

Investigating the Impact of Construction Noise on Work Posture and Productivity with Virtual Reality–Based Masonry Simulation

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Abstract: Construction sites are often characterized by high-intensity noise, which routinely exposes workers to considerable acoustic loads generated by machinery and heavy equipment. Excessive noise contributes to auditory damage and interferes with communication, cognitive processing, and physical control. However, the influence of workplace noise on workers' physical behavior and its subsequent effects on ergonomic risk and productivity remains unexplored. This study experimentally investigated how different levels of construction noise affect ergonomic responses in terms of biomechanical stress and task performance. To this end, controlled experiments were conducted in a virtual reality (VR) environment, which allowed for precise manipulation of noise levels while providing safe, immersive, and reproducible simulation of construction tasks under varying noise conditions. In the experiment, participants performed lifting and placing motions during masonry tasks under noise levels ranging from 50 to 100 dB in 10-dB intervals. The motions were captured using vision-based three-dimensional (3D) pose estimation and then analyzed using biomechanical simulation to estimate joint moments and spinal compression forces. Quantitative biomechanical assessments were conducted on key body regions, including the lower back, torso, and shoulders. The experiment results indicated a notable increase in compressive forces at the lower back (5.74% at L5-S1 and 7.08% at L4-L5) as noise intensity increased, and variations in torso movement were associated with declines in productivity. The results suggest that noise exposure was associated with posture-related biomechanical indicators and productivity in a body-part-specific manner, with clearer patterns for the lower back and torso than for several other posture-related measures. Accordingly, this study provides quantitative evidence on noise-intensity-related, body-part-specific biomechanical responses and task performance in a controlled VR masonry task, which may inform noise-control and ergonomic planning efforts. **DOI:** [10.1061/JMENA.MEENG-7403](https://doi.org/10.1061/JMENA.MEENG-7403). © 2026 American Society of Civil Engineers.

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Introduction

Workers exposed to construction noise are 43% more likely to experience hearing loss than their unexposed counterparts, and are 9% more likely to suffer from high blood pressure. These statistics illustrate the adverse effects of noise on the health of construction workers (House et al. 2010; Kerns et al. 2018; Li et al. 2016). Construction sites typically involve the use of heavy equipment and tools, such as drills and vibrators, which inherently generate significant noise levels. Despite the existence of various regulations aimed at limiting worker exposure to excessive noise, practical challenges in enforcement and compliance often result

in workers near major noise sources remaining at risk (Abatement 1974; Fernández et al. 2009). Additionally, the collaborative nature of construction work necessitates frequent verbal communication to coordinate tasks and ensure safety, which complicates the consistent use of hearing protection devices, such as earplugs, which may hinder communication (Li et al. 2016).

Field measurements in construction have documented that workers may experience a wide spectrum of A-weighted noise levels, with exposures over an entire working day frequently near or above 85 dB and task-based levels often exceeding 90 dB (Li et al. 2016; Neitzel et al. 1999). In addition, exposure to high noise levels has been linked to an increased likelihood of workers adopting

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improper postures, thereby placing additional strain on key body regions. For example, Borz et al. (2019) and Cheța et al. (2018) found that noise exposure increased postural strain in forestry tasks. In addition, Chaharaghran et al. (2022) demonstrated that both noise and poor posture contribute independently to job-related stress, suggesting the need to consider noise as a factor influencing both physical and cognitive outcomes. This strain can lead to work-related musculoskeletal disorders (WMSDs), such as sprains or herniated discs (Cheța et al. 2018). These conditions not only contribute to decreased productivity and increased absenteeism but also impose significant costs related to medical treatment. For example, Habibi et al. (2013) reported that higher noise levels significantly increased error rates and reduced work speed in simulated manufacturing activities. Noise exposure also has been found to diminish productivity in ongoing tasks, potentially causing project delays and additional expenditures due to extended timelines or the need for supplemental resources (Palikhe et al. 2020).

Among various construction trades, masonry workers are particularly vulnerable to noise exposure. According to Neitzel et al. (2011), 62.8% of masonry workers are exposed to noise levels exceeding 85 dBA, the threshold set by the National Institute for Occupational Safety and Health (NIOSH) (Safety and Health 1972) as harmful—with an average exposure of 87.9 dBA. This susceptibility is exacerbated by the physically demanding nature of masonry work, which often involves manual handling of heavy materials, and the task has approximately 43% higher rates of WMSDs than other construction jobs (Entzel et al. 2007). Repetitive and physically demanding tasks such as masonry are known to impose substantial biomechanical stress, particularly on the lower back, shoulders, and wrists (Anton et al. 2020; Hess et al. 2010; Marras et al. 1995; Stürmer et al. 1997). Furthermore, because masonry tasks are labor-intensive and generally are performed without the aid of machinery, workers are directly exposed to noise, which may further influence their productivity (US Bureau of Labor Statistics 2023).

Previous studies have focused predominantly on the direct relationships between noise exposure and poor posture or between noise exposure and reduced productivity. However, limited attention has been given to whether posture-related biomechanical changes are associated with both noise exposure and productivity. To address this gap, this study examined the impact of varying levels of construction noise on workers' postures, particularly those linked to WMSDs, and the effect of these postural changes on productivity. A virtual reality (VR) simulation of masonry tasks was employed because masonry is an ergonomically relevant construction task involving repeated material handling, and also provides a structured work sequence that supports consistent posture extraction under controlled experimental conditions. The VR setting was used to preserve the task sequence and posture demands relevant to brick handling while maintaining control over environmental factors during the noise-exposure experiments. Participants performed masonry tasks under noise levels ranging from 50 to 100 dB, and their movements were recorded for detailed analysis. Using video footage, three-dimensional (3D) poses were estimated, and biomechanical analyses were conducted to quantify musculoskeletal loads on key body regions, including the lower back, torso, shoulders, and ankles. The data were evaluated statistically to establish correlations among noise levels, poor posture, and productivity. From a construction management perspective, this study provides experimentally grounded evidence linking an operational exposure commonly addressed on jobsites (noise) to posture-related biomechanical demands and productivity outcomes under controlled task conditions. The findings of this study may help clarify the effects of noise on work posture and productivity at construction sites

and potentially could contribute to the development of practical strategies for improving the work environment.

Literature Review

This section reviews prior research on two primary topics: (1) the effects of noise exposure on WMSDs, and (2) the effects of noise exposure on productivity. Furthermore, the limitations of existing studies investigating the relationships among noise exposure, WMSDs, and productivity are discussed.

Previous studies predominantly have examined ergonomic risks associated with various body parts, such as the neck and shoulders, in different noise environments, including both indoor and outdoor settings (Table 1). In indoor environments, Ali et al. (2012) assessed discomfort in different body parts of sawmill workers through surveys and analyzed their postures under high noise exposure using rapid entire body assessment (REBA), rapid upper limb assessment (RULA), strain index, and quick exposure check (QEC). Their findings indicated that in high-noise environments (90–100 dB) exceeding the Occupational Safety and Health Administration limits for prolonged exposure, the neck and trunk were at the highest risk of strain. Similarly, Das (2020) estimated subjective discomfort in sawmill workers using surveys and evaluated their postures using the Ovako Working Posture Analysis System (OWAS). Workers exposed to an average noise level of 98 dB (peaking at 104 dB during sawn wood cutting) reported discomfort in the lower back (91%), hands (80%), shoulders (76%), knees (64%), and upper back (58%). In outdoor environments, Rwamamara and Simonsson (2009) utilized the Plan för Identifiering av Belastningsfaktorer (PLIBEL) and QEC methods to assess body part exposure during concrete casting activities under various on-site noise conditions. They reported that vibrated concrete casting with noise levels ranging from 78.4 to 112.5 dB caused significant back strain. Tadele (2020) surveyed ergonomic risk factors, including noise exposure, among construction workers operating machines and equipment. Prolonged exposure to noise from wood cutters (89.5–108 dB), metal cutters (46.9–116 dB), metal grinders (51.9–97 dB), and drilling tools (86.5–92.2 dB) resulted in hearing issues among operators (7.6%) and welding and metal workers (18.1%).

Previous studies have examined the relationship between construction noise and productivity in two primary settings: (1) field environments and (2) laboratory environments. Field environments include both indoor settings, such as steel companies (Aktuğ et al. 2019) and outdoor environments, such as construction sites (Abrey and Smallwood 2014). In indoor environments, Aktuğ et al. (2019) designed a questionnaire to investigate the effects of varying noise levels on productivity concerns, including increased errors, exhaustion, workmanship quality, and production efficiency, in steelwork at a steel company. The study revealed that 70.5% of respondents associated high noise levels with workplace disturbances, and 85.2% agreed that noise adversely affected workmanship and production quality. In outdoor environments, Koushki et al. (2004), Bashir et al. (2024), Lee et al. (2019), Abrey and Smallwood (2014), and Jung et al. (2019) investigated the influence of noise on construction-site productivity using on-site surveys. Koushki et al. (2004), Bashir et al. (2024), and Lee et al. (2019) designed questionnaires to assess whether noise affected worker productivity in terms of slower work pace, equipment calibration delays, work stoppages, and extended project timelines. These studies collectively reported that noise significantly reduced working efficiency (Bashir et al. 2024; Koushki et al. 2004). Specifically, Lee et al. (2019) observed correlation coefficients between noise annoyance and work performance across three noise sensitivity

Table 1. Previous studies of relationships among noise exposure, WMSDs, and productivity in the construction industry

