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Biomechanical assessment while using production tables on mast climbing work platforms

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ABSTRACT

The objective of this study was to assess the impact of using alternative mast climbing work platform (MCWP) designs on trunk motion and postural stability with masonry workers while performing bricklaying and stepping down tasks using a conventional MCWP setting (i.e. with a step deck) as well as two types of production tables (straight- and L-shaped). The trunk angles and postural sway parameters of twenty-five masonry workers were recorded for the following tasks: (1) standing on a simulated MCWP and laying bricks on an adjacent wall, and (2) stepping down onto the step deck to get into position for doing the bricklaying task. Results indicated that the use of the L-shaped production table resulted in the lowest trunk ranges of motion and significantly reduced the workers' trunk angles in all three planes when compared to both the straight-shaped production table and the conventional approach of not using a production table. Data showed that both body sway velocity and area were significantly reduced when using either one of the production tables. The use of production tables significantly reduced impact sway forces when workers stepped from the main platform to the step deck. The use of production tables on MCWPs improved workers' postures and overall stability, which could reduce the risk of injury.

1. Introduction

Mast climbing work platforms (MCWPs), or mast climbers, are elevating equipment, that have been available in the United States since the 1980s. Due to their advantages, MCWPs have become more common throughout the 1990s and 2000s, and their popularity has continued to increase. An essential factor in all MCWPs designs is a powered drive unit that moves the work platform up and down a vertical mast structure. MCWPs are capable of handling much greater loads (including workers and materials) than traditional scaffolding. They also make reaching greater heights much easier, thereby improving efficiency on construction projects. MCWPs can be configured in many ways, from freestanding models that can be used on shorter working heights to anchored models that can reach heights of over 1000 feet. MCWPs are used as an alternative to traditional pole, tubular and coupler scaffolds. Their use frequently avoids idle time for specialty contractors (e.g., masons and labors) and setup crews thus increasing productivity.

Even though MCWPs have been available since the 1980s, there are limited studies in the occupational safety literature concerning their impact on worker safety and health. Published or peer-reviewed materials elucidating the occupational-hazard component of continued use of MCWPs are difficult to find. Hazards associated with MCWPs are apparent based on the reported incidence of injuries occurring with their use. Concerns of potential hazards have also been raised by users, standards committees, renters and manufacturers (American National Standards Institute, 2011; O'Shea, 2014; Wimer et al., 2017). The basis for this project (O'Shea, 2014) are the hazards currently recognized from input by industrial manufacturers and observations by renters and users of MCWPs.

The rate of adopting MCWPs for use on construction sites is high and increasing, especially among masons and other specialty contractors (Susi et al., 2010). Construction job bidders and planners frequently specify mast climbers in contract proposals. This is due to several reasons: 1) there are productivity and efficiency advantages to using MCWPs; 2) time-to-completion of construction projects is frequently a function of the availability of mechanized elevating equipment (Pan et al., 2012a); 3) equipment technology, like the MCWP. frequently shorten the period of construction; and 4) their use allows for rapid, purposeful scheduling of job activities. However, little research has been conducted on the ergonomics and safety of MCWPs.

Of the 22,000 MCWPs in use in the United States, roughly 70% are used daily (O'Shea, 2014). Potentially as many as 50,000 U.S. workers

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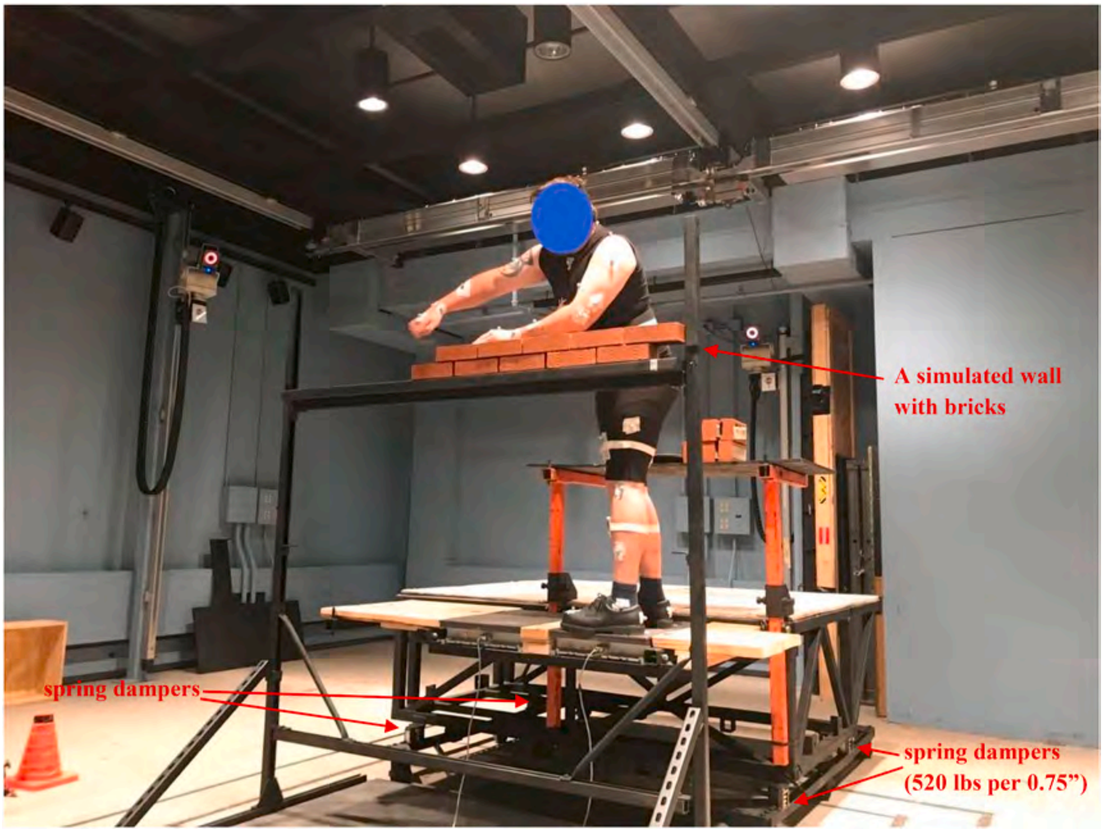

Fig. 1. A mason performing the simulated bricklaying task on the workstation equipped with the manufacturer straight-shaped production table and simulated wall.

can be using MCWPs on a given day considering that three to four construction workers are on the equipment at any given time, plus the workers that set up, move, assemble and dismantle the MCWPs, plus an equal or greater number of specialty contractors, e.g. painters, masons, siding installers, etc., that make use of this type of equipment. One of the main advantages of mast climbers is the ability to assemble/dismantle the equipment easily, allowing it to be moved and used at different areas of a construction site. A personal communication from O'Shea, (2014) has estimated that each mast climber could be dismantled and assembled up to four or five times per year. Each move requires two trained erectors and can take more than 30 h to complete, thus creating 5.3 to 6.6 million-man hours in the moving process each year. It is often during the assembly/dismantling of equipment that incidents have occurred.

