Applied Ergonomics 110 (2023) 104019

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Real-time vibrotactile feedback system for reducing trunk flexion exposure during construction tasks

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A R T I C L E I N F O

Keywords:
Construction work
Vibrotactile feedback
Real-time postural intervention

A B S T R A C T

Workplaces are increasingly evaluating the use of wearables for ergonomic assessment and providing biofeedback as a real-time postural intervention to improve workers' posture. However, the effectiveness of such intervention systems has yet to be thoroughly investigated in different types of industrial tasks. This study tested the immediate effects of using vibrotactile feedback in simulated construction work tasks including lifting-lowering, shoveling, and tying rebar, to investigate the potential for such an intervention as a way to instruct workers in reducing excessive trunk flexion exposures. Fourteen male participants completed simulated work tasks with three different feedback locations, namely, no feedback, back, and wrist. The results demonstrate that the 95th, 90th, and 50th percentiles of trunk flexion angles are significantly lower for lifting-lowering and shoveling tasks when the feedback system is used. No significant postural changes were observed for the rebar tying task at any combination of percentile and feedback location. The rating of perceived exertion (RPE) for each task did not differ significantly between feedback conditions. Productivity remained the same with the feedback for lifting-lowering and rebar tying, while it was significantly reduced (4.5% of working rate reduction) in shoveling. Participants rated the wrist as the most preferred feedback location. The results of this study suggest that vibrotactile feedback has potential as an effective postural intervention for ergonomic risk factors in selected construction work tasks. Implications for the future design of real-time wearable, sensor-based vibrotactile feedback systems for postural control intervention during dynamic work tasks are discussed.

1. Introduction

The construction industry plays a vital role in the US economy (Murie, 2007; Stasiak-Betlejewska and Potkány, 2015). The construction industry is labor-intensive, and labor productivity directly affects construction productivity (Ghate et al., 2016). Consequently, work-related musculoskeletal disorders (MSDs) are very common in the construction industry (Dong et al., 2018; Albers and Estill, 2007; Boschman et al., 2012). Data shows construction workers experience the third-highest number of reported injuries with days away from work (at an incidence rate of 1.1 such injuries per 100 full-time workers for 2019–2020) among various industry sectors (Bureau of Labor Statistics, 2021). The average one-year prevalence of lower back MSD symptoms (defined as at least one episode of pain or symptoms) was 51.1% among 19 construction trades in 15 countries (Umer et al., 2018). Of the various types of construction work, construction laborers are at especially high risk for MSDs due to various job tasks requiring high force exertion and prolonged awkward postures. For instance, many construction laborers' work tasks, such as shoveling, tying rebar, and framing, involve kneeling, crouching, and stooping postures. Such work tasks increase the risk of MSDs because they require workers to bend or twist their backs for prolonged durations in nonneutral postures (Dong et al., 2018). Not surprisingly, the back is the most affected body part (42%), followed by the knees (12%) and shoulders (12%) (Marras et al., 1995).

Among the various work tasks involving work postures that may be harmful to construction workers, lifting and lowering is a major risk factor for work-related MSDs in construction (Dong et al., 2018). Overexertion from lifting and lowering is especially problematic, causing 30% of the MSDs among construction workers, with a higher injury rate compared to all other industries on average (10.6 per 10,000 full-time workers in 2015) (Dong et al., 2018). Shoveling also subjects workers to increased work-related back, shoulder, and wrist MSD risks (Ishwarya and Rajkumar, 2021; Canadian Centre for Occupational Health & Safety, 2017; Parida and Ray, 2012; Schneider and Susi, 1994), and shoveling is the second leading cause of overexertion injuries (10%) in the US (Schneider, 2001). In particular, repeatedly using a shovel to

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https://doi.org/10.1016/j.apergo.2023.104019
Received 31 July 2022; Received in revised form 13 March 2023; Accepted 15 March 2023
Available online 20 March 2023

lift objects for a prolonged period of time can lead to a high risk of back pain (Albers and Estill, 2007). In addition, tying rebar also subjects workers to increased work-related back MSD risks. Rebar refers to iron bars that are tied together and arranged within a structure's form prior to pouring concrete, so as to reinforce the structure (Dababneh and Waters, 2000). Tying rebar is often performed while standing on uneven, semi-stable rebar networks (Forde et al., 2005), while workers bend forward in nonneutral trunk postures for prolonged durations (Umer et al., 2017); this subjects rebar workers to an elevated risk of lower back disorders (Albers and Hudock, 2007). Rebar workers have reported discomfort or pain in the hand, wrist, elbow, shoulder, and lower back (Dababneh and Waters, 2000). Self-reported lower back pain has been shown to occur at rates as high as 56% among rebar workers (Forde et al., 2005).

Identifying and correcting work hazards and worker postures in construction is challenging, as working conditions and phases of construction in field environments are volatile (Knezovich and McGlothlin, 2007). To mitigate work related MSDs in the construction industry, various training and education methods have been developed and tested as prevention strategies. Unfortunately, interventions focused on knowledge transfer through didactic training methods have been found ineffective at reducing lumbar spine flexion (Demoulin et al., 2012; Kamachi et al., 2021). Also, interventions based on technique training were found to have only minor impacts on working practices and injury rates (Hignett, 2003). Meanwhile, real-time assessment and training based on individual workers' performance is known to be effective; however, such personalized training is costly and dependent upon available resources for viability (e.g., ergonomic education programs and ergonomic/safety practitioners). Such evidence suggests a need for more cost effective intervention methods in construction to deliver training through real-time and personalized interventions.

Real-time posture assessment using wearable inertial sensors, also known as inertial measurement units (IMUs), has received attention for occupational ergonomic exposure measurement in recent decades (Lim and D'Souza, 2020a,b). Recently, wearable IMUs have been increasingly used not only as an effective assessment tool, but also combined with other technologies to provide real-time feedback in occupational settings (Yan et al., 2017; Valero et al., 2016; Khan et al., 2021; Yang et al., 2022). Example technologies include augmented reality (AR) (Vignais et al., 2013), virtual reality (VR) (Arbelaez et al., 2020), and handheld devices (such as smartphones or tablets) for providing either visual feedback, auditory feedback, or a combination of both as multimodal feedback. Such real-time sensory feedback is provided as customized guidance to elicit immediate changes in work postures (e.g., extended trunk flexion and other awkward postures). For example, Vignais et al. (2013) implemented a head-mounted AR display to provide real-time visual and auditory feedback based on a computerized posture assessment (i.e., a RULA-based scoring system) of manual industrial tasks, finding a significant reduction in arm exposures with the feedback (Vignais et al., 2013). Kamachi et al. (2019) applied a real-time auditory feedback system in a two-week postural training study for novice caregivers. In the study, the intervention group with real-time auditory feedback showed a significant decrease in end-of-range (80th and 95th percentile) spine flexion after two weeks of intervention while performing patient care tasks (Kamachi et al., 2019).

IMUs combined with vibration actuators are increasingly used as a medium for real-time vibrotactile feedback in occupational settings within postural control interventions. Recent work from Lind et al. (2020b) investigated the effectiveness of real-time vibrotactile feedback provided through a custom-design smart workwear system composed of IMUs and built-in vibration actuators in an order-picking task (Lind et al., 2020b). The feedback system reduced time in truck inclination and upper arm elevation not only with the presence of feedback but also after the feedback withdrawal, suggesting possibilities for retention and motor transfer (Lind et al., 2020b). Accordingly, more and more commercial wearable systems are adopting vibrotactile (or haptic) feedback as a proactive intervention tool. Such systems include the Boost 2.0 system (GoX Labs, Phoenix, AZ, USA), the FUSE system (StrongArm Technologies, Brooklyn, NY, USA), and the Modjoul Wearable system (Modjoul, Clemson, SC, USA) for posture monitoring and intervention (Patel et al., 2022).

Given that visual obstruction is one of the main factors that causes fatal accidents (Hinze and Teizer, 2011) and environmental noise levels are extremely high at construction sites (Sellappan and Janakiraman, 2014), providing realtime feedback using vibration may be adequate in construction settings. Notably, vibrotactile feedback has advantages over other forms of sensory feedback because it can be provided to workers privately (Jones and Sarter, 2008) without interrupting other workers nearby, facilitating individualized and customizable feedback designs (Islam and Lim, 2022). Vibrotactile feedback has been shown to be an effective means of providing safety warnings to construction workers in hazardous environments, such as approaching construction vehicles (Yadav, 2017). However, the effectiveness of such vibrotactile feedback in construction work settings—in particular, its effects on eliciting safe work postures in various types of work tasks, productivity, and usability—has yet to be fully explored.

