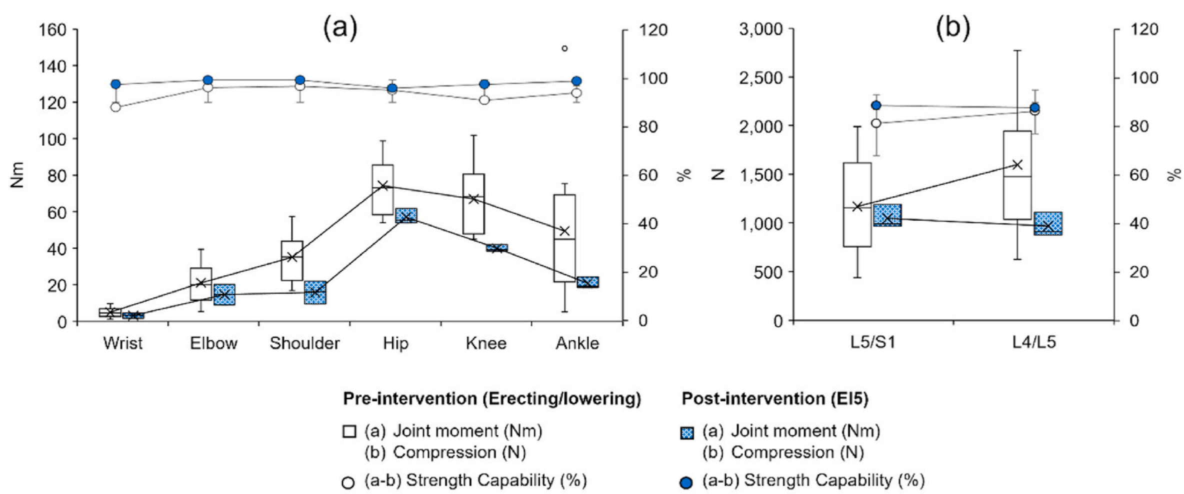

Fig. 9. (a) Joint moments and (b) disc compressions of the postures for the form erection/lowering activity and EI5, along with strength capabilities.

The joint moments and disc compressions resulting from the EI5 posture had lower average values (15.36%–60.32%) at all body parts than the conventional postures for erecting/lowering forms, as shown in Fig. 9. Additionally, the strength capabilities of all the body parts increased by 0.84%–10.90%. In particular, significant moment reductions resulting from the application of EI5 were observed at the ankle

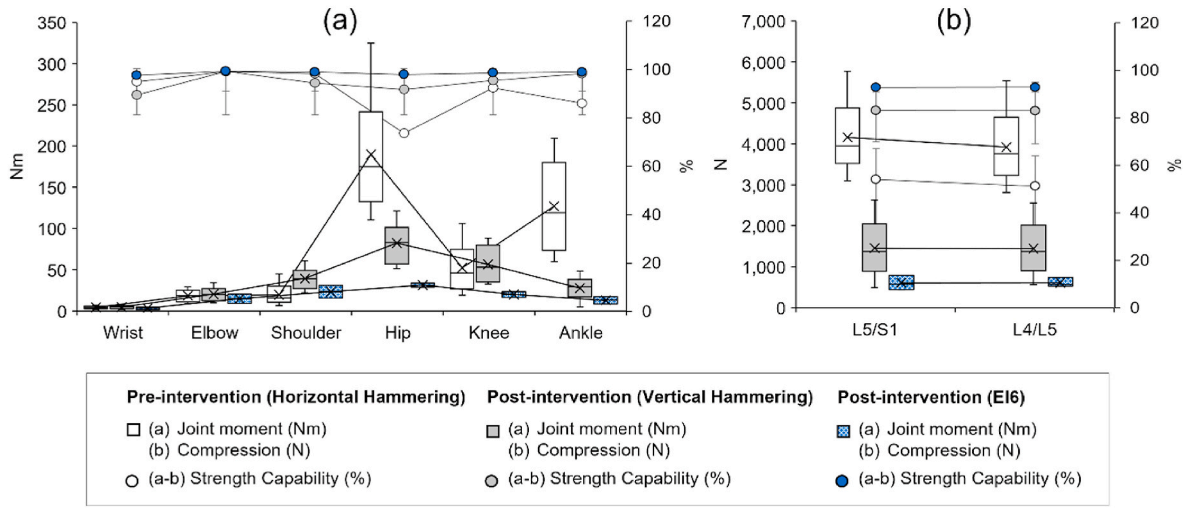

Fig. 10. (a) Joint moments and (b) disc compressions of the postures for the form hammering activities and EI6, along with strength capabilities.