A recent study of the construction industry showed that from 2011 to 2015 there was a total of 1533 fatalities caused by fall to a lower level (CPWR, 2018). Close to 15% of those fatalities were related to scaffolds/staging. In the year 2015 alone, there were 12,100 nonfatal slips, trips, and falls (STFs) on the same level related to scaffolding that resulted in days away from work (CPWR, 2018). MCWPs are currently categorized as scaffolds (CPWR, 2018; Earnest and Branche, 2016; Pan et al., 2012a). Unfortunately, they are not considered separately in available surveillance data. Between 2011 and 2016, the number of fatalities where scaffold/staging was the primary cause remained high totaling 408 fatalities in these 6 years (BLS, 2018). Up to 2010, at least 12 documented MCWP incidents resulted in 18 deaths (Susi et al., 2010). Fall-related injuries have been responsible for fatalities in each of these cases.

From 1990 to 2017, there were a total of 35 recorded fatalities associated with the use of mast climbers. Most of these fatalities were linked to dismantling the equipment. Of the 35 fatalities, 13 were masonry workers, 9 were plasterers, and 13 were from other construction trades (Blackledge, 2015; OSHA, 2015; Pan et al., 2018). In 2015, OSHA reported on a fatal, 100-foot fall incident involving a masonry worker who stepped down 2 feet from the MCWP work platform to the step deck that was not equipped with OSHA approved safety planks (Blackledge, 2015; OSHA, 2015; Pan et al., 2018).

In relation to musculoskeletal and gait-related injuries, walking and working on a MCWP could expose workers to balance and stability challenges due to the unstable nature of the MCWP at heights compared with a rigid ground surface (Wimer et al., 2017). Previous studies have shown that participants demonstrated reduced standing stability when performing manual material handling tasks standing on uneven ground surfaces, especially wobbling work surfaces, (Lin and Nussbaum, 2012). They also had altered trunk biomechanical responses and elevated risks of injury (Hu et al., 2013, 2016; Ning and Mirka, 2010; Zhou et al., 2013, 2015).

Working on a MCWP can also create awkward working postures due to the confined workspace and work surface. Prolonged and/or repeated use of these awkward postures could introduce muscle strain and fatigue, which may lead to further injuries (Hu et al., 2016; Hu and Ning, 2015a, 2015b; Marras et al., 1993) and reduced productivity (Lotters et al., 2005). Incorporating MCWP work surface design improvements (e.g., a level working deck) to reduce STFs and enhance fall prevention is critical to avoid tripping hazards (Pan et al., 2012a).

Masonry workers also experience frequent back injuries associated with various manual material handling tasks when working at heights. The prevalence for back disorders is 45–50% higher than that of other body parts (CPWR, 2018). Presently, it is common practice for masons to store their bricks and other materials directly on the MCWP's working platform while they work from the step deck next to the relevant workspace (Pan et al., 2018).

Based on the above observations, the objective of this study was to assess the impact of using alternative workplace MCWP designs on trunk posture and standing stability with masonry workers. The study considered a traditional MCWP configuration incorporating a step deck as well as an MCWP configured with one of two different designs of a

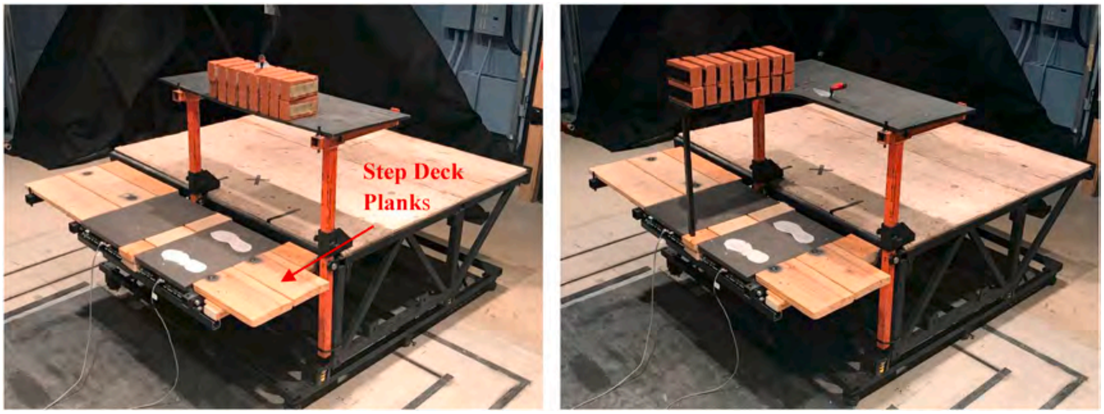

Fig. 2. Simulated workstation equipped with two production table designs and the Bertec force plates, with feet position markers, configured for the beginning of the bricklaying task.

Fig. 3. One of the four extreme mount spring-dampers exhibiting a stiffness of 520 pounds (236 kg) per 0.75 inches (1.9 cm) of compression.

production table. The null hypothesis of this study was that use of production tables on the MCWPs would not reduce the potential for back injury and whole-body postural instabilities.

2. Methods

2.1. Participants

A total of 25 male construction workers (Age: 33.4 ± 10.1 years; Height: 181.8 ± 6.1 cm; Weight: 87 ± 19.2 kg), with at least 6 months of