In this study, we investigated the instant effects of using wearable, sensor-based, real-time vibrotactile feedback as a postural intervention in short bouts of construction work tasks. Three common construction tasks; namely, lifting-lowering, shoveling, and tying rebar, were simulated in a lab while participants received vibrotactile feedback when their sagittal trunk flexion angle exceeded 45°. We hypothesized that the vibrotactile feedback would reduce participants' average sagittal trunk flexion angles while increasing sagittal knee flexion angles as a compensatory movement strategy (e.g., using squat lifting or crouching postures instead of stooping). Participants' productivity, perceived exertion level, and usability ratings were also measured to investigate the effects of using vibrotactile feedback systems on performance and usability. In addition, two feedback locations were compared (upper back and wrist) to investigate possible adverse effects of providing feedback when the target body part needing postural correction (e.g., the trunk) does not match the feedback location. This was to understand whether a convenient sensor location (the wrist) can be effectively used for improved usability as a surrogate for the target location (the back).

2. Methods

2.1. Study participants

A convenient sample of fourteen healthy male participants between the ages of 18 and 35 were recruited from university communities. The age restriction was imposed to ensure that age-related motor learning and sensory feedback processing capabilities would not be confounding factors (Swinnen, 1998). Participants had a mean ± standard deviation age of 26.1 ± 4.6 years, body mass of 75.4 ± 8.6 kg, and stature of 175.8 ± 38.2 cm. Participants were selected if they had no construction work experience and had not received any formal training on safe construction work techniques. The selection of novice and untrained participants was intended to control potential differences in rates of learning, which could have potentially confounded the effectiveness of the vibrotactile feedback. Participants were provided printed informed consent forms before the start of the experiments and then screened using a body discomfort questionnaire (Cohen, 1997) to exclude individuals with preexisting MSDs. The study was approved by the university's institutional review board.

2.2. Experiment procedures

The study had participants perform three simulated construction work tasks; namely, lifting-lowering, shoveling, and tying rebar, in a controlled laboratory environment (Fig. 1). Three simulated work tasks were selected to represent common, physically demanding tasks

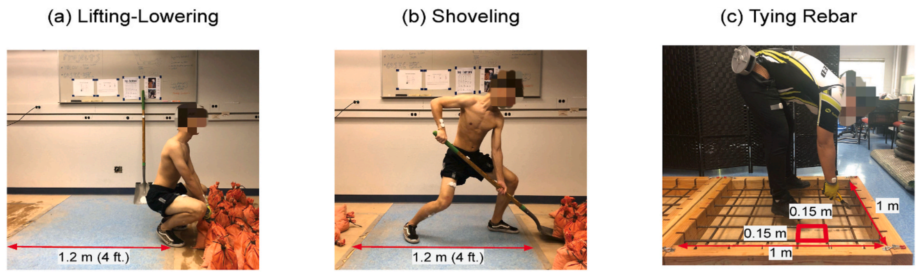

Fig. 1. A sample participant performing three simulated construction work tasks in a laboratory.

performed by construction laborers which involve extensive trunk flexion in repetitive motion or for prolonged durations (Dong et al., 2018), and representing manual material handling with either no tool (e.g., the lifting-lowering task) or using a hand tool (e.g., a shovel or a rebar plier). To investigate effective locations for providing vibrotactile feedback, we tested three different feedback locations. The three locations were the T6 vertebra ("back"); the dominant wrist ("wrist"); and no feedback at all. We selected T6 location instead of L5/S1 to minimize potential interference with work tools such as tool belts around the waist, which could affect the system's usability and the worker's sensitivity to vibrotactile feedback. Each task trial was repeated in a counterbalanced order within the work task with three different feedback locations, for a total of 9 work task trials per participant (3 task types × 3 feedback locations). The three work tasks were as follows.

- ***Lifting-Lowering*** [Fig. 1-(a)]: Participants lifted up pouches (4.5 kg per pouch, 25.4 cm × 35.6 cm) from the ground, carried them to a target location 4 feet away, and lowered them. Participants were allowed to handle multiple pouches per transfer. A maximum of 40 pouches was allowed per trial.
- ***Shoveling*** [Fig. 1-(b)]: Participants transferred the same type of pouch (4.5 kg) used in the lifting-lowering task using a transfer shovel (12.7 cm L × 24.8 cm W × 155 cm H, 1.91 kg) to a target location 4 feet away. Participants were asked to shovel only one pouch per transfer. A maximum of 40 pouches was allowed per trial.
- ***Tying rebar*** [Fig. 1-(c)]: Participants tied rebar using a rebar plier and metal wires. A wooden frame with six pieces of rebar spaced 15 cm apart horizontally and vertically (6 × 6 = 36 crosses) was constructed for this simulation. A heavy-duty tie-wire belt was provided with a reel of metal wire; participants wore it around their waist to conveniently access the wire during the task. Participants were instructed to freely step on the rebar frames, the wooden frame, or the ground as necessary. A maximum of 36 ties was allowed per trial.

All trials were performed for a maximum of 8 min. Trials ended early if 40 pouches were transferred (in the lifting-lowering and shoveling tasks) or 36 crosses were completed (in the rebar tying task) before 8 min had elapsed. We focused on controlling the total volume of work (i.e., the number of pouches moved or crosses tied) along with work duration to avoid a case in which participants work more (e.g., move more pouches) for any of the compared conditions for a given time, which could affect cumulative postural exposures. Heavy-duty utility gloves were provided, and participants could opt to use them to protect their hands. Participants found them to be interfering with their work tasks during practice trials, particularly during the rebar tying task, and therefore chose not to use them.

All participants were provided with visual instructions to warm-up and stretch their bodies prior to the work trials, and also received a brief training on safe material handling. This didactic intervention included three slides, each depicting pictures of safe and unsafe lifting-lowering, shoveling, and rebar-tying work postures with brief descriptive recommendations. Training materials were adapted from proper lifting, shoveling, and rebar-tying postures recommended in multiple resources (Canadian Centre for Occupational Health & Safety, 2017; Andriakos, 2018; Abitbol, 2019; National Telecommunications Safety Panel, 2021). For example, the training material for the shoveling task included such recommendations as keeping the feet wide apart, placing the front foot close to the shovel and putting weight on the front foot, using the legs to push the shovel by flexing the knees instead of using the back, and keeping the load close to the body. Participants were instructed to self-select a comfortable working pace by imagining working on the task for a full shift (8 h) without becoming too tired or exhausted. Participants were given adequate rest breaks between trials. They also participated in practice trials before the start of the experiment to familiarize themselves with the three simulated tasks and the feedback system.

After each trial, participants' perceived physical exertion was assessed using a Borg Rating of Perceived Exertion (RPE) scale (6 = no exertion; 20 = maximum exertion) (Borg, 1982). Participants were also asked to indicate whether it was difficult to distinguish the two types of vibration (short vs. long) and associate them with the required actions, and whether each type of vibration was interrupting or distracting using a 5-point Likert scale (1 = "very easy/not distracting"; 5 = "very difficult/very distracting"). In addition, after completing all of the trials, participants were asked to rate the perceived effectiveness, usability, acceptability of the feedback system, as well as their preference for and overall willingness to use it across the three feedback locations (1 = "least preferred"; 3 = "most preferred"). Finally, participants were asked to provide qualitative feedback and any additional comments they had about the feedback system in an open-ended questionnaire.

2.3. Instrumentation

2.3.1. Vibrotactile feedback system

A custom vibrotactile feedback system (Fig. 2) was developed to accurately assess participants' working posture (i.e., trunk flexion angle) during the work trials and deliver real-time vibrotactile feedback according to their trunk flexion angle. The system was implemented based on an open-source Python API provided by Mbientlab, Inc. (San Francisco, CA, USA) using a custom web-based user interface written in HTML and JavaScript. Four commercial wearable inertial sensors (Mbientlab's MetaMotionR+, comprising a 3-axis accelerometer and 3-axis gyroscope with a 25 Hz sampling frequency) combined with a coin motor (3 V, 70 mA, 12,000 RPM), a Windows PC, and a Raspberry Pi 3 board (model B+) were used to develop the system. Real-time data communications and transmission took place over Bluetooth 4.2 between the PC and the Raspberry Pi.