Purpose	Experiment environment	Methods	Noise sources	Noise levels	Work	References
Effect of noise exposure on WMSDs	Indoor environment	Qualitative (e.g., survey) and semiquantitative methods (e.g., REBA, RULA, strain index, and QEC)	Sawmills	No multiple levels	Logging work	Ali et al. (2012)
		Qualitative (e.g., survey) and semiquantitative methods (e.g., OWAS)	Sawmills	No multiple levels	Logging work	Das (2020)
	Outdoor environment	Qualitative (e.g., PLIBEL) and semiquantitative methods (e.g., QEC)	Construction sites	No multiple levels	Concrete casting	Rwamamara and Simonsson (2009)
		Qualitative (e.g., survey)	Construction sites	No multiple levels	Machine and equipment operating	Tadele (2020)
Effect of noise exposure on productivity	Indoor environment	Qualitative methods (e.g., survey)	Steel company	Multiple levels	Steel work	Aktuğ et al. (2019)
	Outdoor environment	Qualitative methods (e.g., survey)	Construction sites	No multiple levels	Construction work	Abrey and Smallwood (2014), Bashir et al. (2024), Koushki et al. (2004), and Lee et al. (2019)
			Construction sites	Multiple levels	Construction work	Jung et al. (2019)
	Laboratory environment	Quantitative methods (e.g., productivity rate)	Drill machine	Multiple levels	Concrete drilling	Carty et al. (2017)
			Speakers	Multiple levels	Masonry work	Hong et al. (2023)

Note: REBA = rapid entire body assessment; RULA = rapid upper limb assessment; OWAS = Ovako Working Posture Analysis System; and QEC = quick exposure check.

groups—low, medium, and high sensitivity—measuring 0.48, 0.46, and 0.53, respectively.

Abrey and Smallwood (2014) and Jung et al. (2019) designed questionnaires focusing on the impact of physicochemical factors, such as construction noise, which could harm workers by inducing headaches and eyestrain, resulting in lower productivity. Their findings indicated that frequent exposure to excessive noise levels led to reduced productivity (Abrey and Smallwood 2014). Furthermore 7.8%, 15.5%, and 15.2% of workers experienced headache or eyestrain symptoms when exposed to low, moderate, and high noise levels, respectively (Jung et al. 2019).

In laboratory environments, several studies have been conducted under controlled conditions to isolate the effects of noise exposure on productivity, including immersive experimental paradigms increasingly used to balance contextual fidelity with measurement control (Abbas et al. 2023; Xu et al. 2024). For example, Carty et al. (2017) evaluated the noise levels (decibels) generated by a drill machine and corresponding production rates (millimeters/second) during concrete drilling tasks. The findings indicated that increased bit wear increased noise levels, which subsequently reduced drilling productivity (Carty et al. 2017). Similarly, Hong et al. (2023) investigated the productivity rate (square meters/hour) of masonry work under varying noise levels (decibels) in a VR environment in which noise was generated using speakers. Their study identified a negative correlation between productivity and the self-perceived effects of noise exposure. Specifically, mean productivity increased by 1.05% at 60 dBA but decreased by 2.33% at 100 dBA (Hong et al. 2023). Complementing these VR-based productivity assessments, recent immersive-task studies have shown that cognitive and physiological states can be quantified using objective measures [e.g., electroencephalography (EEG) and eye tracking], which can strengthen interpretation of performance changes under environmental stressors (Luo et al. 2024; Shin et al. 2024).

However, these studies have several limitations. First, although some investigations, such as those by Carty et al. (2017) and Hong et al. (2023), evaluated the effects of noise exposure on productivity under controlled laboratory conditions (e.g., regulated noise levels and temperature), the assessment of WMSDs (Ali et al. 2012; Das 2020; Rwamamara and Simonsson 2009; Tadele 2020) within noise exposure contexts was conducted predominantly in field environments. Field environments, such as indoor [e.g., sawmills (Ali et al. 2012; Das 2020)] and outdoor environments [e.g., construction sites (Rwamamara and Simonsson 2009; Tadele 2020)], may offer authentic experiences that yield accurate data in real working conditions. However, external factors, such as humidity and temperature, which cannot be fully controlled on-site, potentially can affect WMSDs (Tadele 2020) and productivity (Hong et al. 2023; Jung et al. 2019). Therefore, changes in these factors in field environments may pose challenges in investigating the relationships between noise exposure, WMSDs, and productivity. To address this limitation, experiments in controlled environments that replicate realistic work experiences while enabling regulation of external factors (e.g., humidity and temperature) are necessary. Such controlled experiments would allow for a more precise evaluation of the direct effects of noise exposure on WMSDs and productivity.

Second, these studies primarily evaluated WMSDs using ergonomic assessment methods that relied on qualitative and semiquantitative approaches. Qualitative methods included surveys (Ali et al. 2012; Das 2020; Mustapha et al. 2022; Tadele 2020) and the PLIBEL checklist (Rwamamara and Simonsson 2009). Surveys utilized self-reported data from workers to provide insights into discomfort, physical strain, or fatigue, and PLIBEL served as an ergonomic checklist to identify risk factors for WMSDs (Rwamamara and Simonsson 2009). Semiquantitative methods encompassed tools such as the REBA (Ali et al. 2012),

RULA (Ali et al. 2012), strain index (Ali et al. 2012), OWAS (Das 2020), and QEC (Ali et al. 2012; Rwamamara and Simonsson 2009). Although these qualitative and semiquantitative methods offered valuable perspectives, they relied heavily on experiential, observational, and subjective assessments rather than direct biomechanical force calculations. This reliance limits the precision of these methods in quantifying ergonomic risks for specific body parts. The absence of accurate quantitative analyses of WMSDs presents challenges in supporting ergonomic decision-making and monitoring improvement over time, motivating recent practice-oriented approaches that incorporate wearable sensing and momentary assessment to capture worker state and fatigue in near real time (Park et al. 2023).

Third, the mechanisms by which varying levels of noise exposure ergonomically affect the human body, contributing to posture-related biomechanical changes, and the resulting ergonomic changes in posture influence productivity performance have not been explored comprehensively. Regarding the former, previous studies have identified cognitive mechanisms by which noise exposure may impair balance and concentration, thereby indirectly affecting postural stability and increasing muscular strain. For example, Juntunen et al. (1987) found that exposure to high-energy impulse noise increased postural sway, indicating diminished balance control. Carey and Balasubramaniam (2025) demonstrated that auditory noise under cognitive load disrupted balance control during quiet standing tasks, suggesting that noise-induced attentional distraction may compromise motor coordination. Ljungberg et al. (2004) demonstrated that combined exposure to noise and vibration was reported to elevate perceived task difficulty, reflecting increased mental or physical strain. Shah and Nanavati (2024) found that increased cognitive demands altered postural responses. Salihu et al. (2022) also confirmed that greater cognitive task complexity, especially in environments involving auditory interference, significantly increased postural sway during dual-tasking.

Building on these observations, noise exposure can be conceptualized not only as an external physical stimulus but also as a source of auditory interference that elevates stress and mental workload, thereby perturbing postural regulation. Meta-analytic evidence indicates that such noise-related resource demands can impair cognitive and motor performance depending on task and noise characteristics, providing a basis for downstream reductions in work output (Szalma and Hancock 2011). Under a compensatory control framework, individuals faced with stress and high workload attempt to maintain task goals by reallocating limited resources and modifying action strategies, which can manifest as systematic adjustments in posture and movement strategy (Hockey 1997). In physically repetitive manual tasks, these adaptations can alter trunk and shoulder kinematics (Kachlan et al. 2025), redistribute biomechanical loading, and accelerate fatigue accumulation, thereby reducing sustainable work pace and productivity (Daneshmandi et al. 2017). This integrated evidence supports the interpretation that posture may be relevant to the association between noise exposure and productivity outcomes in manual construction work.

Despite these mechanistic links, in the construction industry, WMSDs typically have been evaluated under general noise conditions without considering the varying noise levels. For example, previous studies, including those by Ali et al. (2012), Das (2020), Rwamamara and Simonsson (2009), and Tadele (2020), primarily evaluated WMSDs under general noise conditions associated with specific tasks, such as logging, concrete casting, and machine or equipment operations. The levels of construction noise can vary substantially depending on the source, such as the type of equipment or task being performed. Consequently, both different

noise levels and different tasks potentially exert differential effects on WMSDs. For example, logging operations, which involve noise levels reaching 104 dB, predominantly impacted the lower back (91%), hands (80%), and shoulders (76%) (Das 2020). Tasks such as cutting and sawing with tools generating noise levels between 90 and 100 dB primarily affected the lower back (87%), wrists (77%), and neck (73%) (Ali et al. 2012).

Therefore, the assessment of WMSDs under general noise conditions of previous construction studies may be affected by task-specific physical demands, potentially limiting a comprehensive understanding of the specific relationships between different noise levels and WMSDs. With respect to the latter, although numerous studies have examined the relationship between noise and productivity, few have investigated the influence of posture-related biomechanical changes associated with different noise levels on productivity outcomes. Because the effects of noise exposure on the human body can vary depending on the body part affected, the postural adjustments induced by noise exposure are likely to impact work performance differently. Consequently, a thorough understanding of the interrelationships among varying noise levels, WMSDs affecting different body regions, and productivity performance is essential. Such insights could enable the identification of critical body parts that are affected most significantly by noise exposure and contribute to productivity changes. This understanding also could inform the development of targeted strategies to enhance worker health and optimize productivity in environments characterized by varying noise levels.