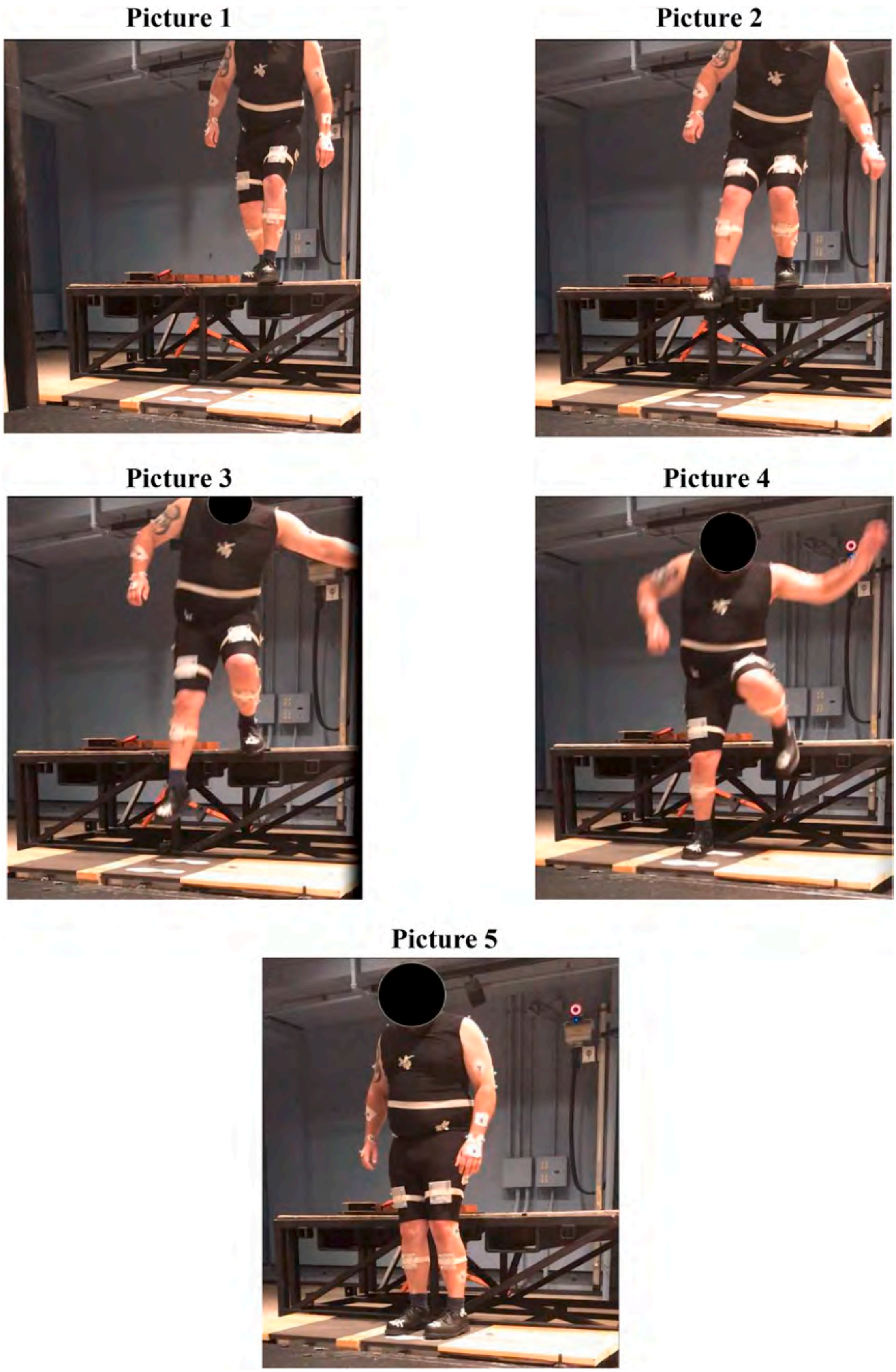

Fig. 4. A mason performing the simulated stepping down task (Pictures 1 to 5) from a MCWP onto the step deck to get into position for doing the bricklaying task.

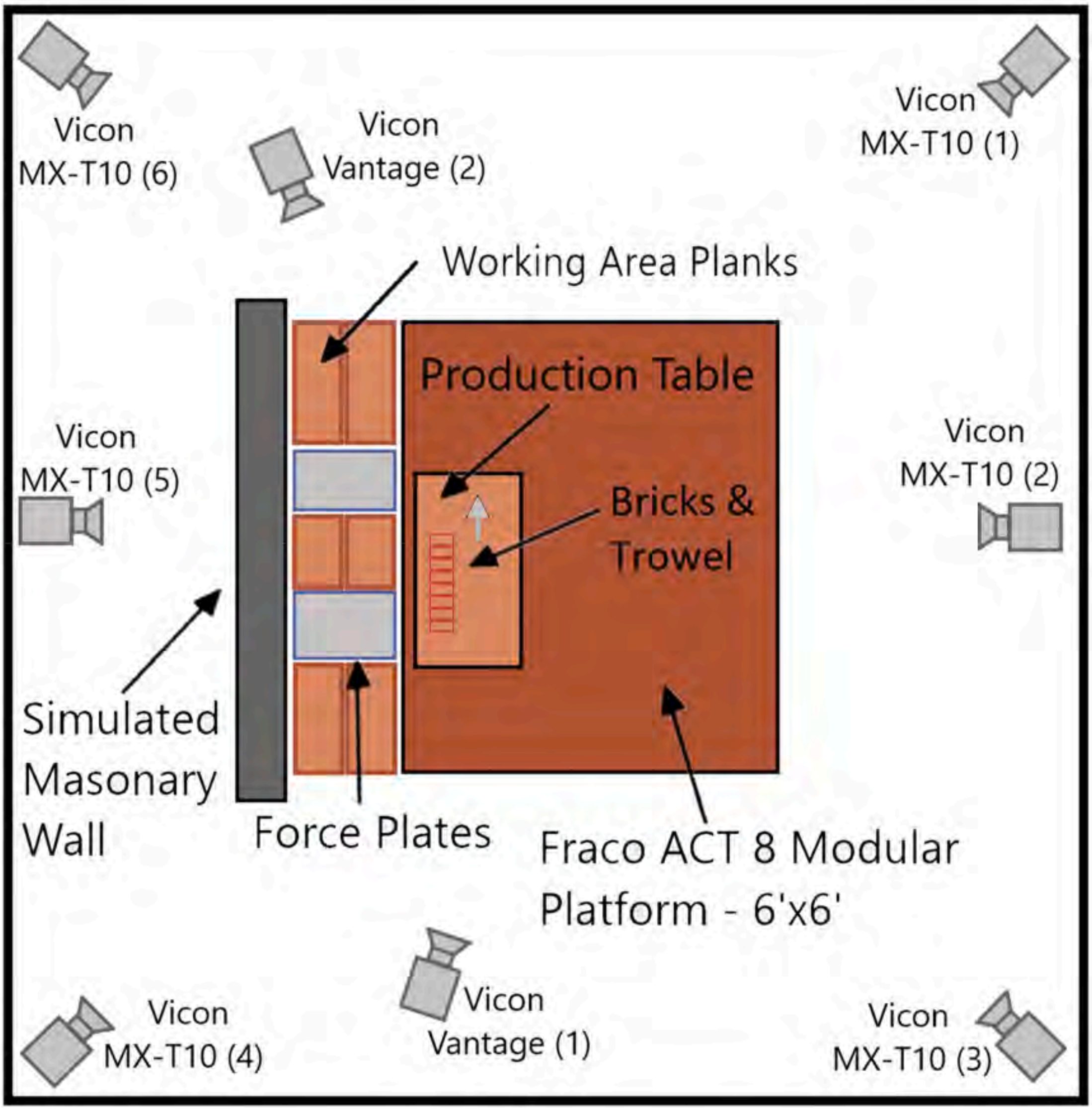

Fig. 5. A layout of the experimental setup (showing a straight-shaped production table) including the location of Vicon cameras, Vantage cameras, the Bertec force plates, and top view of the production table.

masonry work and bricklaying task experience participated in this study. All participants completed a health-history screening before participating in the study to ensure they had no history of dizziness, tremors, vestibular disorders, neurological disorders, diabetes, chronic back pain, and falls within the past year resulting in injury with days away from work. Each participant gave informed consent according to the procedures approved by the National Institute for Occupational Safety and Health (NIOSH) Institutional Review Board (IRB).

2.2. Simulated workstation

An instrumented workstation simulation of a typical MCWP arrangement for bricklaying masons was constructed in the NIOSH laboratory (Fig. 1). The simulated workstation represents a mechanical-equivalent system of a typical MCWP and reproduces the dynamic characteristics experienced by workers on the MCWP. A specially designed and adjustable suspension system and support structure made the dynamic responses of the simulated platform equivalent to that of an elevated MCWP, although the simulated workstation for the study was on the ground for safety reasons. A simulated "wall" was constructed in front of the participants and used for the bricklaying activity.