Before the experiment, sensors were attached to each participant's body using hypoallergenic double-sided tape. A total of four sensors were attached: one each at the sixth thoracic vertebra (T6), the right thigh, the right shin, and the dominant wrist (Fig. 2). Trunk and knee flexion angles were computed from filtered accelerometer and gyroscope data from the T6 (trunk) and right thigh and shin (knee) sensors using a custom algorithm implemented in MATLAB R2021a (The MathWorks, Inc., Natick, MA) (Lim and D'Souza, 2020a) with a previously validated sensor fusion algorithm that employs a Kalman filter

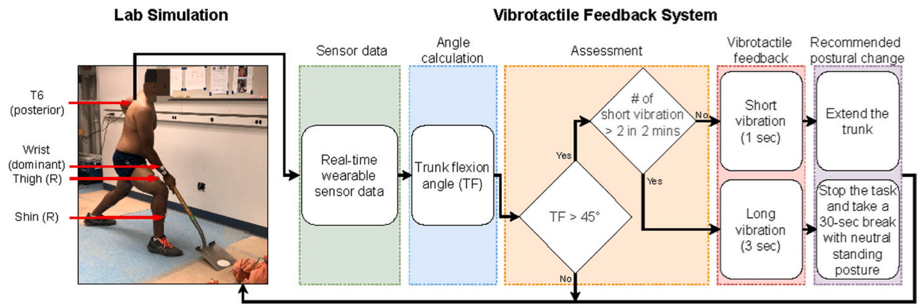

Fig. 2. An image showing a sample participant performing a simulated shoveling task in a laboratory (left) with wearable sensor attachment locations, and a flowchart depicting the real-time vibrotactile feedback system developed for the study (right).

(Chen et al., 2018). Participants' reference trunk and knee flexion angles were obtained by calculating 30-s averages of the trunk and knee angles in an upright standing posture before the work trials. Magnetometer data was neither collected nor used due to potential magnetic interference in work settings, which could affect the calculated postural angles (Robert-Lachaine et al., 2017).

2.3.2. *Vibrotactile feedback design*

Participants received vibrotactile feedback during the task trials when the moving average of calculated real-time trunk flexion (forward inclination) exceeded 45°after reference subtraction. This exposure threshold value was selected as a "severe" trunk flexion exposure level based on prior studies investigating the higher incidence of lower back MSDs at this level of trunk flexion angle (Hughes et al., 1997; Jansen et al., 2004) in industrial work tasks. Example postural assessment tools using the same criteria include PATH (Posture, Activity, Tools and Handling) (Buchholz et al., 1996), RAMP (Risk Assessment and Management tool for manual handling Proactively) (Lind et al., 2020a; Rose et al., 2020) and QEC (Quick Exposure Check) (David et al., 2008).

Two levels of vibrotactile stimulus (short vs. long vibration) were designed and triggered according to the participants' trunk flexion exposure. Initially, a "short" pulse vibration (three pulses lasting for a total of 1 s) was triggered when a participant's trunk flexion exceeded 45°. Participants were instructed to modify their work postures (e.g., extend their trunk) in response to this feedback. If a participant triggered short vibrations more than two times within 2 min, a 3-s continuous "long" vibration was triggered. Participants were asked to stop work immediately and take a 30-s break upon receiving the long feedback event. Feedback delivery continued until participants returned to a neutral standing posture. The 2 min time window for a long vibration was selected based on pilot tests performed prior to the main experiment with multiple iterations. Two minutes was selected as an adequate level for three simulated construction work tasks so as not to produce excessively frequent (and thus interfering) feedback. Fig. 2 describes the custom algorithm of the feedback system developed for the study in detail by showing the sequence of calculations and decisions made in the system.

2.4. *Dependent measures and statistical analyses*

All statistical analyses were performed using version 4.1.1 of the R programming language (R Core Team, 2019). Statistical significance was examined at the conventional level of $\alpha = 0.05$ for all tests.

Vibration feedback counts: Average ± standard deviation (SD) counts of short and long vibrations triggered during each task were calculated across all participants for different feedback locations. Separate repeated-measures analyses of variance (ANOVAs) were used to assess the effects of work task and feedback location on short and long vibration counts. Participant was included as a blocking effect in these ANOVAs. Significant main effects were examined further using Tukey HSD post hoc tests.

Postural exposure–torso and knee flexion angles: Percentiles (95th, 90th, and 50th) of trunk and knee flexion angles during each work trial were computed to investigate the effects of vibrotactile feedback and feedback location on working postures. Separate repeated-measures ANOVAs were again used to assess the effects of feedback location on trunk and knee flexion angles in each work task, with participant as a blocking effect. Tukey HSD post hoc tests were used to assess pairwise differences between feedback locations. In addition, empirical cumulative distribution functions (CDFs) of trunk and knee flexion exposures were fitted for each trial and aggregated for each work task and feedback condition.

Productivity: Since the maximum number of pouches and crosses completed during each task was capped at 40 (lifting-lowering and shoveling) and 36 (rebar tying), the rate of work was calculated for each time interval (1 min) within each trial as a productivity measure, instead of counting the total number of pouches or crosses completed in each trial. The rate of work was compared for different time intervals and feedback locations with participant as a blocking factor in separate repeated-measures ANOVAs for each task.

Ratings of perceived exertion, general experience, and usability: Average ± SD RPE scores were computed for each work task trial and feedback location. Kruskal-Wallis tests were performed to investigate whether the perceived exertion levels differed by feedback location for each work task. Median ratings were computed for four vibration design–related questions and a list of usability questions for each feedback location. Separate Kruskal-Wallis tests were used to investigate whether the feedback location affected RPE and subjective usability ratings in each work task. Pairwise comparisons were subsequently computed using Dunn's method with the Bonferroni correction for significant main effects.

3. Results

A total of 42 work trials (14 participants × 3 trials each with different feedback locations) were collected from each of the lifting-lowering and rebar-tying tasks. Due to instrument errors, only 33 trials (11 participants × 3 trials) were obtained from the shoveling task. The mean ± SD task completion times for lifting-lowering, shoveling, and rebar tying were 3.4 ± 1.5 min, 7.2 ± 1.3 min, and 6.9 ± 1.1 min, respectively, across all feedback locations.

Fig. 3 depicts sample trunk flexion angle trajectories from a participant performing lifting-lowering, shoveling, and rebar-tying tasks without (left panel) and with (right panel) vibrotactile feedback. For the lifting-lowering task with feedback (Fig. 3, top-right panel), participants' trunk flexion exceeded 45° five times (the red horizontal line represents the threshold angle) over the task's 4.5-min duration, which triggered five short vibrations (represented as blue arrows). At approximately 2 and 3 min, long vibrations were triggered, as there were more than two short vibrations within the 2-min window. Participants were asked to stop work immediately (following the instruction provided before the start of the trials) and take a short, 30-s break by returning to