Methodology

This study investigated how variations in workers' postures, induced by different noise levels, biomechanically affect various parts of the body and, consequently, how these postural changes influence productivity. To achieve this objective, experiments were conducted within a VR environment in which participants performed a controlled masonry task designed to preserve the sequence and representative postures of repeated brick handling while enabling precise control of the noise conditions [Fig. 1(a)]. This VR-based simulation provided a controlled environment that effectively minimized interference from external factors such as temperature and humidity, which are inherent to real-world conditions. Specifically, the study involved 32 participants whose movements were recorded as they simulated bricklaying tasks under controlled noise levels ranging from 50 to 100 dB, in increments of 10 dB, during brief experimental exposures designed to compare immediate responses across noise conditions. Then three-dimensional motion data, including the rotation and position of each major joint, were captured from the recorded videos. These data subsequently were converted into a format suitable for biomechanical assessment [Fig. 1(b)]. The biomechanical analysis enabled the computation of forces and stresses exerted on various body parts, including the lower back, wrists, elbows, trunk, knees, and ankles. These quantitative results facilitated the comparative evaluation of posture-related biomechanical indicators across noise conditions. Simultaneously, productivity metrics were measured during the experiments. The relationships among noise level, posture-related biomechanical indicators, and work efficiency were analyzed statistically, with particular attention to whether posture-related biomechanical changes were associated with both noise exposure and productivity. This methodological approach allowed for a comprehensive understanding of how noise exposure influences posture-related biomechanical changes and productivity. By maintaining precise control over noise levels, this study addressed challenges typically encountered in

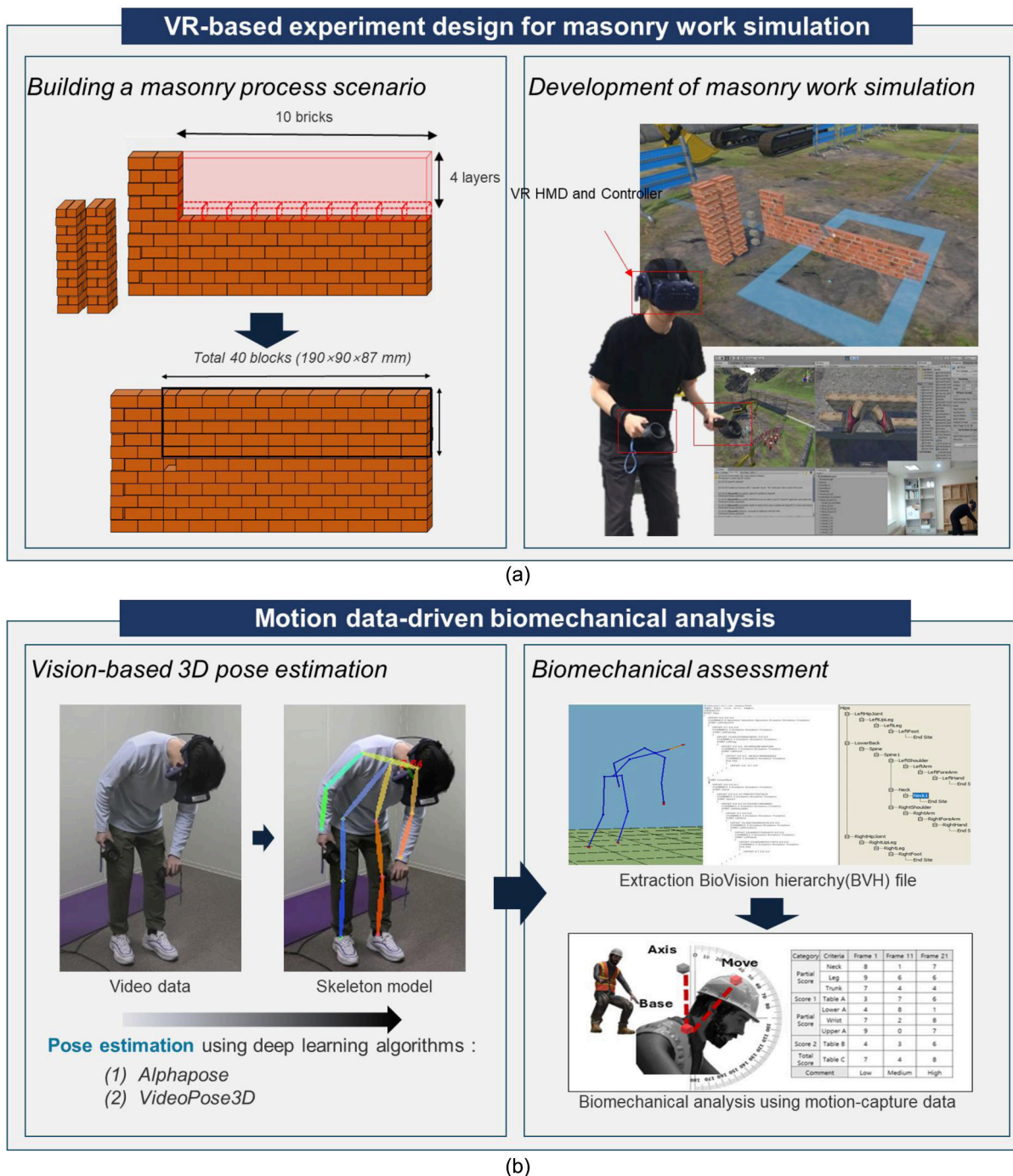


Fig. 1. Overview of the research methodology: (a) VR experiment design; and (b) motion data-driven biomechanical assessment.

real-world environments, in which external variables are difficult to regulate.

VR-Based Experiment Design for Masonry Work Simulation

In this study, a VR-based approach was utilized to enhance the realism of the simulation by integrating authentic visual and auditory elements into the experimental setup. This methodology enabled the evaluation of the effects of noise on worker behavior in a manner analogous to real construction site conditions. The implementation of the VR simulations involved designing a virtual environment and configuring VR devices to facilitate interactive engagement.

The simulation environment was developed using the Unity game engine (version 2022.3.42f1). Unity is a cross-platform game engine and development environment widely used for creating interactive two-dimensional (2D) and 3D simulations, including VR and augmented reality (AR) applications (Buyuksalih et al. 2017). Specifically, the masonry work simulation required participants to construct a wall comprising 4 layers, each containing 10 bricks, for a total of 40 bricks. Each brick measured 190 × 90 × 87 mm (Fig. 2). This task was selected because masonry is an ergonomically relevant construction activity involving repeated material handling, and also provides a well-structured sequence with clearly identifiable handling phases (pick, transfer, and placement) and systematic changes in working height across layers (Faber et al. 2009;

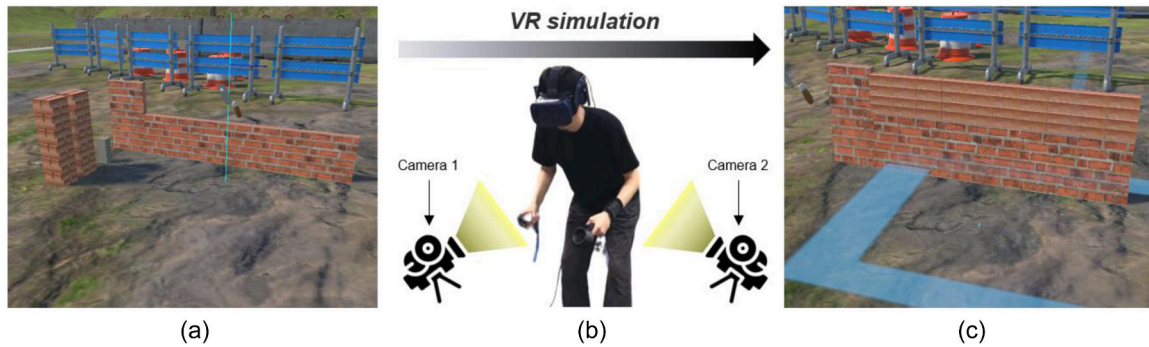


Fig. 2. Development of a VR-based simulation environment to emulate the masonry process: (a) initial state of masonry simulation; (b) simulation in VR environment; and (c) final state of masonry simulation.

Luijsterburg et al. 2005; Luttmann et al. 1991). These characteristics enabled consistent extraction of comparable representative postures at defined task moments across noise conditions, which aligns with the posture-based biomechanical analysis adopted in this study.

The experiments were designed to last an average of 5 min to minimize the potential risk of cybersickness associated with extended VR exposure (Turnbull and Phillips 2017). The VR setup included a head-mounted display (HMD), a VR controller, and motion sensors. The HMD provided users with a visual representation of the simulated environment, ensuring an immersive experience. The VR controller supported multiple hand functions, including squeezing, stretching, and grasping objects, thereby enabling participants to perform diverse activities within the virtual environment. Motion sensors tracked the movements and rotations of the HMD and the controller, ensuring that the simulated environment dynamically responded to user interactions in a realistic manner. To preserve ecological relevance while maintaining experimental control, real brick dimensions and a fixed wall layout were implemented, and uniform visual task cues were provided across conditions to reduce variability unrelated to noise exposure. These design choices were intended to elicit naturalistic reaching, bending, and placing behaviors while improving reproducibility in a controlled VR setting. Participants used handheld VR controllers to simulate the brick-laying task. They performed consistent motions, including grasping, lifting, and placing bricks, following a fixed wall layout rendered in the virtual environment. The system allowed visual guidance for the task but did not reproduce the actual mass, contact resistance, or haptic feedback associated with handling physical bricks, focusing the evaluation on postural changes rather than absolute muscular effort.