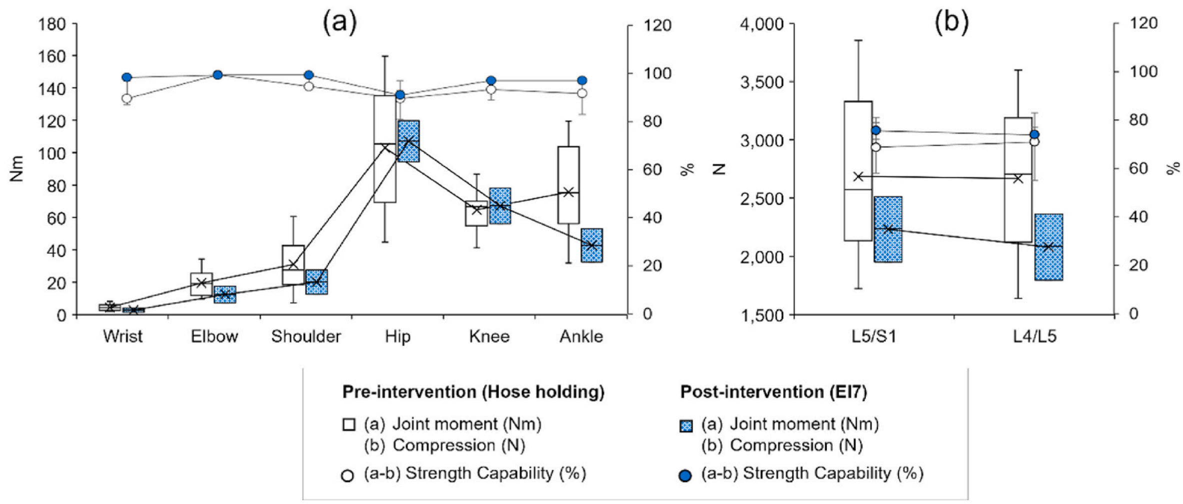

Fig. 11. (a) Joint moments and (b) disc compressions of the postures for the concrete hose-holding activity and EI7, along with strength capabilities.