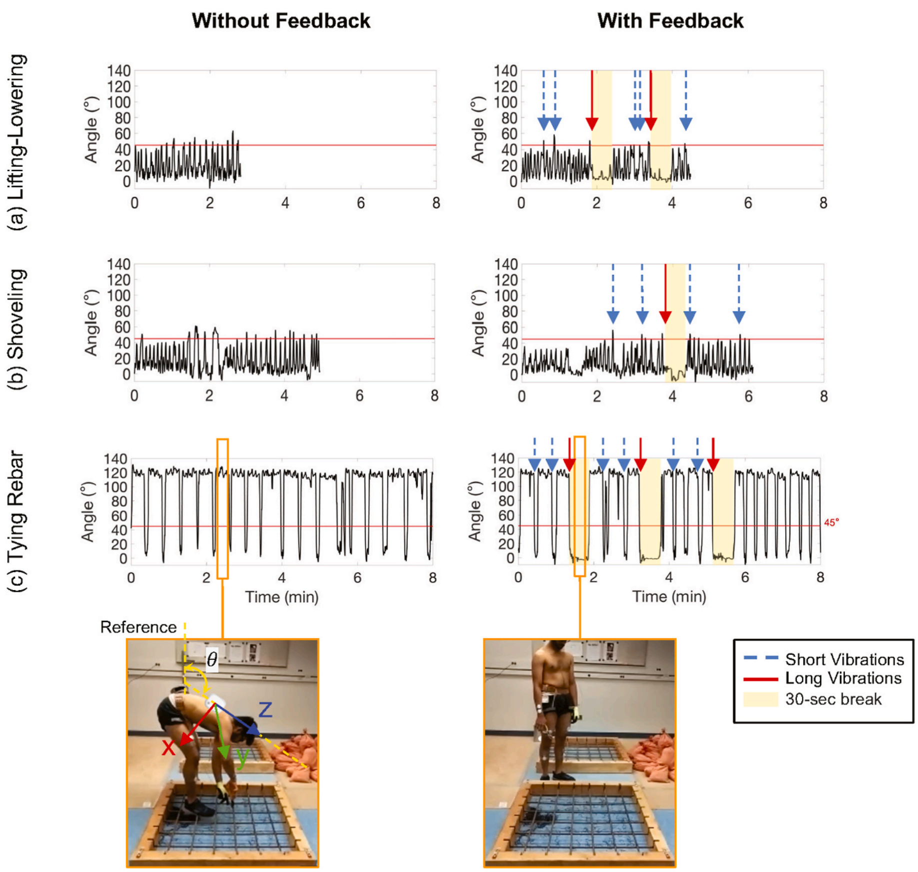

Fig. 3. Example time series of a participant's trunk flexion angle from three simulated work task trials without (left panel) and with (right panel) vibrotactile feedback. Blue and red arrows indicate times when short and long vibrations were triggered, respectively. Yellow bands highlight the 30-s break after a long vibration was triggered. At the bottom, screenshots of a video recording of a participant completing the simulated rebar-tying task are shown. The orientations of the sensor's three-dimensional axes are annotated on the left figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

a neutral standing posture (the yellow highlight), so the trunk flexion angle remained close to neutral during the break.

3.1. Vibration feedback counts

The counts of short and long vibrations triggered for each feedback location (back and wrist) during simulated work tasks are summarized in Table 1. Overall, the mean (SD) numbers of short vibrations triggered in all trials were 4.5 (2.8), 8.0 (5.4), and 6.0 (2.5) for the lifting-lowering, shoveling, and rebar-tying tasks, respectively, across feedback locations. Similarly, the mean (SD) numbers of long vibrations triggered in all trials were 1.5 (1.4), 3.1 (2.8), and 1.8 (1.5), for each work task, respectively. Work task had a significant main effect on the count of short and long vibrations across feedback locations [$F(2, 59) = 5.52$, $p = .006$]. During the shoveling task, short vibrations were triggered significantly more often than in the lifting-lowering task ($p = .003$), while there was no significant difference between shoveling and tying rebar ($p = .141$) or lifting-lowering and tying rebar ($p = .265$).

Table 1
Counts of short and long feedback events (mean ± SD) triggered during each simulated construction work task for different feedback locations. Feedback durations with different superscript letters within each vibration type in the last column differed significantly at $p < .05$.

Vibration Type	Work Task	Feedback Location		Total
		Back	Wrist	
Short	Lifting-Lowering	4.2 ± 3.6	4.7 ± 1.7	4.5 ± 2.8^{a}
	Shoveling	8.7 ± 6.3	7.3 ± 4.6	8.0 ± 5.4^{b}
	Tying rebar	6.0 ± 2.4	6.0 ± 2.7	6.0 ± 2.5^{ab}
Long	Lifting-Lowering	1.4 ± 1.9	1.6 ± 0.8	1.5 ± 1.4^{a}
	Shoveling	3.5 ± 3.1	2.7 ± 2.6	3.1 ± 2.8^{b}
	Tying rebar	1.6 ± 1.7	1.9 ± 1.3	1.8 ± 1.5^{a}

Long vibrations were triggered significantly more often in the shoveling task compared to lifting-lowering ($p = .010$) and tying rebar ($p = .038$). No significant interaction effects between work task and feedback location were observed for short [$F(2, 59) = 0.46$, $p = .632$] or long [$F(2, 59) = 0.65$, $p = .524$] vibrations. Additionally, feedback location had no significant effect for short [$F(1, 59) = 0.13$, $p = .718$] or long [$F(1, 59) = 0.09$, $p = .770$] vibrations.

3.2. Postural exposure

3.2.1. Trunk flexion angles

Participants' average trunk flexion angles (95th, 90th, and 50th percentiles) during all tasks are presented in Fig. 4 (left panel) by feedback location. Significant differences in trunk flexion angles between feedback locations were observed across all three percentile values for the lifting-lowering [95th; $F(2, 26) = 5.73$, $p = .009$, 90th; $F(2, 26) = 7.67$, $p = .002$, and 50th; $F(2, 26) = 13.01$, $p < .001$] and shoveling tasks [95th; $F(2, 20) = 4.64$, $p = .022$, 90th; $F(2, 20) = 5.73$, $p = .011$, and 50th; $F(2, 20) = 11.18$, $p < .001$]. Meanwhile, there was no significant difference in trunk flexion angles between feedback locations during the rebar-tying task across all percentile values [95th; $F(2, 26) = 1.76$, $p = .191$, 90th; $F(2, 26) = 1.78$, $p = .189$, and 50th; $F(2, 26) = 2.17$, $p = .135$].

Within the lifting-lowering task (Fig. 4, upper-left panel), trunk flexion angle was significantly reduced in the presence of vibrotactile feedback compared to no feedback, regardless of feedback location (back or wrist) across all percentile values. The average reduction in trunk flexion angles compared to the no-feedback condition were 5.5° and 6.1° for the back and wrist locations in the 95th percentile exposure, while the average reduction was 6.5° (back) and 7.4° (wrist) for the 90th percentile, and 3.9° (back) and 4.9° (wrist) for the 50th percentile. Overall, there were 13.7–47.7% reductions in trunk flexion angles with

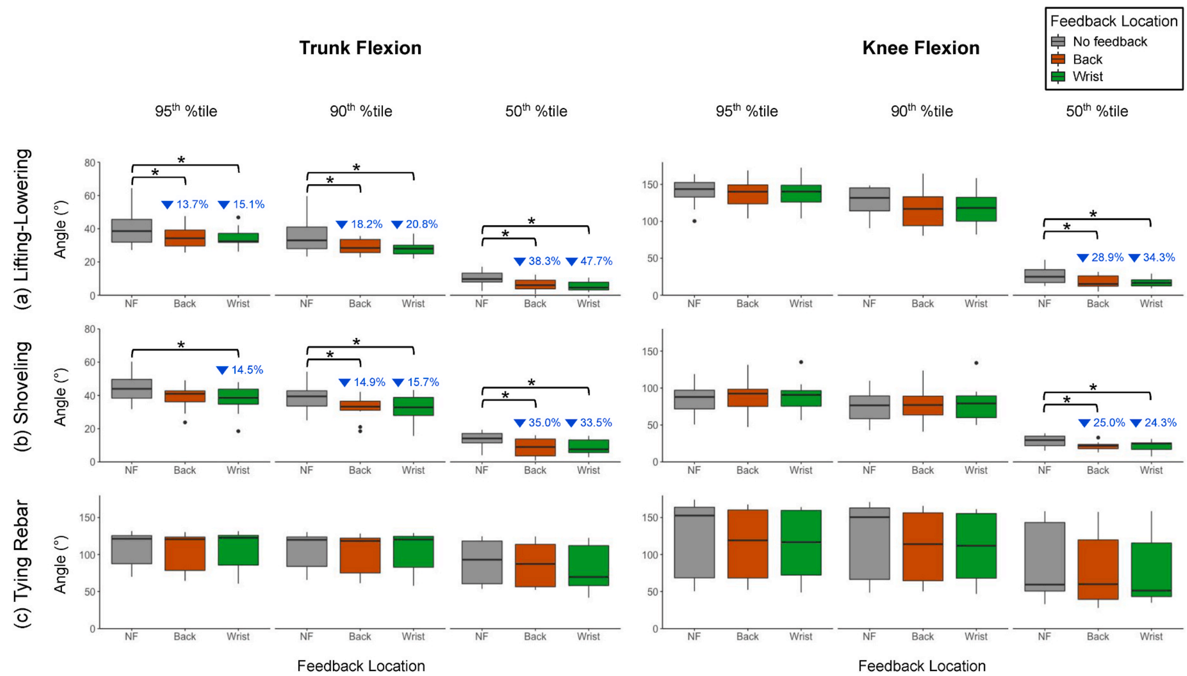

Fig. 4. Box plots of the average trunk (left) and knee (right) flexion angles obtained across all participants ($n = 14$ for lifting-lowering and tying rebar, $n = 11$ for shoveling) for the 95th, 90th, and 50th percentile exposure levels between three different feedback locations, namely, no feedback, back, and wrist. * indicates significant pairwise Tukey HSD comparisons ($p < .05$) within each percentile level. The triangle symbols and accompanying numbers indicate significant decreases in flexion angles from the no-feedback condition.

feedback versus without feedback across all percentile levels. No significant difference was observed between the back and wrist locations across all percentiles.