The VR experiments were conducted in two phases, designed to familiarize participants with the VR setup and task procedure through pretraining sessions, followed by the main experimental phase. In the first phase, participants were given a comprehensive overview of the experiment. This included instructions on using the VR device, an explanation of the experiment's purpose, and a detailed description of the procedure. Subsequently, an average of three pretraining sessions on the masonry work simulation were conducted to mitigate potential productivity declines arising from participants' unfamiliarity with the VR equipment. In the second phase, participants performed masonry tasks under six levels of noise exposure, ranging from 50 to 100 dB. Although the 85-dBA criterion is based on full-shift exposure and does not apply directly to the brief experimental exposures used in this study, it was used as a reference because previous studies consistently have reported full-shift construction noise exposures at or above this level, including among masonry-related occupations (Lewkowski et al. 2018; Neitzel et al. 2011). Accordingly, the selected sound levels

were intended not to interpret short-duration exposures against an occupational threshold, but to define a construction relevant range of sound intensities for controlled comparison. This range was selected to cover a broad span of sound intensities relevant to construction conditions, including task-level levels exceeding 90 dB during high-noise equipment operation, such as the use of jackhammers, concrete saws, and compressors (Leensen et al. 2011; Li et al. 2016; Neitzel et al. 1999; Seixas et al. 2005). A 10-dB step size was adopted to create clearly distinguishable exposure conditions while allowing all conditions to be tested within one experimental session.

Because the purpose of the study was to compare immediate posture-related biomechanical responses across noise levels under controlled conditions, brief exposures were used to reduce the influence of additional factors, such as accumulated fatigue, sustained cognitive demand, and adaptation over time, that could make the specific contribution of noise intensity more difficult to isolate within a single session (Kristiansen et al. 2014; McNeer et al. 2016; Woollacott and Shumway-Cook 2002). In addition, each 10-dB increase represents a 10-fold change in acoustic intensity and commonly is associated with an approximately doubled perceived loudness (Moore 2014). To control for potential order effects and reduce the influence of time-dependent fatigue, participants were randomly assigned to one of two experimental groups. The first group was exposed to noise levels in ascending order from 50 to 100 dB, whereas the second group experienced descending order from 100 to 50 dB. Both groups completed the same tasks under identical conditions except for the sequence of noise exposure. This design allowed for a balanced comparison of acute noise effects while minimizing cumulative fatigue across conditions. The noise stimuli were prerecorded sounds of construction activities, including drilling, hammering, and concrete mixing, sourced from a professional sound database. These base sounds were applied uniformly across all conditions and amplified to match the designated decibel levels, ensuring realistic and consistent auditory exposure. To capture participants' working postures during the tasks, video cameras were placed strategically on both the right and left sides, ensuring that all body parts were recorded accurately. The collected video data then were used for three-dimensional pose estimation, allowing for the analysis of body movements and key joint positions. Additionally, productivity data were gathered during this phase, measured in terms of unit area (square meters) completed per hour. This was calculated by dividing the fixed wall area by the time each participant took to complete the masonry task. Because participants followed an identical layout and placement accuracy was constrained by the VR system, the productivity metric reflects task completion speed rather than placement precision.

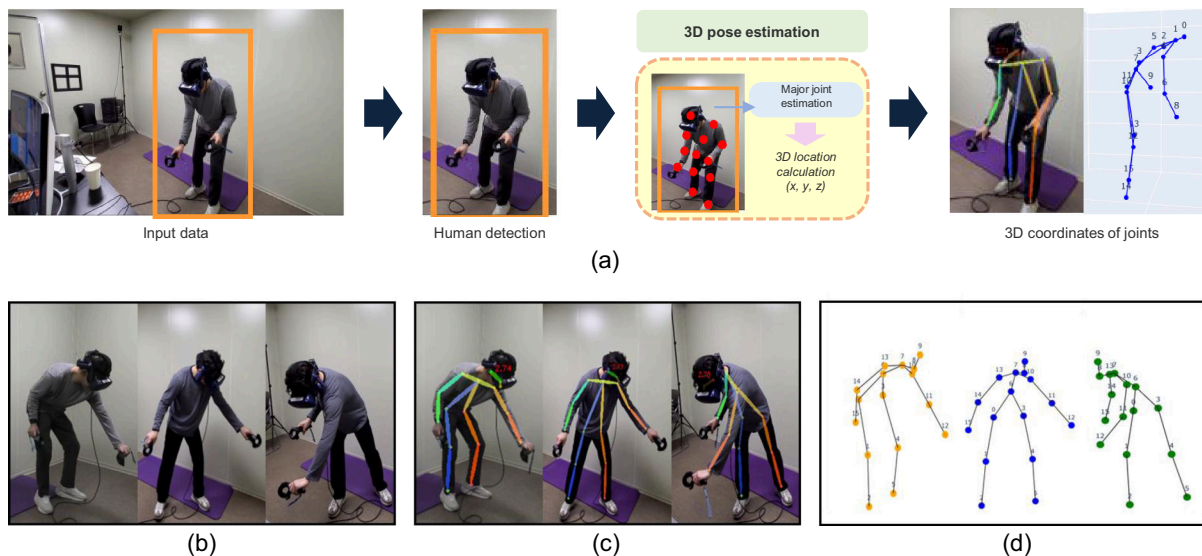


Fig. 3. Vision-based pose estimation using video data: (a) process of 3D pose estimation; (b) examples of input video data; (c) results of pose estimation; and (d) resulting skeleton models with 3D coordinates of major joints.

Vision-Based 3D Pose Estimation for Motion Data Collection

The video data collected during the experiments were used to estimate the three-dimensional coordinates of the participants' major joints through 3D pose estimation techniques [Fig. 3(a)]. To facilitate motion data collection, vision-based pose estimation algorithms, such as AlphaPose (Fang et al. 2017) and VideoPose3D (Pavlo et al. 2019), were employed to extract participants' postures from individual image frames.

For implementation, the video data initially were segmented to isolate image patches that specifically included the bricklaying postures from the broader scene [Fig. 3(b)]. To ensure consistent biomechanical evaluation, a total of 16 postures were selected per participant, with 4 representative postures extracted from each of the 4 working-height layers. The selection focused specifically on the brick placement phase, because this phase generally involves the end range of trunk flexion and requires a forward-leaning posture that increases lumbar loading. For each brick placement task, the recorded motion was segmented into 3–4-s intervals (approximately 90–120 frames) during which the participant's hand approached the target location to place a brick. Within each segment, the frame showing the maximum trunk flexion was selected as the representative posture for ergonomic analysis (Paquet et al. 2001), which emphasizes postures with the highest musculoskeletal load. This approach enabled posture comparisons to be made under uniformly controlled task conditions, minimizing the influence of sampling variation. In addition, to maintain comparability across participants, only postures in which all key body segments (e.g., upper limbs, torso, and legs) were clearly visible from a fixed camera perspective were included. All posture extractions were conducted using the same video angle and visibility criteria, regardless of the participant's identity or performance. This approach enabled a consistently applied, high-load posture analysis across varying noise and height conditions.

From each selected posture, 3D joint coordinates were converted into joint angles and used to compute compressive and shear forces (L5-S1 and L4-L5) as well as percentage capable values for other joints (e.g., torso, hips, and ankles). Following segmentation, two-dimensional pose estimation was performed on the extracted image patches containing the participants' postures using

the AlphaPose algorithm. This algorithm minimizes discrepancies in joint coordinates between consecutive frames, thereby reducing abrupt changes in joint positions. By ensuring temporal consistency, it provides a stable and accurate estimation of the participants' poses across sequential frames. Using this approach, the 2D positions (i.e., x - and y -coordinates) of the major joints, such as the head, shoulders, elbows, arms, and legs, were estimated successfully [Fig. 3(c)]. Subsequently, the 2D joint coordinates were converted into 3D coordinates (i.e., x -, y -, and z -coordinates) using the VideoPose3D algorithm, which is designed specifically for 3D pose estimation from monocular 2D images [Fig. 3(d)]. This algorithm employs a temporal convolutional network (TCN) to capture temporal dependencies in sequential data, enabling the prediction of the most probable depth (i.e., the z -coordinate) for each joint. This process ensures the temporal consistency of joint positions across frames, resulting in accurate estimations of 3D joint coordinates. Consequently, the 3D positions of 27 body joints, including the head, neck, hips, shoulders, arms, and legs, were extracted from each video frame. These joint positions provide critical insights into the full range of body mechanics, such as bending, twisting, and setting down movements, which are integral to masonry work.

Biomechanical Assessment Using Motion Capture Data

Motion capture data derived from 3D pose estimation were utilized to conduct biomechanical assessments, enabling a detailed evaluation of the mechanical forces and interactions within the human body. This assessment aimed to identify and quantify the ergonomic risks associated with each body joint. The proposed methodology (Fig. 4) involved several key steps: (1) converting the 3D coordinates of body joints into an input format suitable for biomechanical analysis, (2) adjusting the body configuration for each participant to account for individual variations, and (3) applying an external load, corresponding to the weight of a brick. Each step is described in this section, along with an interpretation of the results obtained from the biomechanical simulations.