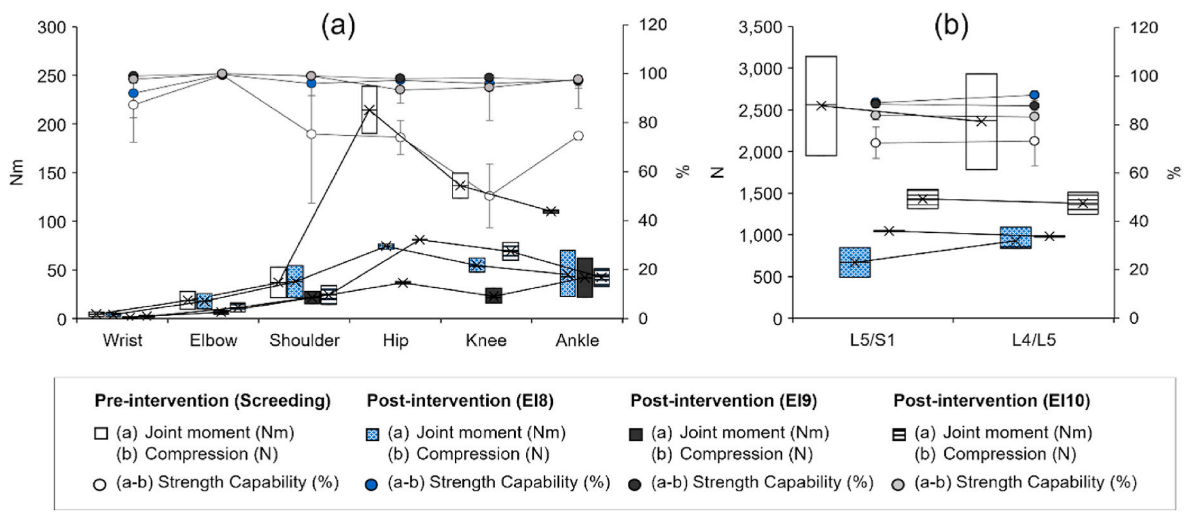

Fig. 12. (a) Joint moments and (b) disc compressions of the postures for the concrete screeding activity, EI8, EI9, and EI10, along with the strength capabilities.

(60.32%) and shoulder (51.14%), and the strength capabilities increased significantly at the wrist (10.90%), disc (L4/L5) (9.09%), and knee (7.25%), as shown in Fig. 9(a) and (b). Although the moment and compression reductions at the shoulder and ankle were larger than those at the wrist, disc, and knee, they did not directly lead to more comfortable postures. In contrast, the moment reduction at the wrist

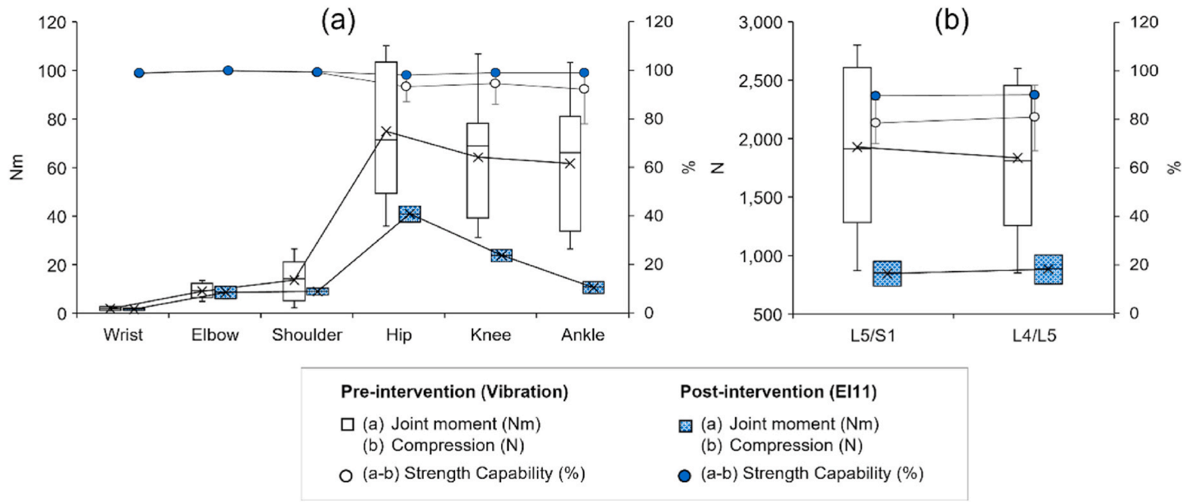

Fig. 13. (a) Joint moments and (b) disc compressions of the postures for the concrete vibration activity and EI11, along with the strength capabilities.

resulted in significant postural comfort.