Within the shoveling task (Fig. 4, mid-left panel), trunk flexion angle was significantly reduced with feedback versus without it, with the exception that there was no significant difference between no feedback and back in the 95th percentile ($p = .088$). The average reduction in trunk flexion angle was 6.4° for the wrist location compared to the no feedback condition in the 95th percentile exposure, 5.7° (back) and 6.0° (wrist) for the 90th percentile, and 4.7° (back) and 4.5° (wrist) for the 50th percentile. This indicates a 14.5–35.0% reduction in truck flexion angles with feedback compared to no feedback. Similar to the lifting-lowering task, no significant difference was observed between the back and wrist locations across all percentiles.

Fig. 5 (left panel) presents the cumulative probability distribution of trunk flexion angles across all participants for each work task and feedback location. To the right, histograms showing the probability of trunk flexion angles are presented for each work task and feedback location. Overall, delivering vibrotactile feedback to the back and wrist improved overall trunk flexion exposures; the cumulative probability is greater for lower trunk flexion angles in both the back and wrist feedback conditions compared to the no-feedback condition. In the histograms, the distribution of trunk flexion exposures is similar across lifting-lowering and shoveling tasks, with a right-skewed distribution peaking around 0–10° across all feedback conditions. However, rebar tying shows slightly different patterns than the other two tasks, with a trimodal distribution concentrated around three modes at approximately 0–10°, 50–60°, and 100–110°. From video observation, it was found that the angles around 0–10° occurred principally during voluntary and forced breaks, especially in the feedback condition, while 50–60° occurred when tying rebar in a squat posture versus 100–110° in a stoop posture.

3.2.2. Knee flexion angles

Participants' average knee flexion angles (95th, 90th, and 50th percentiles) are presented in Fig. 4 (right panel) by work task and feedback location. Significant differences in knee flexion angles between feedback locations were observed only at the 50th percentile for the lifting-lowering [$F(2, 26) = 5.20$, $p = .013$] and shoveling [$F(2, 26) = 8.75$, $p = .002$] tasks. No significant difference across all levels of exposures between feedback locations was observed for the rebar-tying task. Tukey HSD tests revealed that both feedback locations (back and wrist) showed significantly lower average knee flexion angles compared to the no-feedback condition at the 50th percentiles [back: 28.9% reduction ($p = .045$); wrist: 34.3% reduction ($p = .018$)] during the lifting-lowering task. Similarly, feedback delivered to the back (25.0% reduction; $p = .004$) and wrist (24.3% reduction; $p = .005$) significantly reduced knee flexion exposure at the 50th percentile during the shoveling task.

Fig. 6 (left panel) represents the cumulative probability of knee flexion angles across all participants for each work task and feedback location. The probability plots illustrate that delivering feedback to either the back or the wrist reduced knee flexion exposure levels compared to providing no feedback, especially at the 50th percentile level. To the right, knee flexion exposures from lifting-lowering and shoveling show right-skewed distributions, while tying rebar shows a bimodal distribution with modes at 0–10°and 150–160°. The prominently high knee flexion angles at around 150–160° are from the squat posture while tying rebar.

3.3. Productivity

3.3.1. Lifting-lowering

All participants finished lifting and lowering all 40 pouches within the given 8-min time limit. Average (SD) completion times were 4.1 (1.9), 3.5 (1.2), and 2.7 (1.0) in the no-feedback, back, and wrist feedback conditions, respectively. On average (SD), participants moved 13.0 (7.9), 11.7 (4.5), 7.9 (3.5), 7.8 (2.7), 5.7 (2.5), 5.5 (1.8), 2.0 (0.0), and 3.0 (1.4), pouches per time interval (1st to 8th minute), respectively, across all feedback locations [Fig. 7(a)]. As a majority of the participants completed the task within 3–5 min, there were few samples in the intervals beyond 5 min ($n = 8$, 3, and 2 for 6th, 7th, and 8th interval,

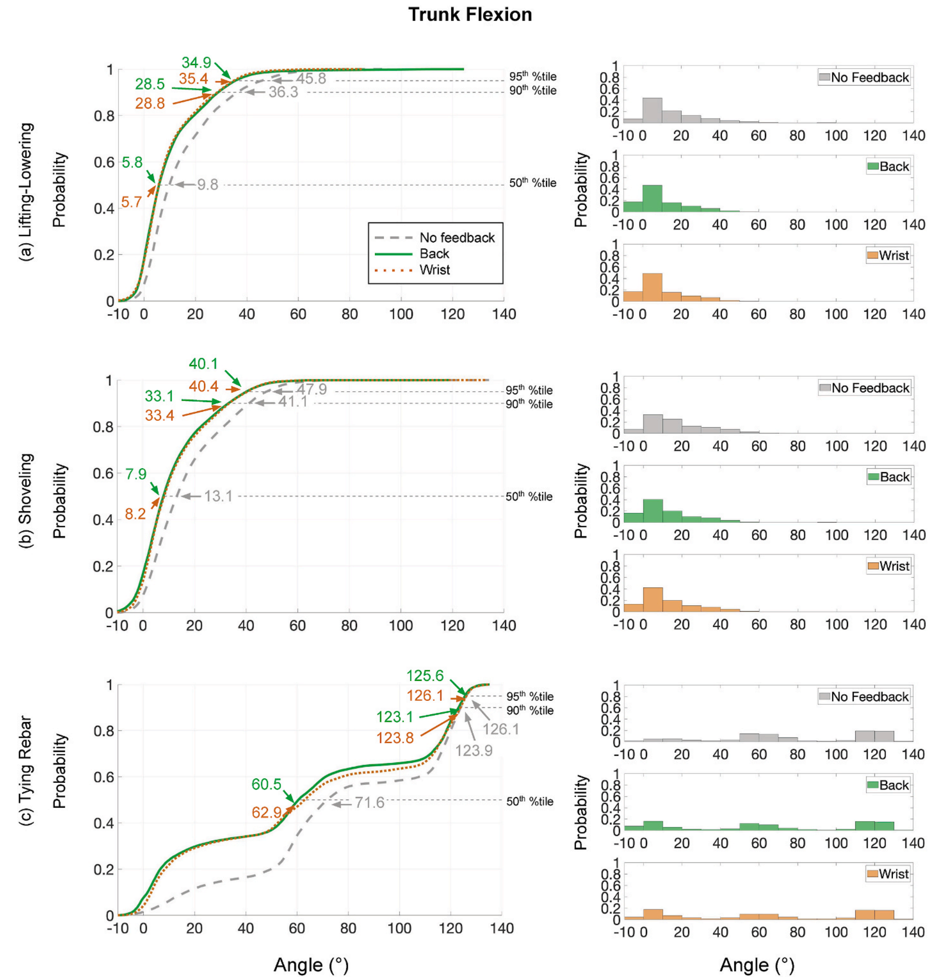

Fig. 5. Empirical cumulative density function plots (left) and histograms (right) from the measured trunk flexion angles across all participants ($n = 14$ for lifting-lowering and rebar-tying tasks, and $n = 11$ for shoveling task) for each work task by feedback location.

respectively). Due to these limited group sizes, working rates at the 6th, 7th, and 8th minute intervals were not included in further statistical tests.