In this study, a biomechanical assessment was conducted using the 3D Static Strength Prediction Program version 7.0.0 (3D SSPP) (Chaffin et al. 2006), which calculates the biomechanical stress on specific joints, such as the lower back, wrists, elbows, torso, and

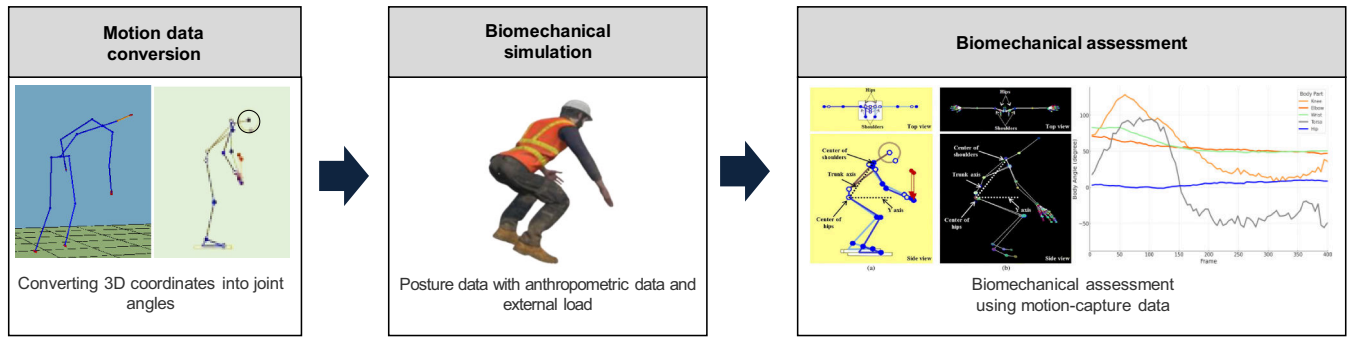


Fig. 4. Computational process of biomechanical assessment using motion capture data.

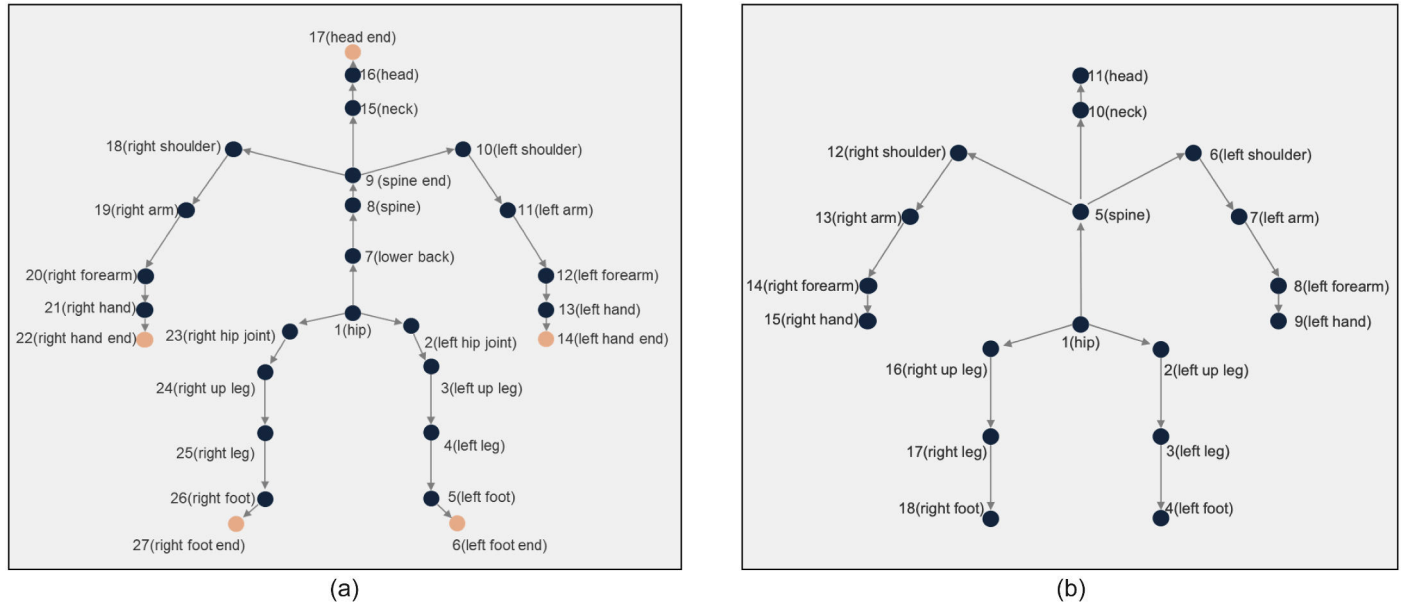


Fig. 5. Body configurations: (a) from 3D pose estimation; and (b) with body joints selected for biomechanical assessment (i.e., 3D SSPP).

ankles, in order to evaluate the ergonomic risk relative to population strength capabilities. This facilitates the interpretation of ergonomic risks in alignment with the tolerance of each joint. The tool requires joint angles (e.g., vertical and horizontal angles) between relevant body segments and a 2D plane, which is specifically defined for each joint. Therefore, the 3D joint coordinates obtained from 3D pose estimation were converted into horizontal and vertical angles at each body joint. Specifically, the pose-estimation results provided the 3D coordinates of 27 body joints [Fig. 5(a)], including joints not relevant to the 3D SSPP. Consequently, 18 body joints [Fig. 5(b)] were selected for conversion from 3D coordinates to angular data. Using the adjusted body configuration, the horizontal and vertical angles for each body joint were computed as follows:

$$\theta_{\text{horizontal}} = \text{atan2}\left(\frac{\Delta z}{\Delta x}\right) \quad (1)$$

$$\theta_{\text{vertical}} = \text{atan2}\left(\frac{\Delta y}{\Delta x}\right) \quad (2)$$

First, the horizontal angle of a body segment (e.g., the left shoulder) defined by two joints (e.g., the left shoulder joint and left arm joint) was calculated as the angle between a vector projected onto a horizontal plane (i.e., the x, y -plane) and a reference vector in that plane (i.e., the x -axis) [Eq. (1)]. In this calculation, Δx represents

the difference between the x -coordinates of the two joints, and Δz represents the difference between their z -coordinates. Second, the vertical angle of a body segment was computed from a vector projected onto a vertical plane (i.e., the x, z -plane) and a reference vector in that plane (i.e., the x -axis). Here, Δx is the difference between the x -coordinates of the two joints, and Δy represents the difference between their y -coordinates. In this manner, the horizontal and vertical angles for 12 major joints, including the forearms, upper arms, clavicles, upper legs, lower legs, and feet, as well as the flexion, rotation, and bending angles of the trunk and head, were calculated and used as postural inputs for the 3D SSPP.

Anthropometric data and external loads are essential for the biomechanical computation of joint forces, torques, and posture-based load distributions in the human body. Anthropometric information includes measurements such as limb lengths, body part weights, and joint positions, which represent each individual's unique physical characteristics and are crucial for biomechanical assessments. For example, the participants' height and weight influence both the location and magnitude of the estimated stress experienced by their joints and muscles (Li and Zhang 2009). External load data correspond to the forces or weights applied to the body during activities such as lifting and pushing. These external loads directly affect the compressive and twisting forces acting on the joints and muscles, thereby assisting in the identification of body regions subjected to excessive stress during specific tasks. In this study, a nominal

external hand load of 22.24 N (5 lb) was computationally applied downward to the hand segment during each evaluated posture in the 3D SSPP analysis to represent a brick unit load. This value was selected as a representative modeling load based on typical manufacturer specifications because brick unit weights vary by product type and material. Although participants did not physically handle the load during the VR task, this modeling approach aligns with the intended use of static biomechanical tools such as 3D SSPP, which estimate internal forces based on posture-derived joint angles and specified external load inputs (Chaffin et al. 2006). In addition, prior work using pseudo-haptic VR has reported that key kinematic characteristics during lifting tasks can be comparable to those observed under real-weight conditions, supporting the interpretation of VR-derived motion data for posture-based comparative analysis under controlled settings (Moosavi et al. 2024). Therefore, the same load was applied across all samples to support consistent comparison of estimated lumbar compression and joint strength under varying noise conditions.

A biomechanical assessment was conducted using motion capture data. In interpreting the results, the outputs from the 3D SSPP indicate the stresses on major joints, including the lower back, wrists, elbows, shoulders, torso, hips, knees, and ankles. For the lower back, specifically at the L5-S1 and L4-L5 levels, the estimated compressive force (in pounds) applied to the joint was measured. This implies that a greater magnitude of the applied force corresponds to a higher risk of injury to the joint. Additionally, other body parts were assessed in terms of percent strength capability, which represents the estimated percentage of the population capable of performing a given task without exceeding their biomechanical limits, thus minimizing the risk of injury. For example, a strength percentage of 10% for the ankle suggests that only 10% of the reference population is estimated to possess the necessary ankle strength, flexibility, and endurance to safely perform the task. In 3D SSPP, the reference population was derived from data provided by the National Institute for Occupational Safety and Health (NIOSH) (Ann Arbor 2017). The biomechanical analysis using 3D SSPP was conducted based on static postures. Each posture was extracted from the brick placement phase, which involves significant trunk flexion and is biomechanically critical for assessing lumbar loading. This selection criterion was applied uniformly to all 32 participants, resulting in 3,072 posture samples (6 noise levels $\times$ 16 postures $\times$ 32 participants). The extracted 3D joint coordinates using pose estimation were converted into joint angles and used as input for 3D SSPP, which computed compressive and shear forces at the L5-S1 and L4-L5 spinal levels, as well as strength capability percentages for joints such as the torso, hips, and ankles. The results of these simulations were utilized in statistical analyses to evaluate the relationships among noise exposure, worker posture, and productivity.