The effect of EI6 compared with conventional hammering postures is presented in Fig. 10. The postures of the horizontal and vertical hammering activities were analyzed in two groups to determine the effectiveness of ergonomic intervention strategies under different conditions. The use of a hydraulic lifting machine in EI6 ergonomically improved most body parts by 19.58%–89.83% for both horizontal and vertical hammering activities (Fig. 10(a) and (b)). Before the intervention, the average disc compressions due to the horizontal hammering activity exceeded the NIOSH AL. However, with the intervention, the disc compressions were significantly reduced from 3920.07 to 4161.28 to 609.71–615.45 N (Fig. 10(b)). The use of a lifting machine (EI6) allows the adjustment of the workspace height with its attached movable platform for comfortable postures. Consequently, there may be less bending in EI6 (Fig. 3) than in the conventional postures (F11–F16 in Fig. 2). However, in horizontal hammering, the moment at the shoulder when EI6 was adopted (23.33 N m) exceeded that of the conventional posture (19.42 N m), as shown in Fig. 10(a). This exception may have occurred because in using the machine in EI6, the worker's back is straightened, similar to the alignment of the back in vertical hammering. Schoenmarklin and Marras (1989) reported that hammering on a vertical surface requires a larger angular rotation of the upper body (with the shoulder as the central axis) than hammering on a horizontal surface, possibly leading to higher shoulder moments. Nevertheless, the strength capabilities at the upper extremities due to EI increased by 0.17%–9.12% for both the horizontal and vertical hammering activities. The results suggest that although the ergonomic intervention strategy (EI6) may significantly reduce the stress on most body parts, the postural change can increase the moments at body parts (e.g., shoulders). In addition, despite the increase in the moment at a specific body part due to ergonomic intervention, a worker may remain comfortable.

The use of a skid plate (EI7) is suggested to hold a hose during concrete placement. Overall, the results (Fig. 11) indicated that the joint moments and disc compressions were generally 16.67%–44.63% lower than those of the conventional hose-holding postures (except for the hip and knee). With the use of a skid plate, the moments at the hip and knee increased slightly by 3.86%–4.00%. Owing to the required fixed posture of EI7 (holding an extension bar of the skid plate), workers tend to remain in a half-squatting posture (EI7 in Fig. 3); this awkward posture can produce considerable pressure (e.g., joint moment) at the hip and knee. Despite this unintentional effect, the strength capabilities of these body parts increased in the range of 0.20%–9.77%. Hence, all the body parts of a worker using the skid plate associated with EI7 remain comfortable.

The body effects of using screeding tools, such as vibratory (EI8), roller (EI9), and laser (EI10) screeds, were compared with those of the conventional postures in a screeding activity. Overall, these intervention strategies provided apparent positive effects, such as reductions in the joint moments: 4.87%–73.73% for EI8, 41.63%–82.90% for EI9, and 38.20%–62.35% for EI10 (Fig. 12). These exclude the moment increase (2.89%) at the shoulder for EI8, which possibly occurred because EI8 requires the worker to pull the handle toward the body, shifting the center of gravity to the shoulder (Fig. 3). Nevertheless, for EI8, the strength capabilities at all body parts increased by 0.34%–92.00%. This result suggests that ergonomic intervention strategies EI8, EI9, and EI10 significantly reduce the body reactions, contributing to the prevention of WMSDs.

The body effects of the EI11 posture using a backpack vibrator and the conventional posture employing a concrete vibrator hose were compared, as shown in Fig. 13. Overall, the joint moments at the wrist, elbow, shoulder, hip, knee, and ankle decreased by 3.42%–82.59%, as shown in Fig. 13(a). Accordingly, the strength capabilities of these body parts increased from 78.48%–99.80% to 89.64%–100%. The improvement may have occurred because the load applied to the body parts when holding a vibrating hose is evenly distributed with the application of EI11 (Tables 6 and 7), although the total applied load is the same. The disc compressions also decreased by more than half as the strength capabilities increased with EI11 compared with those of the conventional posture for the concrete vibrating activity (Fig. 13(b)). Thus, it be concluded that the use of a backpack vibrator (EI11) can significantly reduce the magnitude of the internal load exerted on body parts, leading to less body stress in concrete placement.