A repeated-measures ANOVA found no significant difference in the rate of work across feedback locations [$F(2, 134) = 2.10$, $p = .126$], nor did it reveal a significant interaction between feedback location and time interval [$F(8, 134) = 0.27$, $p = .976$]. However, the rate of work was significantly reduced as time progressed [$F(4, 134) = 2.31$, $p = .041$]. Post hoc analysis revealed working rates were significantly reduced at the 3rd, 4th, and 5th minutes compared to the first minute ($p < .001$, $p = .001$, $p < .001$, for each time interval, respectively), and also compared to the second minute ($p = .007$, $p = .034$, $p = .003$, respectively).

Participants were allowed to move multiple pouches at a time, and the average (SD) numbers of pouches handled at each transfer was 2.2 (0.4) across all intervals and feedback locations. There was no significant difference in the number of pouches handled at each transfer across feedback locations [$F(2, 137) = 1.93$, $p = .149$] and time intervals [$F(7, 137) = 0.24$, $p = .946$].

3.3.2. Shoveling

The average (SD) numbers of pouches shoveled within the given 8 min were 37.5 (4.6), 31.2 (10.1), and 32.2 (10.2) in the no-feedback, back, and wrist conditions, respectively. Participants completed fewer shovel transfers with feedback compared to the no-feedback condition [$F(2, 191) = 3.71$, $p = .026$]. On average, participants completed 1.7 fewer shovel transfers when the feedback was delivered to the back ($p < .001$) and wrist ($p < .001$), indicating slightly reduced productivity with feedback. In each 1-min interval (1st to 8th minute), participants transferred 5.8 (3.0), 6.4 (3.0), 5.2 (3.0), 5.3 (2.3), 4.2 (2.2), 4.6 (2.0), and 3.3 (2.2) pouches, respectively, across all feedback locations [Fig. 7-(b)]. Post hoc tests revealed reduced work rates in the 6th and 8th intervals which were statistically significant compared to the 1st ($p = .007$ and $p = .002$, respectively) and 2nd ($p = .001$ and $p < .001$, respectively) intervals. Additionally, the working rate in the 5th interval was also reduced compared to the 2nd interval ($p = .001$). There was no statistically significant interaction between feedback location and time interval [$F(14, 191) = 1.15$, $p = .319$].

3.3.3. Rebar-tying task

Average (SD) numbers of crosses tied within 8 min were 32.4 (7.3), 33.0 (6.1), and 30.4 (7.6) in the no feedback, back, and wrist conditions, respectively. No statistically significant difference was observed between feedback locations [$F(2, 2) = 0.62$, $p = .538$]. Participants tied 4.3 (1.8), 4.5 (2.1), 5.1 (1.9), 4.5 (2.2), 4.2 (1.9), 3.7 (1.8), 3.5 (1.4), and 3.3 (1.5) crosses in each interval (1st–8th), respectively, across all feedback locations [Fig. 7-(c)]. They showed statistically slowed working pace between time intervals, [$F(7, 267) = 2.22$, $p = .033$]. Specifically, the working rate in the 3rd interval was significantly greater than in the 6th ($p < .001$), 7th ($p < .001$), and 8th ($p < .001$) intervals. The 4th interval also had a significantly greater work rate than the 8th ($p = .045$).

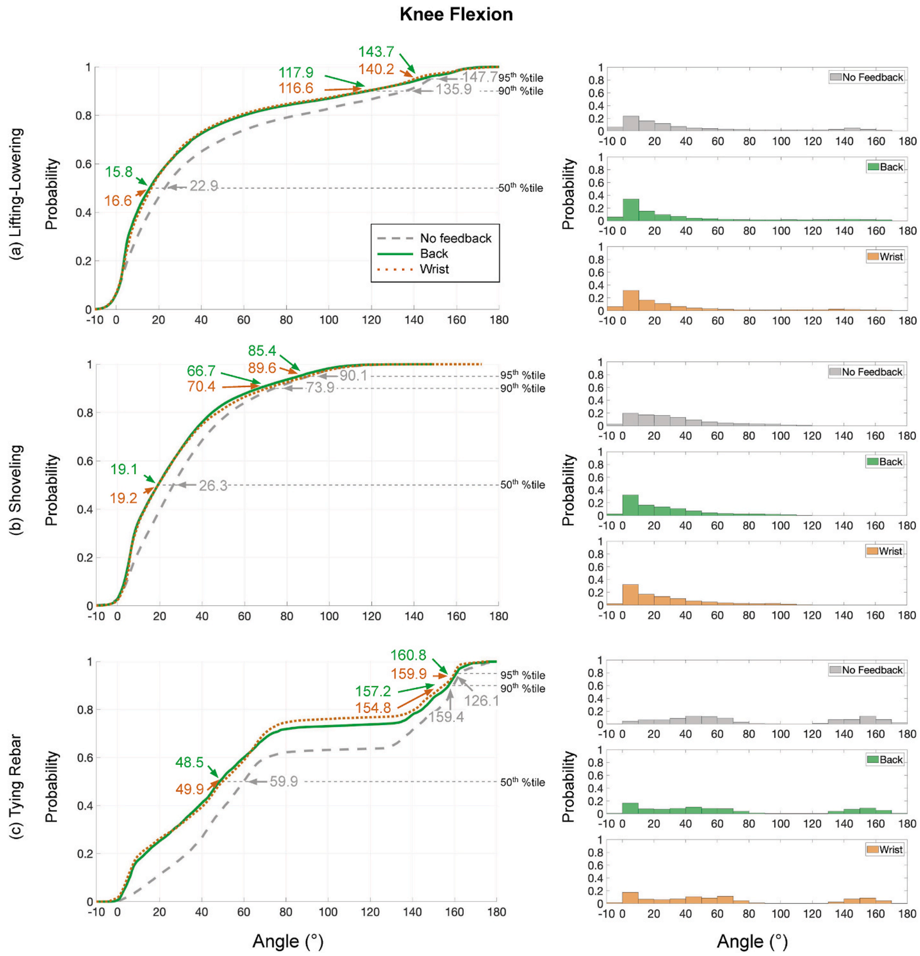

Fig. 6. Empirical cumulative density function plots (left) and histograms (right) from the measured knee flexion angles across all participants ($n = 14$ for lifting-lowering and rebar-tying tasks, and $n = 11$ for shoveling task) for each work task by feedback location.

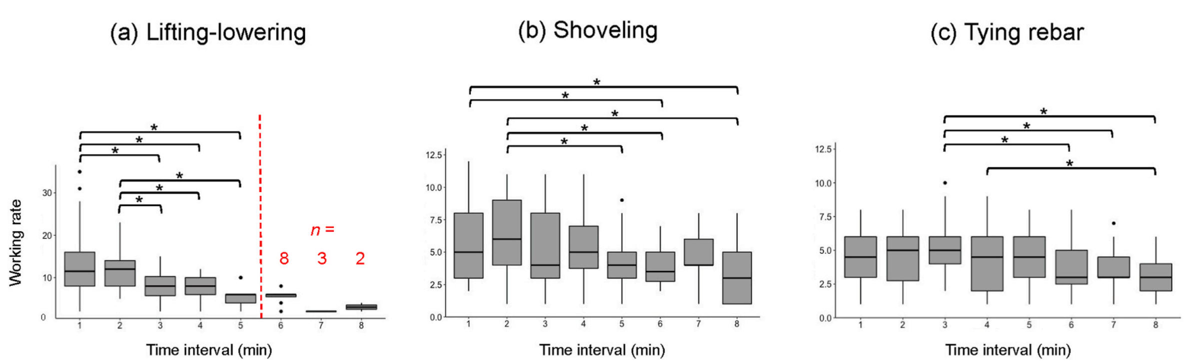

Fig. 7. Box plots of the average number of pouches (or crosses) handled per minute interval across all participants ($n = 14$ for lifting-lowering and tying rebar tasks, and $n = 11$ for shoveling task) for the three construction work tasks. Asterisks indicate significant differences ($p < .05$) following the Tukey HSD post hoc tests. For lifting-lowering, the 6th–8th time intervals were not included in statistical tests due to the small group sizes.

3.4. RPE, general experience, and usability of the vibrotactile feedback system

3.4.1. RPE

The mean (SD) RPEs were 9.29 (2.12), 11.91 (2.71), and 10.96 (2.40) for the lifting-lowering, shoveling, and rebar-tying tasks, respectively. No statistically significant difference in RPEs was found between feedback locations across all work tasks: lifting-lowering [$H(2) = 0.71$, $p = .703$], shoveling [$H(2) = 0.44$, $p = .804$], and tying rebar [$H(2) = 0.34$, $p = .842$].