Statistical Analysis

The experimental results were analyzed to determine (1) whether changes in working posture in response to varying construction noise levels are statistically significant from an ergonomic perspective, and (2) whether correlations among noise exposure levels, worker postures, and productivity are statistically significant. To address the first question, the Kruskal–Wallis test (McKnight and Najab 2010) was employed to compare biomechanical data across different groups defined by noise levels and working conditions (e.g., working height). This test was chosen because it is particularly suitable for handling data that do not follow a normal distribution, as was observed in this study. By examining differences in rankings between groups, the Kruskal–Wallis test assesses whether noise

levels significantly impact the biomechanical loads experienced by various body parts. For the second question, Pearson correlation analysis (Cohen et al. 2009) was conducted to examine the relationships between noise exposure levels, biomechanical risks, and worker productivity. This analysis calculates a correlation coefficient for each body part, thereby providing insight into which joints and body regions are most affected by noise exposure. In turn, it represents the relationship between risk and productivity for each body part. The significance of these correlations was evaluated using p -values to determine whether the observed relationships were statistically significant. These statistical methods offer valuable insights into how environmental factors, such as noise, induce significant changes in physical strain and productivity. Moreover, these methods facilitate the identification of potential impacts of environmental and physical factors on productivity during masonry tasks.

Results

This section presents the results that demonstrate the effects of various noise levels on worker posture and productivity during masonry operations. The experimental findings include quantitative biomechanical risk measures for the lower back (L5-S1 and L4-L5), wrists, elbows, shoulders, trunk, hips, knees, and ankles. The biomechanical risk for each body part was analyzed in conjunction with noise exposure levels and productivity measurements to provide a comprehensive assessment of the relationship among these three parameters.

Ergonomic Impact of Noise Exposure Levels on Worker Postures

To examine the ergonomic impact of noise exposure levels on worker posture, the biomechanical assessment results were categorized according to each noise level (Table 2). Overall, increasing noise levels negatively affected biomechanical risks for most body parts. Specifically, the loads of the lower back regions such as L4-L5 and L5-S1 were 401.77 and 387.52 lb, respectively, at the lowest noise level (50 dB) and increased to 430.21 and 409.77 lb at the highest noise level (100 dB). For most other body parts such as wrist, elbow, torso, hip, knee, and ankle, the strength capabilities decreased from 98.90%, 99.97%, 97.52%, 90.32%, 94.37%, and 72.26% to 98.85%, 99.95%, 96.82%, 89.11%, 92.61%, and 69.61%, respectively, when the noise level increased from 50 to 100 dB. These changes were statistically significant for most body parts based on the Kruskal–Wallis test (Table 3). Specifically, the results at the lower back regions (i.e., L5-S1 and L4-L5), wrists, elbows, torso, knees, and ankles had p -values of less than 0.05, indicating statistically significant changes in their response to noise level variations. These results imply that noise exposure significantly impacted the lower back and major joints, which contributed to the stability and movement of individuals during masonry tasks. However, for shoulders, the strength capabilities did not follow the decreasing trend; the results were 99.00% at 50 dB and 99.07% at 100 dB. This change also was not statistically significant, with a p -value of 0.608. This reason for this result may be that the compensatory postural adjustments or localized muscle activation may reduce shoulder strain under noisy conditions, differentiating its response from those of other joints.

In addition, biomechanical assessments also were conducted for each layer of the masonry stack [Fig. 1(a)] due to the fact that changes in working height affect posture and load distribution, potentially imposing varying levels of biomechanical risk on

Table 2. Results of biomechanical analysis under various noise levels

Noise level (dB)	Biomechanical analysis results								
	L5-S1 [N (lb)]	L4-L5 [N (lb)]	Wrist (%)	Elbow (%)	Shoulder (%)	Torso (%)	Hip (%)	Knee (%)	Ankle (%)
50	1,723.77 (387.52)	1,787.16 (401.77)	98.90	99.97	99.00	97.52	90.32	94.37	72.26
60	1,735.43 (390.14)	1,796.95 (403.97)	98.87	99.95	98.99	97.45	89.61	93.81	72.66
70	1,728.27 (388.53)	1,804.51 (405.67)	98.88	99.96	99.02	97.29	89.87	92.58	67.76
80	1,773.51 (398.70)	1,831.11 (411.65)	98.89	99.93	99.05	97.31	88.94	92.23	66.11
90	1,790.81 (402.59)	1,873.46 (421.17)	98.85	99.95	98.86	97.20	89.27	92.10	67.64
100	1,822.75 (409.77)	1,913.67 (430.21)	98.85	99.95	99.07	96.82	89.11	92.61	69.61

Table 3. Kruskal–Wallis test results for relationships between biomechanical assessment outcomes at each body part and noise levels

Body parts	<i>N</i>	Chi-squared	Kruskal–Wallis statistic (<i>H</i>)	df	<i>p</i> -value
L5-S1	—	19.696	19.696	5	0.001 ^a
L4-L5	—	32.696	32.696	5	0.001 ^a
Wrist	—	12.042	12.042	5	0.034 ^a
Elbow	—	13.176	13.176	5	0.022 ^a
Shoulder	3,072	3.603	3.603	5	0.608
Torso	—	27.359	27.359	5	0.001 ^a
Hip	—	9.998	9.998	5	0.075
Knee	—	12.213	12.213	5	0.032 ^a
Ankle	—	33.213	33.213	5	0.001 ^a

Note: *N* = number of samples collected from the experiments; chi-squared is a distribution used to compare variability of data; and Kruskal–Wallis statistic (*H*) is a test statistic that measures the difference in ranks between different groups.

^aStatistical significance (i.e., *p*-value < 0.05).

different body parts. Overall, increasing working heights (from Layer 1 to 4) reduced biomechanical stress, whereas increasing noise levels (from 50 to 100 dB) increased biomechanical stress (Table 4). For example, when the heights decreased from Layer 4 to Layer 1, the back compressions achieved average increases of 54.38% and 53.12% at L5-S1 and L4-L5, respectively. When the noise levels increased from 50 to 100 dB, the back compressions had the average increases of 5.62% and 6.93% at L5-S1 and L4-L5, respectively. For other body parts, the strength percentage capabilities of the wrists, shoulders, torso, hips, and knees consistently decreased when the heights decreased from Layer 4 to Layer 1, with reductions of 0.04%, 0.16%, 2.32%, 8.83%, and 3.96%, respectively. In contrast, when noise levels increased from 50 to 100 dB, the strength capabilities of the wrists, elbows, torso, hips, knees, and ankles had average decreases of 0.05%, 0.03%, 0.72%, 1.35%, 1.87%, and 3.62%, respectively. These results can be explained by the fact that the lower layer required more bending and twisting of the posture than the higher layer, resulting in higher biomechanical risk at all noise levels.

Furthermore, a higher noise level may increase physical strain on body parts, thereby raising the risk of musculoskeletal disorders and work-related injuries. However, for elbows and ankles, the strength percentage capabilities did not have a decreasing tendency when the heights decreased from Layer 4 to Layer 1; the average results were 99.94% and 67.84% at Layer 4 and 99.98% and 68.87% at Layer 1, respectively. These results could be due to the fact that elbows exhibited relatively low biomechanical risk, with strength capabilities of approximately 100%, and therefore were minimally affected by variations in height. Compared with core body parts such as the lower back and torso, which were directly affected by height variations, the ankles primarily functioned as stabilizers to maintain balance and distribute weight, and therefore were affected less directly by the bricklaying task at various heights. In addition, for shoulders, the strength capabilities did not have a decreasing trend when the noise levels increased from 50 to 100 dB; the average

results were 99.00% at 50 dB and 99.07% at 100 dB. This result implies that compensatory postural adjustments or localized muscle activation may reduce shoulder strain compared with that of other body parts, thereby decreasing the effect of noise variations on this part.

The Kruskal–Wallis test was applied to examine the effect of noise level variations on biomechanical risk across individual body parts during different layers of masonry work (Table 5). The results indicated significant changes in the lower back (L5-S1 and L4-L5), and this region was the most affected by increased noise levels. Statistically significant changes were observed at L5-S1 in both the first (*p* = 0.007) and second layers (*p* = 0.035), as well as at L4-L5 in both the first and second layers (*p* = 0.001). These findings support the conclusion that higher noise levels correspond to greater biomechanical loads on the lower back during masonry work. Additionally, work in lower layers, which necessitated more bending and twisting, was associated with the highest biomechanical risk to the lower back, particularly under high noise conditions. Other body parts also were affected by noise exposure. For example, the torso exhibited a significant change in the second layer (*p* = 0.001), suggesting that increasing noise levels contribute to postural stress in this region. However, certain body parts, such as the elbows and shoulders, did not have significant differences across layers. Specifically, the biomechanical risk at the shoulders remained relatively stable, with no significant differences between layers, suggesting that the shoulders may be less affected by noise exposure than the lower back or torso. These results emphasize the complex relationship between noise exposure, worker posture, and biomechanical risks during masonry work.