In summary, Tables 8 and 9 present the summaries of ergonomic improvement by each intervention strategy, showing how ergonomic issues can be alleviated or aggravated by ergonomic intervention strategies. Overall, it was found that with the application of ergonomic intervention strategies (EI1–EI11), the compression of the disc significantly decreased, while the strength capability increased. These findings are similar to those of previous studies reporting that the use of EI2 (Albers and Hudock, 2007; Lingard et al., 2019), EI3 (Umer et al., 2017a), EI5 (Mirka et al., 2003), and EI7 (Hess et al., 2004) reduced disc compression and torque in conventional postures. Meanwhile, except for the disc, the effectiveness of the strategy varied according to the body part and type of intervention. For example, one case was that the strategy (e.g., EI4, EI5, EI6, EI9, EI10, and EI11) significantly reduced the stress in every body part. Another case was that the intervention (e.g., EI1, EI2, EI3, EI6, EI7, and EI8) seldom reduced the joint moment at a specific part and even caused an increase at other body parts. These phenomena revealed that the application of ergonomic intervention strategies may possibly increase the internal body joint stress owing to the increase in the weight of the intervention tool (EI2), the change in the center of mass (e.g., EI3 and EI8), and the constrained freedom shift to a comfortable posture (e.g., EI1, EI6, and EI7). Nevertheless, although the total force applied to each body part was slightly increased, the overall strength capability was also increased (e.g., EI1, EI2, EI7, and EI8), suggesting the beneficial effects of intervention strategies for reducing body stress. Lastly, an exceptional case was that the use of a stool (EI3) in the horizontal reinforcement activity significantly reduces the strength capability despite the decrease in the moment at the knee where the reinforcement trade presents the most significant pain. In this case, the use of a sitting stool (EI3) can be more effective when given with other types of interventions (e.g., appropriate breaks, job rotation) as sitting stools can increase muscle contraction in the gastrocnemius lateralis and medialis (Umer et al. 2017b).

5. Discussion

Our contributions to knowledge are two-fold. First, this study identified the stresses (e.g., moment and compression) at a wide range of body parts of numerous selected conventional postures observed on RC construction sites to determine ergonomically awkward postures among conventional ones. Second, we identified and evaluated reduced loads at specific body parts when applying ergonomic intervention strategies (e.g., postural changes, workload adjustment) to analyze comprehensive effect of ergonomic interventions (e.g., positive and negative impacts) on different body parts. Based on that, the practical contributions of this study are not only providing the guideline of what ergonomic intervention can be adopted to mitigate musculoskeletal risk for a certain RC activity, but also further support in understanding the potential risk at different parts of a whole body when adopting a specific ergonomic intervention. Based on this understanding, other solutions (e.g., appropriate breaks, job rotation) may be combined with the ergonomic intervention strategies (e.g., postural changes, workload adjustment) studied in this paper to more efficiently prevent WMSDs at specific body parts during RC activities. Specifically, examples of how to use the outcomes of this study in practice are as follows: First, this study identified which conventional postures exceed the acceptable stress (e.g., compression) and strength capacity to provide a comprehensive knowledge of which postures of RC activities require a specific ergonomic intervention to prevent WMSDs. For instance, the disc compressions of selected conventional postures such as R5, F13, F14, C3, and C4 were 3230.33 N, 3197.98 N, 3340.82 N, 3026.62 N, and 3240.28 N for L5/S1 and 3232.02 N, 3502.58 N, 3555.09 N, 3027.56 N, and 3466.05 N for L4/L5, exceeding the maximum force that a person is allowed to exert following the NIOSH Action Limit (AL) (AL = 3400 N). Based on these results, workers should pay more attention to riskier postures such as R5 for horizontal reinforcement, F13 and F14 for horizontal hammering, and C3 and C4 when performing hose holding. Second, we also provided the knowledge of how much loads are reduced and what specific parts of body may be biomechanically affected when changing a posture by applying ergonomic intervention strategies. For example, for the installation of horizontal reinforcement, sitting on a small mobile stool (EI3) decreased the moment of 61.18% at the knee but significantly reduced the strength capability of 58.49% at this body part (Tables 8 and 9). This example indicates that some ergonomic intervention strategies can unexpectedly cause a negative impact on a specific part (e.g., knee). Thus, a further solution integrated with using a small mobile stool may be proposed by construction managers such as appropriate breaks and job rotation to efficiently support ergonomic intervention. This ergonomics management is valuable as a cost reduction, quality improvement, performance improvement and productivity-enhancing process (Rowan and Wright, 1994).