A straight and L-shaped production table was evaluated in this study (Fig. 2). The difference between the two production tables is that the NOISH "L" shaped table added a perpendicular section to the manufacturer's straight-shaped table. This feature allowed bricks, building materials and tools to be placed on the right side of the masonry worker when facing the bricklaying wall (Figs. 1 and 2).

Four spring-damper systems were used to support the simulated MCWP workstation so as to mimic the flexible platform surface and unstable work conditions that exist on an actual elevated MCWP (Figs. 1 and 3). These adjustable dampers allowed for the structural stability of the platform to be adjusted according to measured values found on typical MCWP configurations. The structural stability conditions used in this study were determined using the following method:

(1) A person walking/moving on the platform served as the load/weight. The loading point on the platform was measured at a distance from the center of the MCWP structure and was taken at the middle of the platform section at the platform surface height.
(2) The platform displacement of a freestanding, elevated MCWP platform was measured at one of the NIOSH testing field sites (Pittsburgh, PA). As an initial measurement experiment and for safety reasons, the MCWP elevation was held to a height of 1-foot (0.3-m) from the bottom of the ground base bump stops (lowest

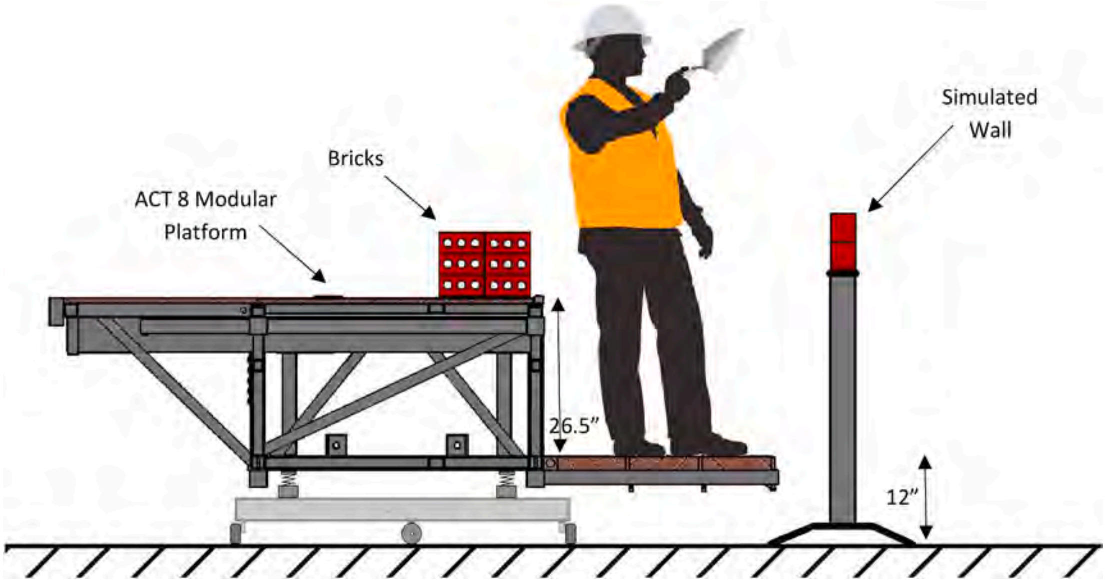

Fig. 6. MCWP in the conventional work configuration with the adjustable spring-dampers.

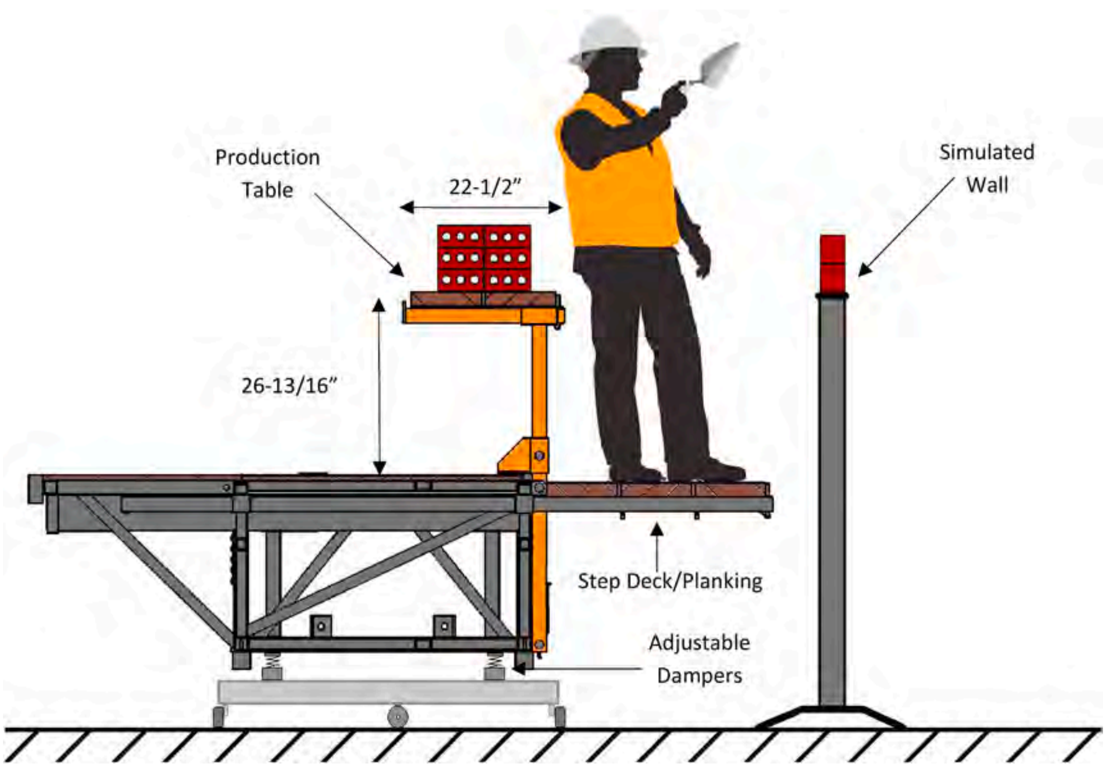

Fig. 7. MCWP in the production table work configuration with the adjustable spring-dampers.

Table 1
Repeated measures analysis of variance results for trunk range of motion – p-values.

Experimental Condition	Spine			Pelvis		
	Frontal	Transverse	Sagittal	Frontal	Transverse	Sagittal
Production Table (Straight-Shaped Table vs. L-Shaped Table vs. Conventional No Table)	**<.0001**[a]	**<.0001**[a]	**<.0001**[a]	**<.0001**[a]	**<.0001**[a]	**<.0001**[a]
Structural Stability (Maximum vs. Minimum)	0.44	0.37	0.66	0.62	0.43	0.59
Production Table * Structural Stability	0.75	0.70	0.17	0.66	0.21	0.43

[a] Indicates statistically significant effects.