Correlations Among Noise Levels, Biomechanical Risks, and Productivity Measurements

Pearson's correlation analysis was performed to examine the significance, strength, and direction (positive or negative) of the

Table 4. Biomechanical assessment results by noise levels and working heights (stacking layers)

Biomechanical analysis results for each layer	Noise exposure level						(6)/ (1) (%)
	50 dB (1)	60 dB (2)	70 dB (3)	80 dB (4)	90 dB (5)	100 dB (6)	
L5-S1 [N (lb)] ^a							
(1) Layer 1	2,043.91 (459.49)	2,081.19 (467.87)	2,081.68 (467.98)	2,124.29 (477.56)	2,141.86 (481.51)	2,148.89 (483.09)	5.14
(2) Layer 2	1,865.23 (419.32)	1,919.58 (431.54)	1,894.67 (425.94)	1,926.48 (433.09)	1,918.61 (431.32)	2,014.02 (452.77)	7.98
(3) Layer 3	1,629.87 (366.41)	1,609.32 (361.79)	1,604.70 (360.75)	1,675.29 (376.62)	1,722.75 (387.29)	1,718.57 (386.35)	5.44
(4) Layer 4	1,355.95 (304.83)	1,331.53 (299.34)	1,332.02 (299.45)	1,367.96 (307.53)	1,380.02 (310.24)	1,409.42 (316.85)	3.94
(1)/(4) (%)	50.74	56.30	56.28	55.29	55.21	52.47	1.15
L4-L5 [N (lb)] ^a							
(1) Layer 1	2,126.34 (478.02)	2,151.74 (483.73)	2,175.62 (489.10)	2,199.64 (494.50)	2,238.57 (503.25)	2,273.26 (511.05)	6.91
(2) Layer 2	1,911.62 (429.75)	1,982.88 (445.77)	1,949.92 (438.36)	1,977.28 (444.51)	2,004.72 (450.68)	2,103.25 (472.83)	10.02
(3) Layer 3	1,699.62 (382.09)	1,660.12 (373.21)	1,678.05 (377.24)	1,717.95 (386.21)	1,788.81 (402.14)	1,789.74 (402.35)	5.30
(4) Layer 4	1,411.02 (317.21)	1,392.96 (313.15)	1,414.36 (317.96)	1,429.61 (321.39)	1,461.77 (328.62)	1,488.46 (334.62)	5.49
(1)/(4) (%)	50.70	54.47	53.82	53.86	53.14	52.73	1.35
Wrist (%)							
(1) Layer 1	98.89	98.82	98.84	98.90	98.85	98.84	−0.05
(2) Layer 2	98.88	98.87	98.89	98.86	98.85	98.84	−0.04
(3) Layer 3	98.90	98.87	98.87	98.91	98.84	98.83	−0.07
(4) Layer 4	98.92	98.92	98.91	98.88	98.87	98.87	−0.05
(1)/(4) (%)	−0.03	−0.01	−0.07	0.02	−0.02	−0.03	0.00
Elbow (%)							
(1) Layer 1	99.98	99.95	99.96	99.94	99.97	99.94	−0.04
(2) Layer 2	99.99	99.95	99.98	99.92	99.96	99.95	−0.04
(3) Layer 3	99.95	99.95	99.95	99.93	99.95	99.96	0.01
(4) Layer 4	99.97	99.93	99.95	99.91	99.93	99.93	−0.04
(1)/(4) (%)	0.01	0.02	0.01	0.03	0.04	0.01	0.00
Shoulder (%)							
(1) Layer 1	98.80	98.99	99.00	98.98	99.02	99.02	0.22
(2) Layer 2	99.02	98.77	98.90	99.04	99.02	99.04	0.02
(3) Layer 3	99.05	99.08	99.07	99.06	98.25	99.09	0.04
(4) Layer 4	99.13	99.13	99.11	99.13	99.14	99.14	0.01
(1)/(4) (%)	−0.33	−0.14	−0.11	−0.15	−0.12	−0.12	0.21
Torso (%)							
(1) Layer 1	96.50	96.35	95.91	96.38	96.02	95.39	−1.15
(2) Layer 2	97.25	97.02	96.93	96.95	96.91	96.23	−1.05
(3) Layer 3	97.84	97.95	97.88	97.66	97.59	97.37	−0.48
(4) Layer 4	98.48	98.47	98.45	98.25	98.28	98.30	−0.18
(1)/(4) (%)	−2.01	−2.15	−2.58	−1.90	−2.30	−2.96	−0.97
Hip (%)							
(1) Layer 1	86.90	85.46	86.33	84.41	85.26	86.33	−0.66
(2) Layer 2	88.45	87.45	87.50	86.91	87.40	85.96	−2.82
(3) Layer 3	91.59	91.35	91.09	90.75	90.29	90.49	−1.2
(4) Layer 4	94.34	94.17	94.54	93.70	94.12	93.66	−0.72
(1)/(4) (%)	−7.89	−9.25	−8.68	−9.91	−9.41	−7.83	0.07
Knee (%)							
(1) Layer 1	92.60	91.00	90.69	90.12	90.69	91.41	−1.29
(2) Layer 2	93.30	93.07	91.23	90.97	90.98	90.44	−3.07
(3) Layer 3	95.84	95.40	93.87	93.92	92.63	93.59	−2.35
(4) Layer 4	95.74	95.77	94.51	93.92	94.11	95.01	−0.76
(1)/(4) (%)	−3.28	−4.98	−4.04	−4.05	−3.63	−3.79	−0.53
Ankle (%)							
(1) Layer 1	70.82	69.00	69.86	65.43	67.10	71.03	0.3
(2) Layer 2	73.84	74.34	66.13	68.01	66.80	69.63	−5.7
(3) Layer 3	73.52	75.88	69.15	67.78	69.46	69.30	−5.74
(4) Layer 4	70.85	71.40	65.88	63.21	67.19	68.48	−3.35
(1)/(4) (%)	−0.04	−3.36	6.04	3.51	−0.13	3.72	3.77

^aStatistically significant difference ($p < 0.05$) between layer changes according to the Kruskal–Wallis analysis.

Table 5. Kruskal–Wallis test of noise level changes and biomechanical assessment results for each layer

Body parts ($N = 768$)	Kruskal–Wallis test results for each layer							
	Layer 1		Layer 2		Layer 3		Layer 4	
	H^a	p -value	H	p -value	H	p -value	H	p -value
L5-S1	16.02	0.007 ^a	12.00	0.035 ^a	8.62	0.125	4.18	0.524
L4-L5	30.99	0.001 ^a	21.93	0.001 ^a	9.98	0.076	4.20	0.521
Wrist	4.98	0.419	3.55	0.616	5.70	0.336	4.42	0.490
Elbow	3.93	0.559	9.64	0.086	1.48	0.916	4.26	0.513
Shoulder	4.41	0.492	4.55	0.473	7.95	0.159	0.81	0.977
Torso	10.09	0.073	20.82	0.001 ^a	13.77	0.017 ^a	5.14	0.399
Hip	8.99	0.110	3.18	0.672	4.65	0.460	7.07	0.216
Knee	0.49	0.992	3.92	0.562	8.40	0.135	5.11	0.402
Ankle	8.44	0.134	11.67	0.040 ^a	10.37	0.065	10.94	0.053

Note: Kruskal–Wallis statistic (H) is a test statistic that measures the difference in ranks between different groups.

^aStatistical significance at 0.05 level.

relationships between construction noise levels, worker postures, and productivity measurements. This analysis provided an in-depth understanding of the impact of noise-induced biomechanical stress on specific body parts and its subsequent effect on productivity. Noise levels exhibited a strong positive correlation with biomechanical stress in most body parts, particularly in the lower back (L5-S1 and L4-L5) and torso (Fig. 6). The results indicate positive associations between noise level and biomechanical stress for several regions, with comparatively stronger relationships observed for the lower back and torso than for some upper-extremity measures. Biomechanical stress in core regions also was associated with productivity, suggesting a potential pathway linking posture-related demands and task performance rather than confirming a mediation effect.

The Pearson correlation analysis primarily focused on three aspects: (1) the effect of noise levels on worker posture, (2) the effect of worker posture on productivity, and (3) the association between noise levels and productivity. The results revealed a statistically significant positive correlation between noise levels and biomechanical risks. In particular, the lower back (L5-S1 and L4-L5) exhibited strong positive correlations with noise levels, with correlation coefficients of 0.946 (p -value = 0.004) and 0.956 (p -value = 0.003), respectively. These findings suggest that increased noise levels are associated with greater compressive forces on the lower back, which may reflect noise-related attentional interference and increased task demand that disturb postural regulation during repetitive manual work. Under such conditions, workers may rely more heavily on trunk stabilization and whole-body balance control to maintain movement accuracy, thereby shifting biomechanical demand toward the lower back (Carey and Balasubramaniam 2025; Hockey 1997; Salihu et al. 2022). The torso also had a strong positive correlation (correlation coefficient = 0.917) with noise levels, which was statistically significant ($p = 0.009$). This pattern may reflect compensatory postural adjustments adopted to preserve stability and task performance in a noisy environment, particularly during repeated reaching and brick placement motions that require control of the upper body and trunk (Kachlan et al. 2025; Minino et al. 2023).

Similarly, the hips and knees had strong correlations, with correlation coefficients of 0.827 ($p = 0.042$) and 0.828 ($p = 0.042$), respectively. This indicates that noise exposure affects the lower body parts to a slightly lesser extent than the core region. In contrast, the arm regions, such as the wrists, elbows, and shoulders, did not have statistically significant correlations ($p = 0.069, 0.287$, and 0.989 , respectively). The relatively low impact on these joints may

be attributed to their primary role in facilitating accuracy and fine motor control, rather than bearing the significant loads associated with maintaining core stability during physically demanding tasks (Winter 2009). In summary, these results imply that noise levels have strong associations with major muscle groups and joints associated with core stability (e.g., lower back, torso, and hips), whereas other joints, such as the wrists and elbows, may be less sensitive to noise-induced strain during masonry work.

Second, the correlation between biomechanical risk and productivity had a consistent pattern, wherein posture-related stress was negatively associated with worker performance. This pattern was especially evident in core body parts, such as the lower back and torso, which likely contributed to a reduction in worker productivity. Specifically, the correlation between the lower back (L5-S1 and L4-L5) and productivity exhibited moderate negative correlations, with correlation coefficients of -0.591 for L5-S1 (p -value = 0.216) and -0.712 for L4-L5 (p -value = 0.113). Although these correlations did not achieve statistical significance, the results suggest that workers with greater biomechanical risk in the lower back tend to exhibit lower productivity. This relationship is particularly noteworthy, considering the critical role of the lower back in supporting core stability and managing the physical demands of tasks. For the torso, a strong and statistically significant relationship with productivity was observed, with a correlation coefficient of -0.834 (p -value = 0.039). This finding suggests that postural stress in the torso may hinder sustained task performance due to increased energy expenditure and diminished task concentration (Burns et al. 2017).