3.4.2. General vibrotactile feedback experience

Participants reported that their general experience with the vibrotactile feedback system was positive. The short and long vibration patterns were “very easy” to distinguish, with median ratings of 1 and 1 for the back and wrist locations, respectively, on a 5-point scale (1 = “very easy”; 5 = “very difficult”). Associating different vibration patterns to the required actions was also “very easy,” with median ratings of 1 and 1 for the back and wrist locations, respectively. Short and long vibrations were both reported to be “not too distracting” on a 5-point scale (1 = “not distracting”; 5 = “very distracting”), with the median ratings of 2 and 2 for each back and wrist location, respectively.

3.4.3. Usability ratings and user feedback

Fig. 8 presents subjective preference ratings for the three feedback locations as a rank order (i.e., values represent median participant ratings). Two participant responses were discarded due to misinterpretation of the survey items. Overall, the plot for vibrotactile feedback provided on the wrist encompasses the largest area in Fig. 8, indicating that it received the most positive responses across all rating questions among different feedback locations. Specifically, the wrist was the top choice among all feedback locations for every category except usability. Statistically significant differences were detected by Kruskal-Wallis tests for effectiveness, $H(2) = 6.10$, $p = .047$; and willingness to use, $H(2) = 11.88$, $p = .003$. Meanwhile, preferences, $H(2) = 4.17$, $p = .124$; acceptability, $H(2) = 0.96$, $p = .618$; and usability, $H(2) = 5.14$, $p = .077$ did not differ significantly between locations. Post hoc tests revealed that feedback delivered to the back and wrist were significantly more effective than no feedback at all ($p = .047$ and $p = .023$, respectively). Regarding willingness to use, ratings were statistically lower in the no-feedback condition compared to both feedback locations; specifically, back ($p = .005$) and wrist ($p = .001$).

In an open-ended questionnaire asking about their overall experience about the system, some participants commented that the current system is slightly too sensitive to their posture: “The upper back sensor can be a little less sensitive.” In addition, participants mentioned that the feedback system is easy to follow and master: “It was easy to follow the instruction on the proper way of shoveling based on the feedback.”; “Once I find how the system works, it was easy to follow.”

4. Discussion

4.1. Trunk and knee postures

Overall, real-time postural training using vibrotactile feedback was effective in reducing trunk flexion angles at all percentile levels (95th, 90th, and 50th) regardless of the location of the feedback in both the lifting-lowering and shoveling tasks. The average reduction in truck flexion angle was 13.7–47.7% across percentile levels and feedback locations for lifting-lowering. Similarly, a significant reduction in trunk flexion angle (14.5–35.0%) was observed in the shoveling task. Contrary to our initial hypothesis that a reduction in trunk flexion angles would be accompanied by increased knee flexion (e.g., use of squat posture more than stoop posture), a significant reduction in knee flexion was observed for both lifting-lowering and shoveling (25.0–34.3% reduction from no feedback condition) at the 50th percentile.

In a similar study performed with a manual sorting task, real-time vibrotactile feedback reduced time in trunk flexion (>30°, >45°, and

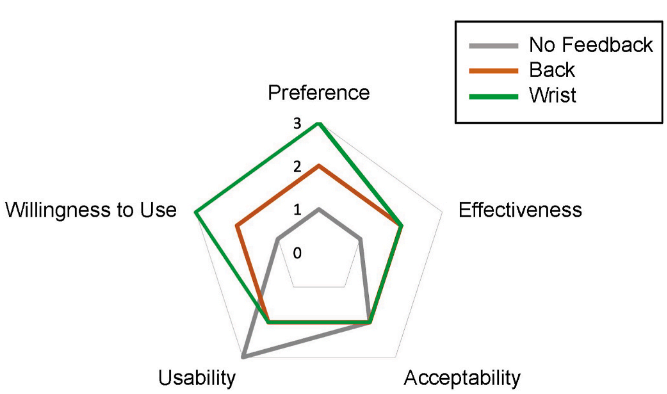

Fig. 8. A graphical representation of subjective ratings by feedback location (no feedback, back, and wrist) depicted as ordered ranks (1 = least preferred, 3 = most preferred). Values represent median participant ratings ($n = 12$).

>60°) as well as flexion angles in the 90th, 95th, and 99th percentiles when delivering feedback and immediately after its withdrawal (Lind et al., 2023). The declines in trunk flexion were 34% and 36% for the 90th and 99th percentile angles (Lind et al., 2023) and 31% and 37%, respectively, in a study with an order-picking task performed by the same research group (Lind et al., 2020b). In patient-handling tasks among home caregivers, use of real-time vibrotactile posture training reduced 80th and 95th percentile trunk flexion angles after two days (15.3–17.2% reduction), two weeks (21.4–22.5% reduction), and two months (12.7–14.1% reduction) of the intervention (Kamachi et al., 2021). The present study follows the overall trend in the existing literature by showing similar reductions in trunk flexion angles with a real-time feedback system in selected construction tasks (i.e., lifting-lowering and shoveling).

The ineffectiveness of the feedback system in the rebar-tying task is noteworthy, as it demonstrates that work tasks requiring different types of postural exposures cannot be effectively corrected with this simplistic type of realtime postural intervention, which is common in current commercial intervention systems. Tying rebar is a task that involves excessive nonneutral postures for prolonged periods (e.g., tasks involving one-legged or two-legged kneeling, squatting or stooping while using hand tools) (Umer et al., 2017). This is slightly different from lifting-lowering and shoveling, where the exposure to a nonneutral posture is less prolonged and the task is more dynamic compared to rebar tying. Specifically, tying rebar with a non-powered plier requires workers to pull, wrap, twist, and cut the wire while in a drastically bent posture (Albers and Hudock, 2007). In this type of task, postural training alone often cannot provide an effective solution to reduce workers' trunk flexion exposure. In Fig. 3-(c), right-side trunk flexion trajectory with the feedback system showed that a participant received a short vibration feedback after almost every cross; consequently, this participant was required to take a 30-s forced break after tying about 3–4 crosses. After the feedback events, the participant's trunk flexion exposure pattern did not change much from a visual inspection of the trajectory [Fig. 3-(c)], indicating the feedback was not helpful in changing the postural behavior. Also, such frequent vibration alerts (e.g., triggered after every cross) can negatively affect workers' productivity by generating alarm fatigue (Cvach, 2012), which could deteriorate work performance (Deb and Claudio, 2015). Furthermore, such frequent feedback can demotivate workers to use intervention systems, as they become more bothersome than helpful and effective.

This suggests potential implications in developing effective feedback designs, which should be either adaptive or task-specific to be more effective for the target work activity, rather than providing feedback following a universal trigger and criteria. In addition, we observed large personal differences in work postures during the rebar-tying task, which triggered more frequent feedback events for participants who preferred a stooping posture over a squatting posture. For some participants, sitting in a squat position while balancing and maneuvering a hand tool for a prolonged duration might not be feasible. For such participants, delivering frequent vibration feedback just because they preferred a stooping posture during the task could only server to frustrate them without much positive educational effect for postural changes. Construction work involves diverse types of tasks, and the types of tasks performed change over time according to the phase of the construction project. Thus, the design of the feedback, such as the trigger design (e.g., threshold trunk flexion angle and time duration) and frequency, needs to be adaptive according to workers' work tasks and postural exposure levels over time. Most current commercial feedback systems and laboratory-based prototypes use uniform feedback designs based on simple criteria (e.g., cumulative or instant trunk posture) regardless of the type of work tasks performed in each industry or by each worker. Some commercial systems allow users to adjust the trigger threshold value (e.g., trunk flexion level) according to their industry's (or company's) standards, but these fixed values are not adaptive to workers or work tasks.