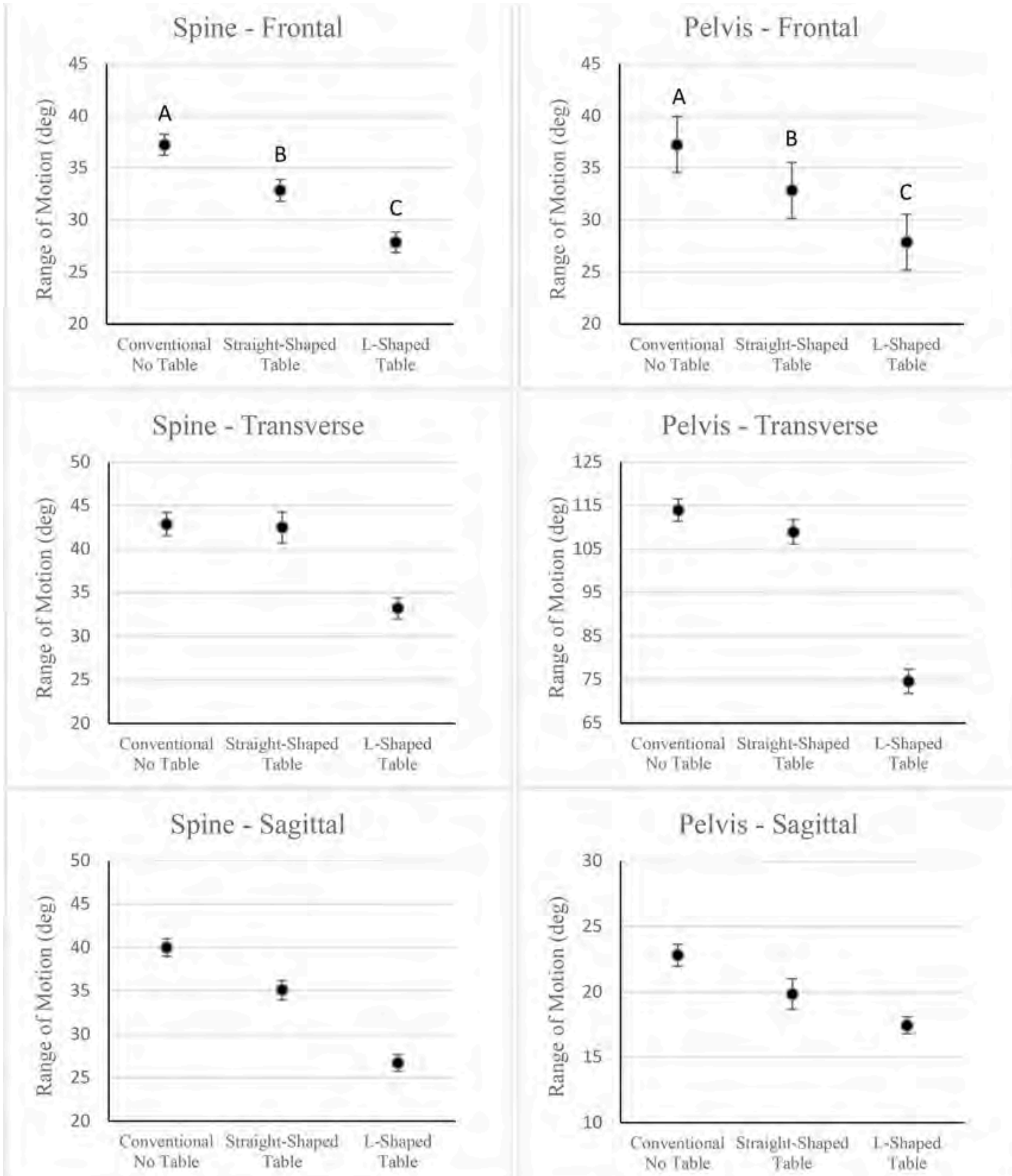

Fig. 8. Use of L-shaped table decreased ROM significantly when compared to Conventional No Table (all three planes of spine and pelvis) and straight-shaped production table (all except sagittal plane of pelvis). Use of both production tables also reduced ROM significantly for frontal and sagittal planes of spine and pelvis when compared to Conventional No Table. Note that different letters denote significantly different least square means. Vertical bars in each graph represent standard errors.

position). Vertical displacements were measured at select horizontal distances from the center of the MCWP structure and were recorded, respectively: (a) a vertical displacement of 0 inches (0 cm) at a horizontal distance of 5 feet (1.5 m); (b) a vertical displacement of 0.5 inches (1.3 cm) at a horizontal distance of 15 feet (4.5 m); and (c) a vertical displacement of 0.75–1 inches (1.9–2.5 cm) at a horizontal distance of 30 feet (9.1 m). We selected four off-the-shelf extreme mount spring-damper systems, each with a maximum capacity of approximately 650 pounds or 295 kg, that had a stiffness of 520 pounds (236 kg) per 0.75 inch of displacement.

These test conditions mimicked the platform displacement that workers might experience while working on a MCWP. The dampers were built into the four bottom corners of the simulated workstation platform section to support its entire weight (Figs. 1 and 3). At the lowest setting, the platform had minimal vertical displacement during the bricklaying task. With the spring-damper systems set at the highest setting, the platform had a vertical displacement of approximately 0.75–1 inch of movement during the bricklaying task.

Subjects were also asked to perform a “stepping-down” task. The stepping-down task simulates a worker stepping down from the work platform of the MCWP onto the step deck to get into position for doing the bricklaying task (Fig. 4). Test subjects were asked to step onto foot-shaped icons (see Fig. 2) placed on the force plate (Fig. 4). This task was done without the presence of a production table. The walking-forward task was done with both production table configurations. It was to simulate the worker walking forward to begin the work task. Again, test

Table 2
Repeated measures analyses of variance results of sway data – p-values.

Experimental Condition	V	V AP	V ML	Area CC[a]	Area CE[a]
Production Table Use (Yes, No)	**<.0001**[b]	**<.0001**[b]	**<.0001**[b]	**<.0001**[b]	**<.0001**[b]
Structural Stability (Maximum vs. Minimum)	0.58	0.07	0.92	0.99	0.77
Production Table Use * Structural Stability	0.78	0.44	0.83	0.85	0.74

[a] Area CC: area of the 95% confidence circle; Area CE: area of the 95% confidence ellipse.
[b] Indicates statistically significant effects.

subjects completed the task by placing their feet on the icons on the force plate (Fig. 2). A 5-min rest period was given between trials to reduce the effects of fatigue on standing stability and postural sway.

2.3. Biomechanical apparatus

Biomechanical data were collected via a motion capture system (Vicon Nexus, Denver, Colorado) synched with two force platforms (Bertec 4060–08, Columbus, Ohio). The motion system used six motion capture system cameras (MX-T10) mounted on the walls of the laboratory to determine joint kinematics. Images from the cameras were combined to capture the three-dimensional position of the reflective markers worn by the test subjects. Two Bertec force plates were used to determine impact forces and postural sway in each of the experimental conditions (Fig. 5). Two additional high-speed Vantage motion capture cameras mounted on tripods were synchronized with the other six MX-T10 motion capture system cameras to allow for post-test review of the tasks. The study team followed the standard calibration procedures for the Bertec instruments. A comparison of the force data collected on the simulated workstation and at ground level found no significant differences. The sampling frequencies for the Vicon cameras and Bertec force plate were 100 Hz and 1000 Hz, respectively. Data were filtered using Woltring (digital) and Butterworth (analog) filters. Full body modeling was done with the Vicon Motion Systems Plug-in Gait model for the upper body to calculate kinematics information.