The implication of the experimental results is discussed as follows. First, the physical stress caused by the work activities at each body part numerically presented different degrees of the joint moment, compression, and strength capability although they may belong to the same trade (Figs. 6–13). Thus, the biomechanical simulation results provide an objective baseline for intervention targeting specific body parts for each activity. The findings also serve as evidence supporting the claim of previous studies that activity (task)-specific intervention is necessary (Kramer et al., 2010; Boatman et al., 2015). Second, the selected 36 conventional postures observed in the reinforcement-installation, formwork-installation, and concrete-placement trades exhibited correlation coefficients of 0.86, 0.63, and 0.77 to trade-specific WMSDs, respectively. (Fig. 5). The strong correlations imply that a comprehensive range of RC tasks (activities and postures) performed on construction sites were reviewed in this study, and the results can be used to define the potential physical demand of each work process leading to actual injuries. Moreover, the ergonomic intervention strategies that have been adequately demonstrated as effective for alleviating these injuries may be adopted. Third, the biomechanical assessment revealed that the 11 applicable ergonomic intervention strategies for the RC trade reduced all disc compressions by 45.21% and the joint moments by 31.86% on average (Table 7) while improving the strength capabilities of discs by 19.06% and other body joints by 11.41% (Figs. 6–13). Thus, it was quantitatively demonstrated that ergonomic intervention strategies can straighten the disc to neutral postures (Figs. 2 and 3) and disperse the applied forces throughout the body (Table 7).

Further research can be performed to address the following limitations. First, laboratory experiments were conducted to collect reliable motion data using a commercial motion-capture system. When the motion-capture technology (e.g., computer vision-based 3D pose estimation) becomes sufficiently advanced that 3D motions can be reconstructed with high precision in an outdoor environment, the motions of

Table 8
Comparison summary of joint moment and disc compressions between postures with and without ergonomic intervention strategies (Unit: %).

Abbreviation	Body Parts							
	Wrist	Elbow	Shoulder	Hip	Knee	Ankle	L5/S1	L4/L5
EI1	−81.69	−78.56	−35.36	−24.98	−31.27	14.16	−34.06	−43.24
EI2	54.59	100.77	212.59	−37.54	−52.18	−79.79	−44.69	−45.93
EI3	−1.79	45.67	106.86	−61.62	−61.18	−31.96	−23.63	−18.38
EI4	−42.51	−38.82	−41.62	−31.34	−14.55	−30.71	−25.41	−30.21
EI5	−44.96	−28.00	−51.14	−19.89	−39.69	−60.32	−15.36	−42.92
EI6_H	−23.87	−19.53	20.06	−83.46	−61.86	−89.83	−85.35	−84.30
EI6_V	−30.87	−26.82	−40.55	−61.80	−64.76	−52.97	−58.03	−57.35
EI7	−37.40	−36.10	−35.04	4.00	3.86	−44.63	−16.67	−21.91
EI8	−9.44	−4.87	2.89	−65.02	−60.63	−60.98	−73.73	−63.78
EI9	−70.69	−64.85	−41.63	−82.90	−84.23	−61.99	−59.00	−58.42
EI10	−44.10	−38.20	−34.65	−62.35	−49.69	−60.95	−43.94	−41.61
EI11	−10.79	−5.14	−34.32	−45.36	−62.95	−82.80	−51.88	−56.05

Note: A minus sign represents a decrease after the intervention compared to pre-intervention.

Table 9
Comparison summary of strength capabilities between postures with and without ergonomic intervention (Unit: %).

Abbreviation	Body Parts							
	Wrist	Elbow	Shoulder	Hip	Knee	Ankle	L5/S1	L4/L5
EI1	18.68	3.99	2.94	1.73	1.28	6.24	5.69	7.55
EI2	0.51	0.00	0.17	2.57	4.49	0.85	18.27	17.65
EI3	0.51	0.00	0.50	4.35	−58.49	0.85	9.65	7.05
EI4	19.38	1.71	8.55	3.94	2.36	6.83	7.63	9.08
EI5	10.90	3.19	2.62	0.84	7.25	5.24	1.64	9.09
EI6_H	2.81	0.17	0.68	32.88	6.67	15.00	81.23	71.63
EI6_V	9.12	0.00	4.76	6.72	3.23	0.68	11.90	11.67
EI7	9.77	0.20	5.02	1.58	3.93	5.82	4.14	10.04
EI8	5.34	0.34	27.43	31.53	92.00	30.36	25.93	23.21
EI9	13.36	0.67	31.42	32.43	96.67	29.91	19.92	22.35
EI10	11.83	0.67	31.42	26.13	88.67	30.80	13.77	15.91
EI11	0.27	0.20	0.20	5.08	4.72	7.38	11.29	14.23