In such situations, a technological intervention that aids in either reducing nonneutral postures or time spent in such postures can be more effective than simply alerting workers to use safe work postures. For rebar tying, either providing tools (e.g., powered tying tool, rebar stapler, stand-up rebar tying tool, extension arm) or using a prefabricated rebar mesh could result in substantial postural changes that cannot be achieved by simply educating workers for postural intervention. Also, prior studies recommend practicing regular variation in working postures when tying rebar to avoid maintaining a particular posture for a prolonged duration (Umer et al., 2017), given that all alternative postures (e.g., stooping, squatting, or kneeling postures) for rebar-tying tasks exceed the ISO 11226:2000 standard (60°) (Umer et al., 2017). Since wearable feedback systems often provide both assessment and intervention, comparing the effectiveness of feedback in different work task scenarios can illuminate the practical implications of whether more higher-level control is needed as an intervention.

4.2. Productivity and RPE

No significant loss of productivity with the feedback system was observed except for in shoveling, in which the average shovel transfers fell by 4.5% (1.7 shovel transfers), compared to the no-feedback condition. Shoveling triggered the greatest number of short and long vibrations regardless of the feedback location compared to other tasks; consequently, participants took many mandatory 30-s breaks, which slowed down the rate of work (i.e., the number of shovel transfers per minute). Except for in shoveling, the results did not reveal a significant loss of productivity with the feedback system, even though the long vibration forced participants to take a 30-s break before resuming the task. As time progressed, working rates significantly dropped with all of the tasks, and this reduction did not appear to be affected by the presence or absence of feedback, so there is no indication as to whether the feedback system decreased workers' productivity. Demonstrating positive changes in biomechanical exposure (e.g., reduction in trunk flexion angle) with the use of the feedback system with little to no productivity loss may be valuable information for industry stakeholders in deciding whether to adopt such preventive systems considering potential economical losses due to decreased productivity.

4.3. Usability

Although different feedback locations (back and wrist) did not produce significant differences in postural exposures, productivity, and RPE scores, participants rated the wrist as the most preferred location across all categories, followed by the back, while the targeted intervention location was the back. Localizing vibrotactile feedback to the target location needing intervention is known to be beneficial and effective in the context of motor learning (Bark et al., 2014; Martinez et al., 2011). Our study showed that feedback can be effectively delivered and recognized by workers even when vibrotactile feedback is provided away from the target location (here, the back), confirming that a convenient location (such as the wrist) can be used for such interventions to improve wearability and avoid potential sensor positioning errors due to self-positioning of the sensor on the back. In Esfahani and Nussbaum (2018)'s study, participants most strongly preferred the ankle and wrist as IMU sensor placement sites for activity monitoring involving sitting, walking, and carrying (Esfahani and Nussbaum, 2018). For vibrotactile feedback, the most frequent body sites selected for actuator attachment were the hand and the fingertips, followed by the wrist for motor learning applications (Islam and Lim, 2022). The back and chest are less preferred (Esfahani and Nussbaum, 2018), yet most commercial systems use such locations for sensor attachment, mainly to collect trunk kinematics and deliver vibrotactile feedback to the same location. Some commercial sensors use both back and wrist locations for postural assessment and feedback delivery, respectively (e.g., GoX Boost, Gox Labs, Phoenix, Arizona, USA). In that commercial system, visual, auditory, and vibrotactile feedback are provided using a smart watch worn around the wrist to provide a more detailed guidance. In this study, we did not provide any sensory feedback other than vibrotactile feedback, so investigating whether providing such additional sensory information is helpful along with vibration is not feasible. However, considering the aforementioned visual and auditory clutter in construction sites, investigating which type of sensory feedback is the best to use in conveying particular types of information to workers, and also whether using unimodal or multimodal sensory feedback would be helpful for postural interventions, would be worth investigating in future studies. Also, a few participants (2 out of 14) commented that the system was too sensitive to their movements, mirroring observations from Lind et al. (2023). To resolve this issue, the feedback design can be revised to provide either alerts based on cumulative exposure (such as providing the "long" vibrations in this study and omitting the "short" vibrations between them), limiting the frequency of the alerts, or replacing real-time alerts with terminal feedback.

4.4. Methodological considerations and limitations

This study used short work bouts of up to 8 min; thus, effects found in our short-term study might not be maintained after longer periods or after the feedback system is no longer in use. Also, real-time feedback was provided as a type of communication to alert participants that their trunk flexion exceeded a predetermined threshold (45°; participants were instructed about this in advance). This type of communication may not be necessary or advisable for longer time periods, once workers understand when and how they trigger such thresholds during work tasks. There are still limited studies performed in investigating the long-term effects of such real-time, concurrent vibrotactile feedback in working postures across different occupational work tasks. Thus, more thorough investigation is needed to understand the optimal frequency of the feedback and the total learning duration necessary for effective learning and retention. Although this study was limited by the short task duration, to the best of the authors' knowledge, this is the first study investigating the effectiveness of real-time vibrotactile feedback in various construction work tasks. Thus, the outcome of this study will serve as valuable input toward designing real-time postural intervention systems in the construction industry by providing design considerations that can potentially enhance work postures among construction workers.

We did not observe any adverse effects of providing immediate, concurrent feedback in worker perception and posture during our study. However, providing vibrotactile feedback while workers are in an extreme forward bend might unintentionally affect their safety (if workers abruptly change their posture to stop the vibration). In construction, where work sites often have uneven or sloped surfaces, such sudden movements or postural corrections could potentially affect workers' balance, resulting in falls and slips. Also, providing different vibration patterns as investigated in this study could be good options to deliver different messages to workers according to their exposure levels, but such patterns must be readily understood, such that workers can perceive and distinguish patterns without too much cognitive work. In this study, participants rated distinguishing "short" and "long" vibrations and following the required actions as very easy, but this perception might be affected in field settings if other sources of vibration are present (e.g., machinery and hand tools). Thus, providing simple and intuitive feedback is essential for the effectiveness of the feedback in field settings. Overall, further studies are needed to understand the long-term effects of such feedback beyond short-term use in longitudinal, real-world field settings.

As our feedback system was tested in a controlled lab environment, any conclusions regarding its effectiveness and usability in various construction environments such as different weather conditions are beyond the scope of the study. Interference with clothes and protective gears can also be a concern, as it may affect the accuracy of the sensor readings and the ability of the user to receive and interpret feedback.

Lastly, our study had a small sample size ($n = 14$) and involved only novice young male participants with no history of back injury or pain lasting for more than a week to avoid confounding factors that could have affected the learning of the feedback system and construction work performance. This could limit the ecological validity of the study results, so future studies would be needed to investigate the feedback system in field settings, (i.e., in a real work setting rather than a simulation) with workers of varying ages, genders, and work experience levels.

5. Conclusions

This paper investigated the effects of using wearable, sensor-based, real-time vibrotactile feedback during manual construction work tasks. Vibrotactile feedback was effective in reducing trunk flexion exposure at the 95th, 90th, and 50th percentile levels, and also in reducing knee flexion at the 50th, for both the lifting-lowering and shoveling tasks. The feedback did not appear to produce postural changes in the rebar-tying task. The two feedback locations (i.e., the back and wrist) did not significantly differ in terms of reducing postural exposures in this study. Participants' productivity was maintained with the vibrotactile feedback and the forced 30-s breaks in both the lifting-lowering and rebar-tying tasks, while the working rate was reduced with the shoveling task compared to the no-feedback condition. Participants' perceived exertion levels measured with RPE showed no statistical difference across all feedback locations and tasks. Lastly, participants rated feedback delivered to both the back and the wrist as more effective, and indicated they were more willing to use it, compared to the no-feedback condition. The overall experience of using the feedback system was also positive, as participants rated the feedback as easy to understand and not too distracting. The results of this study revealed that real-time vibrotactile feedback is a viable solution to immediately change workers' posture in selected work tasks (i.e., lifting-lowering and shoveling), while caution should be taken to develop effective feedback designs for different types of work tasks, as the feedback events in this study were not effective in the rebar-tying task, which involves extreme trunk and knee flexion postural angles for prolonged durations. Future works will expand on the current study by investigating the long-term effects of postural intervention systems in motor learning, behavioral changes, skill transfer, and retention in occupational settings involving manual material handling.

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.

Acknowledgment

This work was supported by the National Institute for Occupational Safety and Health (NIOSH) at the Centers for Disease Control and Prevention (CDC) under the training grant T42OH009229 from the Mountain and Plains (MAP) Education and Research Center. Its contents are solely the responsibility of the authors and do not necessarily represent the official views of the CDC NIOSH and MAP Education and Research Center.

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