2.4. Experimental design

This experiment used a within-subject, repeated measures design to evaluate the effect of MCWPs production table condition, structural stability, and their interactions on trunk motion and postural stability. Two independent variables, MCWPs production table condition and structural stability were included in the experiment.

There were three conditions of simulated MCWPs: (i) a conventional MCWP configured with a step deck about 26 inches below the work platform without a production table; (ii) a MCWP configured with the step deck level with the work platform that used a straight-shaped production table designed by a MCWP manufacturer (Figs. 2 and 7); and (iii) a MCWP configured with the step deck level with the work platform that used an L-shaped production table designed by NIOSH (Figs. 2 and 7). Structural stability refers to maximal or minimal platform surface flexibility. Structural stability has been defined as the ratio of the vertical displacement of the main platform surface in relation to a vertical load positioned at a point on the platform (Dong et al., 2012).

There were three groups of dependent variables: (i) trunk range of motion; (ii) whole-body sway and; (iii) ground impact forces. For this study, trunk of the body is defined to include both the spine and pelvic region (BLS, 2020).

Three variables were selected to evaluate potential back injury based on each participant's trunk range of motion (ROM) in frontal, transverse, and sagittal planes including both spine and pelvis. The complexity of postural sway and stability of a human body cannot simply be represented by just one variable. Eight variables were used to evaluate postural sway and propensity of instability based on the participant's center of pressure (COP) data measured on a force plate during the experiment. The eight variables related to posture sway were: mean speed (Speed, V); anterior-posterior speed (V AP); medial-lateral speed (V ML); confidence circle area (CC Area); confidence ellipse area (CE Area) (Zolghadr et al., 2018); frontal plane force (Fx); sagittal plane force (Fy); and transverse plane force (Fz) (Zolghadr et al., 2018).

2.5. Experimental procedures

Subjects came to the laboratory for one day of testing. Upon arrival, subjects were required to review experimental procedures and provide informed consent, which were both approved by the NIOSH IRB. Subjects first completed a health-history screening, followed by collection of basic anthropometric data including body mass, height, leg length, anterior superior iliac spine (ASIS) trochanter distance, knee width, ankle width, elbow width, hand thickness, and shoulder offset. Next, subjects completed a five-minute warm-up session that included arm stretching, squatting and back bending/stretching to reduce the risk of injury during the experiments. Subjects were then instructed and familiarized with the experimental apparatus and bricklaying task by a NIOSH researcher. Each test subject was outfitted with a set of motion capture markers for doing Full Body Plug-in Gait Modeling. Their joint kinematics were determined by using the Vicon Nexus motion capture system to compare postures (Figs. 1 and 5).

Subjects wore tightly fitted clothing and safety shoes, provided by NIOSH, while performing the simulated bricklaying work task on each simulated configuration of the MCWP. The bricklaying task required subjects to grasp, with their left hand, one brick, from a stack of bricks, which were located behind their back either on the production tables or with the conventional condition on the platform deck of the MCWP (Fig. 2). The trowel was in the right hand of each subject, getting mud to butter the brick (Figs. 6 and 7). Simulated motions were used to mimic application of mortar to the bricks. They then placed five bricks in a row followed by an additional 3 rows of 5 bricks on top of the first row using Velcro tape on the top and bottom of each brick to hold it in place (Fig. 1). Each trial consisted of subjects laying 20 bricks with a self-selected work pace.

As described in section 2.4, there was a total of 3 simulated MCWP configurations (or conditions). The condition was a conventional setup incorporating a "step-down" section located below the work platform of the MCWP. The step-down section was connected to outriggers under the main MCWP work platform (Fig. 6). Participants stood on the "step-down" section of the work platform while performing bricklaying. The other 2 conditions involved the worker standing level with the MCWP work platform and using either a straight-shaped or L-shaped production table intervention device designed to improve worker posture/ergonomics and efficiency (Fig. 7).

Using the production table configurations (Figs. 2 and 7) enabled masons to perform work tasks while standing on the step deck positioned level with the work platform of the MCWP. This MCWP configuration minimized tripping hazards compared to the MCWP "step-deck" configuration shown in Fig. 6.

2.6. Data processing

Signals from the force plates and reflective markers were recorded simultaneously using the Vicon Nexus version 2.6 software. Trunk ranges of motion were defined as the maximal amount of angular movement in the sagittal, frontal and transverse planes during the work task activity. Peak ground reaction forces were obtained in X, Y and Z coordinates respectively in the medial-lateral (ML), anterior-posterior (AP) and vertical (Z) directions. The reaction forces were normalized