Note: A minus sign represents a decrease after the intervention compared to pre-intervention.

workers on an actual construction site can be captured. Second, for the posture analysis, the external loads (e.g., weights of tools) were applied at varying magnitudes based on the relevant literature with an assumption of common working conditions of reinforced concrete tasks such that those objects were mostly placed perpendicular to the ground. However, for field ergonomic assessment, the loads of actual tools, and actual working conditions should be measured at the investigation site to obtain precise results under a specific working condition. Additionally, in order to comprehend the diverse range of worker anthropometric distribution under numerous human factors (e.g., general characteristics, ethics, nationality, and occupational type), it is necessary to consider various ranges of anthropometric population with a larger number of participants and different gender. Lastly, this study focused on the effectiveness of ergonomic intervention strategies from a biomechanical viewpoint. Future research may consider other factors, such as productivity, complexity, usability, and compatibility of ergonomic interventions in the field (Weinstein et al., 2007).

6. Conclusion

This paper conducts a case study of motion data-driven biomechanical assessment to identify awkward postures by analyzing a wide range of common postures frequently observed in the RC trade, ascertain the body parts at high risk of injury by comparing the physical loads with musculoskeletal pains at specific body parts, and evaluate reduced loads at these parts of employing ergonomic intervention strategies by comparing the physical stresses between pre- and post-interventions. The major findings of this study are summarized as follows: First, the body parts with high musculoskeletal risks found in this study may potentially lead to the development of WMSDs. The conventional postures (Fig. 5) showed a high correlation with the WMSDs survey (0.86, 0.63, and 0.77 for reinforcement, formwork, and concrete placement, respectively), supporting the causal relationships between the bodily stresses and injuries. Second, for RC trades, severe body reactions occur mostly in the lower extremities and discs. For example, the mean moments of the lower parts were higher than those of the upper parts (Table 6). Notably, some postures (e.g., R5, F11–F14, C3, and C4) involved in horizontal reinforcement activity, horizontal hammering activity, and concrete hose-holding activity can cause severe disc compressions exceeding or approaching the NIOSH AL (3400 N). Lastly, the biomechanical assessment supports that the ergonomic intervention strategies in this study can effectively reduce the musculoskeletal risk of RC trades. For example, the application of 11 ergonomic-intervention strategies to 36 conventional postures resulted in average body force reductions of 45.21% at the discs (i.e., L5/S1 and L4/L5) and 31.86% at the major joints (i.e., wrist, elbow, shoulder, hip, knee, and ankle). The strength capabilities were also increased by 19.06% at two discs and 11.41% at the remaining body parts. However, strategies such as EI3, which has not really prevented WMSDs risks effectively at specific body parts (e.g., knee), need to be integrated with other solutions (e.g., appropriate breaks and personal protective equipment) for better WMSDs prevention.

This study emphasizes the importance of an objective, quantitative, and comprehensive biomechanical evaluation for various body parts over a wide range of conventional work-related postures when determining the effectiveness of ergonomic intervention strategies. In addition to certain types of awkward postures commonly investigated in previous studies such as stooping, squatting, and lifting, the proposed comprehensive approach may enable a better understanding of what ergonomic intervention strategies can be adopted and what effect can be expected in practice, by which it can be expected to aid in the adoption of ergonomic intervention tools at a workplace. The findings of this study also serve for the education and training of RC workers by helping them understand the benefits of using intervention strategies and the importance of performing ergonomically safe posture in reducing the risk of injuries and illnesses. Thus, this study can potentially lead to a safer, healthier, and more productive environment for construction workers and ensure that a building is designed and operated with safety as the top priority.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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