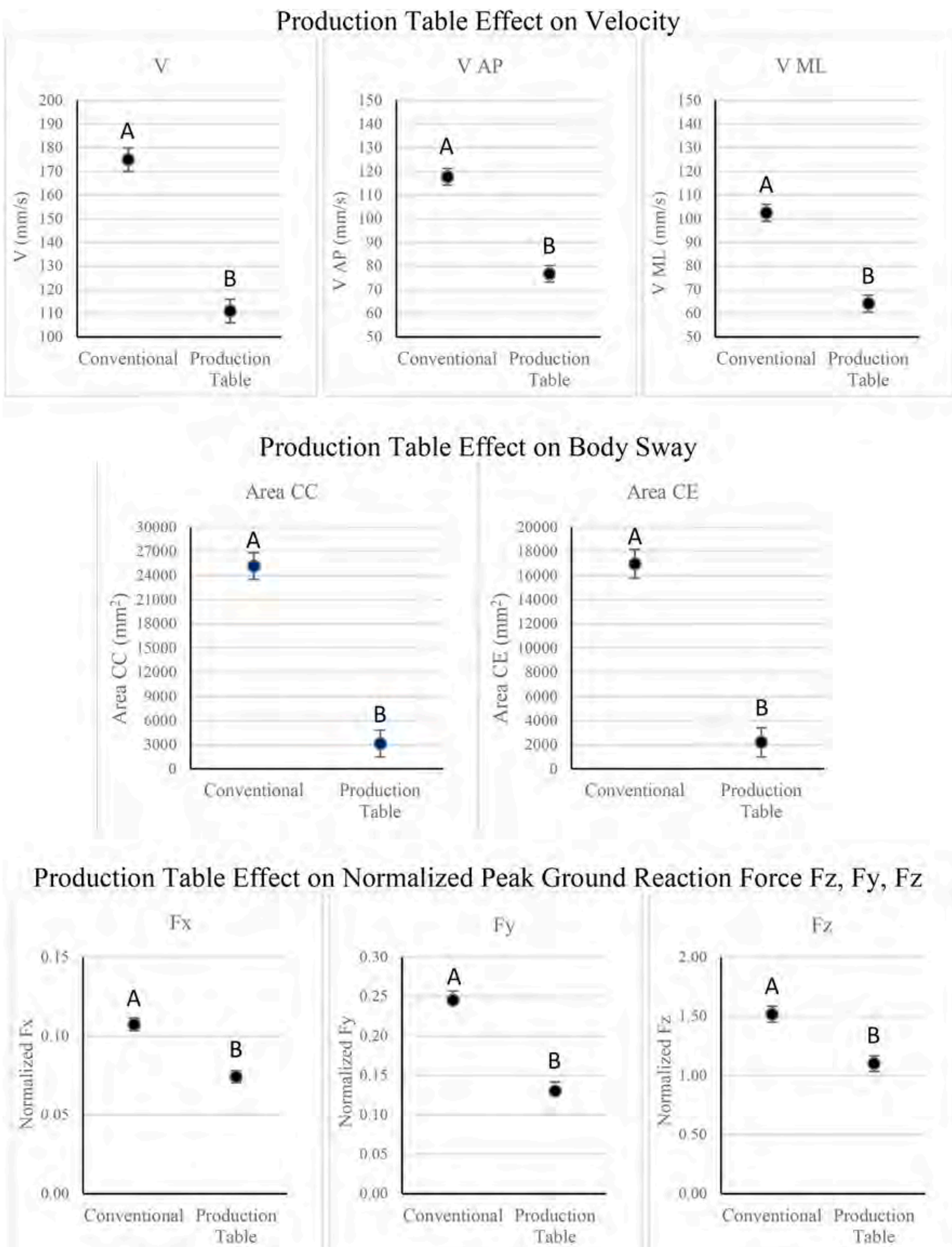

Fig. 9. Use of production table significantly reduced the velocity (V: velocity, V AP: Velocity from Anterior-Posterior, V ML: Velocity from Medial-Lateral); body sway (Area CC: area of the 95% confidence circle, Area CE: area of the 95% confidence ellipse), and peak ground reaction forces (Fx, Fy, Fz - normalized to participant's body weight). Note that different letters denote significantly different least square means. Vertical bars in each graph represent standard errors.

to each participant's body weight. Trunk sway related variables were derived from force plate data. Overall sway velocity was defined as the total traveled distance of the center of pressure (COP) during each task divided by its corresponding total time of performance. The associated COP velocities in the medial-lateral direction (V ML) as well as anterior-posterior direction (V AP) were also calculated based on the total COP traveled distance in each direction. To represent body sway, a 95% confidence circle and confidence ellipse of the COP sway area were calculated (Zolghadr et al., 2018).

2.7. Statistical analysis

Statistical Analysis System (SAS) software (SAS Institute Inc., Cary, NC, USA) was used to perform all data analyses. Prior to any statistical testing, the normality assumption was examined using a probability plot. For post-hoc multiple comparisons, the Bonferroni-adjustment was

Table 3
Repeated measures analyses of variance results of normalized impact force – p-values.

Experimental Condition	Normalized		
	Peak Fx	Peak Fy	Peak Fz
Production Table Use (Yes, No)	**<.0001**[a]	**<.0001**[a]	**<.0001**[a]
Structural Stability (Maximum vs. Minimum)	0.92	0.82	0.95
Production Table Use * Structural Stability	0.83	0.57	0.95

[a] indicates statistically significant effects.

used to determine significant differences among different experimental conditions. All significance levels (α) in hypothesis testing were set at 0.05 for this study.

For trunk range of motion, body sway and impact force, repeated measures analyses of variance (ANOVAs) were performed using the SAS MIXED procedure to evaluate the effect of different experimental conditions. In this mixed model approach, the fixed effects included 3 levels of MCWP condition and two levels of structural stability. Random effect included the participant effect. The analysis also included an interaction term of MCWP condition by structure stability in the final model. For trunk range of motion data, the MCWP condition included three levels: (1) Straight-Shaped Table, (2) L-Shaped Table, and (3) Conventional No Table. However, for body sway and impact force data, the MCWP condition included only two levels: (1) Production Table Use and (2) No Production Table Use since both Straight-Shaped and L-Shaped production tables had the same working platform configuration.

3. Results

The design of the production table configuration had significant effects on the trunk range of motion (ROM) in all three planes: sagittal, frontal and transversal ($p < .0001$, Table 1). The level of structural stability used with the production table showed no significant effect for both the spinal and pelvis ROM in any plane ($p > .05$, Table 1). Post hoc analysis found that the "L" shaped production table resulted in the lowest ROM in all three planes (frontal, transverse, and sagittal planes) as compared to the manufacturer straight-shaped production table configuration and the conventional step-down use configuration (Fig. 8). Use of the "L" shaped production table significantly improved ROM in all three planes for spine and pelvis as compared to the conventional "step-down" configuration. Use of the "L" shaped production table significantly improved ROM in all three planes for spine, and frontal and transverse planes for pelvis as compared to the manufacturer's straight-shaped production table configuration (Fig. 8). There was no observed significant difference of ROM in the transverse plane for spine and pelvis between the conventional step-down configuration and the manufacturer straight-shaped production table use configurations (Fig. 8).

Body sway data showed that both sway velocity and sway area were significantly reduced when using either production table configuration as compared to the conventional platform configuration (Tables 2 and 4, Fig. 9). However, no significant differences were observed between structural stability levels (Table 2). Stepping down from either the manufacturer straight-shaped or the NIOSH L-shaped production table demonstrated the same working platform configuration condition.

The impact force generated when stepping down to the work platform in the conventional platform configuration was significantly higher than the impact force observed with the walking forward activity when the working platform was configured with the production tables (Tables 3 and 4, Fig. 9). This observation was obvious and expected. No significant difference was observed from different structural stability levels (Table 3).

4. Discussion

Work-related musculoskeletal disorders (WMSDs) and falls to the same level and lower level are significant occupational safety and health issues among construction workers (CPWR, 2018; Dieleman et al., 2016; Liberty Mutual, 2019; Marcum and Adams, 2017; West et al., 2016). One segment of this workforce, brick and block masons, the focus of this study, experience a significant number of WMSDs. Interventions and engineering redesigns to reduce back injuries are evidently needed for these workers (Boschman et al., 2012; Hess et al., 2012).

Results of this study found that using the MCWP configured with a production table, especially the L-shaped table design, significantly reduced the range of trunk motion during a simulated bricklaying task as compared to the MCWP configured with a conventional step-down. One study investigated over 400 industrial jobs and found that excessive trunk motion, 31.5°, 24.4° and 20.7° in sagittal, frontal and transverse plane respectively, is linked to a significantly higher risk of WMSDs (Marras et al., 1993). The higher risk of WMSDs is likely due to elevated spinal compression and shear loadings resulting from increased trunk motion which may, in turn, lead to lower back pain (Marras et al., 1993, 2004; Norman et al., 1998; Ning et al., 2014; Pan and Chiou, 1999a; Pan et al., 1999b, 2003). In this study, using a production table with the MCWP proved to be an effective intervention tool to help reduce trunk range of motion by more than 10° from around 40° to around 30° (Fig. 8). This reduction in trunk range of motion will help reduce the associated risk of back-related WMSD injuries for masons performing a bricklaying task. A study involving manual materials handling tasks in a chemical plant also found that the use of a mobile, elevating, adjustable work platform was an effective intervention tool to help prevent WMSDs (Chao et al., 2018). Other studies in agriculture (Jin et al., 2009; Kato et al., 2006), fishing (Mirka et al., 2011), mining (Dempsey et al., 2018), retail (Bajaj et al., 2006; Draicchio et al., 2012) and construction (Jia et al., 2011; Kim et al., 2008; Pan et al., 2006; Pan et al., 2012b) have also demonstrated the effectiveness of engineering design interventions in reducing back injury risks and improving worker productivity (Nussbaum et al., 2009). Engineering design interventions, such as the use of a production table, can be used to reduce the risk of WMSDs to workers using MCWPs.

In our study, workers experienced significantly smaller whole-body sway and ground impact forces after stepping onto a MCWP configured for use with a production table. The reduction of sway area was the most significant among all sway-related variables, especially the 95% confidence circle and ellipse of body sway registered on the force plate. These variables were reduced by nearly 80% when the MCWP was configured with a production table (Fig. 9). Based on Zolghadr's study (2018), significant reduction of both the 95% confidence circle and 95% confidence ellipse were observed among subjects with improved standing balance. Since ground reaction forces and body sway related variables are affected by individual factors such as body height, weight, age, whole body stability etc., there hasn't been a reported threshold

Table 4
Mean and standard deviation of peak ground reaction forces and sway related variables by production table use.

Conditions		V (mm/s)	V AP (mm/s)	V ML (mm/s)	Area CC (mm^2)	Area CE (mm^2)	Fx (N)	Fy (N)	Fz (N)
Conventional	Mean	179.8	120.4	105.6	25207	16979	91.6	209.6	1355.3
	Std	43.3	31.6	31	17485	13317	33.6	81.4	512.3
Production Table	Mean	113.5	78.2	64.6	3180	2215	60.4	110	922.2
	Std	22.2	16.5	13.2	2581	1382	16.5	39.3	246.9

over which a loss of balance would occur. Numerous studies have collectively suggested that body sway is a direct indication of body balance and is associated with the risk of falling (Bagchee et al., 1998; Bhattacharya et al., 2003; Chiou et al., 2000, 2008; Kincl et al., 2002; Pan et al., 2009, 2017; Johansson et al., 2017; Sun et al., 2019). The results of the current study indicate that a MCWP configured with a production table reduces body sway during the stepping forward/down task and thereby reduces the risk of falling.

The construction workforce is aging, and when older workers are injured, their fall and overexertion injuries tend to be more severe, and their compensation and rehabilitation costs are higher (Dong et al., 2011; Sokas et al., 2019). The aging of the U.S. construction workforce requires immediate attention and improved interventions to prevent fatal and nonfatal injuries in older workers (Dong et al., 2019; Sokas et al., 2019). Due to fall and MSD injuries, many construction workers experience physical limitations or pain levels that force them to retire in their mid-50s. This limits their income-earning potential and negatively impacts the quality of their retirement life (Carnide et al., 2011; LeMasters et al., 2006; Welch et al., 2010). It has been suggested that aging results in reduced sensorimotor functions, muscle weakness in the legs, increased reaction time, and increased body sway (Lord et al., 1991; Teasdale and Simoneau, 2001). These functional deteriorations are all important factors associated with postural instability and overexertion which may lead to increased risks of loss of balance, fall incidents, and musculoskeletal injuries at construction worksites when working at heights (de Zwart et al., 1997; Hildebrandt, 1995; Pan et al., 2017). Another study (Dong et al., 2011) indicated that the fatality rate caused by falls is significantly higher for aging construction workers than younger counterparts in various construction trades, including masons. Therefore, using effective and improved intervention techniques (e.g., a production table) associated with MCWPs can help construction workers maintain good posture/balance while working at heights and may help reduce fall and overexertion hazards (Pan et al., 2018; Wimer et al., 2017).

The usefulness of both the manufacturer straight-shaped and NIOSH L-shaped production tables to reduce risk factors for WMSDs and falls was clearly demonstrated. Future studies will be needed to properly validate the effectiveness of production tables for reducing risks of falls and back injuries associated with using MCWPs and other emerging elevated work platform equipment (Pan et al., 2018). We believe this study to be the first research study specifically designed to evaluate falls and WMSD interventions for brick masons who most commonly use MCWPs.

Results of this study show that the structural stability did significantly influence any of the measured dependent variables. It was expected that structural stability would not affect body range of motion while performing the bricklaying task. Due to the nature of the step-down task, the results of this study show that structural stability associated with body weight would not significantly affect postural-sway or back-injury hazards. Different from our expectation, structural stability did not significantly impact motion or sway related factors. These results could have possibly been due to using only4 dampers or due to their capacities, 650 pounds or 236 kg (Fig. 3). Reducing the stiffness of the dampers on the simulated workstation may generate more structural stability and possibly produce "bottoming out effects". This may more accurately mimic elevated conditions of a MCWP. It would allow for a more unstable condition to be simulated and studied (Steffan and Moser, 1996; Stewart, 2000). The measurement of MCWP stiffness was conducted at a 1-foot elevated height, which is almost the highest stiffness value for the selection of the dampers. The NIOSH research team selected a height of less than 10 feet or 3 m because the majority of nonfatal fall injuries and 46% of fall-related incidents occurred at 10 feet (or 3 m) or less (CPWR, 2018). Future studies should include conditions when the work platform has higher flexibility to further evaluate structural stability effects. This study's main focus was on the use of production table interventions for reducing the risk of both back injuries and postural instabilities and not on structural stability.

The current study has several limitations. First, in order to standardize the testing procedure, all subjects in this study were required to perform bricklaying tasks from only the right side of each mason and using only one type of brick. Also, results of this study cannot be generalized to the process of installing other type of materials (e.g. stone, glass, metal sidings etc.). Second, the influence of using the straight-shaped or the L-shaped table on brick and block mason's workflow and associated productivity was not evaluated. Based on trunk kinematic results, it is suspected that using either the manufacturer's designed production table or the NIOSH designed production table could enhance productivity by reducing trunk motion. However further analysis is required to confirm this conjecture. Third, two studies (Viester et al., 2012, 2015) have indicated that the effectiveness of interventions designed to reduce WMSDs for construction workers were limited without incorporating psychosocial factors. Future studies could incorporate measures of psychosocial factors related to the use of production tables.

5. Conclusions

Results of this study found that use of either the manufacturer designed straight-shaped production table or the NIOSH designed L-shaped production table significantly reduced postural-sway hazards while working on a MCWP as compared to using the MCWP in its conventional step-down use configuration.

Results of this study also found that both production tables significantly reduced some key risk factors that might associate with back injury hazards for bricklaying masons using a MCWP.

In the future, additional experimental data collected during this study, including gait/step characteristics (e.g., speed, step width and stride length) will be analyzed to focus on behavioral modifications that workers adopt when working at heights on a MCWP.

Disclaimers

The findings and conclusions in the report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH or CDC. In addition, citations to websites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products. Furthermore, NIOSH is not responsible for the content of these websites. All web addresses referenced in this document were accessible as of the publication date.

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.

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