In addition to the lower back and torso, other body parts exhibited various relationships with productivity. Among these, the shoulders and elbows had weak negative correlations of -0.085 and -0.001 , respectively. These body parts were relatively less affected by noise exposure [Fig. 6(a)], which may explain the low correlation with productivity. Specifically, the shoulders were almost unaffected by noise exposure (i.e., correlation coefficient = 0.007), and their impact on productivity also was relatively low (i.e., correlation coefficient = -0.085). In contrast, certain body parts, such as the wrists, hips, knees, and ankles, had positive correlations with productivity. For example, the wrists exhibited a moderate positive correlation of 0.594, likely due to their role in fine motor control rather than overall productivity. Similarly, the hips, knees, and ankles had positive correlations of 0.335, 0.675, and 0.521, respectively. These lower-body joints are essential for stability and mobility; however, they did not exhibit biomechanical load levels sufficiently significant to statistically indicate their effect on

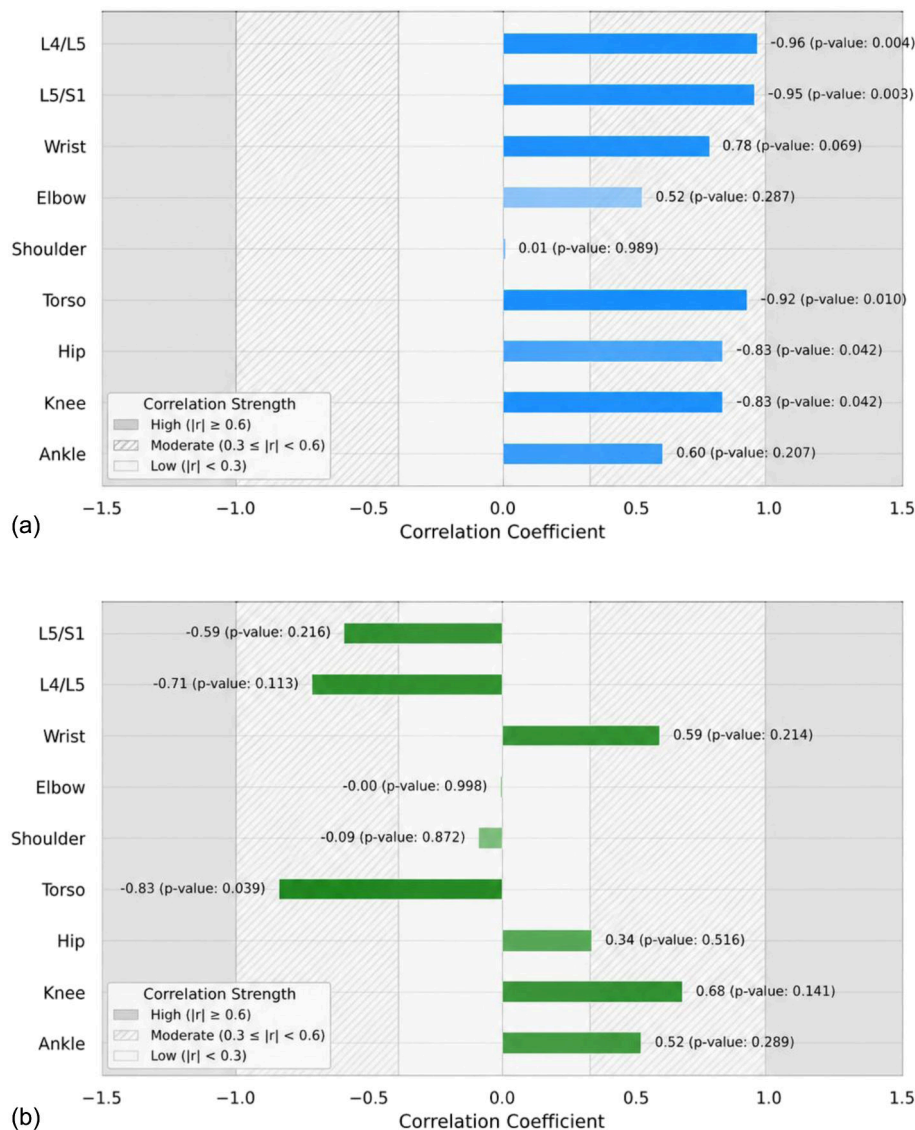


Fig. 6. Heatmaps of Pearson correlation analysis results: (a) correlation between biomechanical risk at individual body parts and noise levels; and (b) correlation between biomechanical risk at individual body parts and productivity measurements. (* indicates statistical significance at the 0.05 level.)

productivity (Altai et al. 2024). These results underscore the limited role of these body parts in productivity and highlight the importance of focusing on major body parts, such as the lower back and torso, for which more significant correlations were observed.

Lastly, the correlation coefficient between noise levels and productivity was -0.761 , indicating a moderately strong negative correlation. This result suggests that higher noise levels are associated with decreased productivity. However, this relationship did not reach statistical significance at the commonly accepted p -value of 0.05. Despite the lack of statistical significance, the finding implies that noise exposure may hinder concentration and motor coordination, both of which are critical for performing work, ultimately leading to reduced productivity (Li et al. 2016).

Discussion

The contributions of this study are fourfold. First, unlike previous studies that encountered challenges in investigating the relationships between noise exposure, WMSDs, and productivity in

field environments—in which various uncontrolled external factors (e.g., humidity and temperature) may influence WMSDs and productivity—this study was conducted in a controlled laboratory setting. This controlled environment enabled the evaluation of associations between noise exposure, posture-related biomechanical indicators, and productivity. Specifically, a controlled VR environment was employed to analyze biomechanical stresses on various body parts and productivity during masonry work at different noise levels.

Second, in contrast to previous studies that assessed WMSDs based on qualitative methods (e.g., surveys) and semiquantitative approaches (e.g., REBA and RULA), which hinder direct calculations of biomechanical forces, this study quantitatively evaluated posture-related biomechanical indicators at different body parts through biomechanical analysis. Notably, 3D SSPP was utilized to precisely quantify the stress on various body parts, facilitating body-part-specific comparison of posture-driven biomechanical changes under various noise levels.

Third, this study provides quantitative insights into the relationships between noise exposure, WMSDs in different body parts, and

productivity. For example, the results indicated that as noise levels increased, so too did the biomechanical load (i.e., postural stress), whereas productivity tended to decrease (Fig. 6). Consequently, strain on the lower back and trunk significantly increased with higher noise levels, whereas other body parts (e.g., shoulders) exhibited relatively stable biomechanical risks (Fig. 6).

These findings suggest that key body parts, such as the lower back and trunk, which are responsible for stability and movement during physically demanding tasks such as masonry work, are notably affected by various noise levels. Rather than indicating a direct causal relationship, this may be explained by the influence of noise on postural stability and cognitive resources (Carey and Balasubramaniam 2025; Juntunen et al. 1987). This can be explained by the possibility that high noise exposure increases attentional interference and mental workload during repetitive manual work, which may reduce the stability of postural regulation and movement coordination. To maintain task performance under these conditions, workers may adopt compensatory movement strategies that rely more heavily on trunk stabilization and altered body support patterns. In masonry tasks requiring repeated reaching, accurate placement, and whole-body balance control, these adjustments are more likely to be reflected in core regions such as the lower back and torso than in distal joints such as the wrist or elbow. These changes could increase biomechanical strain in core body regions during physical tasks. These results suggest that the lower back and torso, which are responsible for stabilizing the upper body during dynamic work, are particularly vulnerable to biomechanical strain under noisy conditions. This vulnerability may be partially attributed to the cognitive mechanisms through which noise affects postural control. For example, Carey and Balasubramaniam (2025) demonstrated that auditory noise under cognitive load impaired postural stability, and Salihu et al. (2022) showed that increased cognitive task complexity led to greater postural sway. These findings suggest that noisy environments can overload attentional resources, impairing balance control and increasing muscular strain in core body regions responsible for maintaining stability during physically demanding tasks.

Finally, this study proposes a strategy to mitigate the effects of noise on worker health by examining biomechanical stress under different working height conditions. The results demonstrated that most body parts experienced high stress levels when workers performed tasks at lower heights (Table 4). This finding suggests a potential strategy for reducing postural risks under various noise levels by optimizing working height.

Compared with prior studies that examined noise under broader or less-controlled conditions, this study provides noise-level-specific, body-part-specific quantitative characterization of biomechanical indicators and productivity within a controlled VR masonry task. For example, Ali et al. (2012) and Das (2020) surveyed the discomfort experienced in different body parts of sawmill workers in a high-noise environment (90–100 dB) (Ali et al. 2012), with an average noise level of 98 dB. The body parts most at risk were the lower back (87%), wrists (77%), and neck (73%) (Ali et al. 2012), and the lower back (91%), hands (80%), and shoulders (76%) (Das 2020). Similarly, Rwamamara and Simonsson (2009) reported high exposure levels for the back during concrete casting, with noise levels ranging from 78.4 to 112.5 dB. However, those studies did not accurately quantify biomechanical forces acting on different body parts at various noise exposure levels.

To address this gap, the present study quantitatively analyzed WMSDs in various body parts and productivity across noise levels of 50, 60, 70, 80, 90, and 100 dB. The results indicate that the lower back experienced the most significant effects at different noise levels, with L4-L5 and L5-S1 forces measuring 401.77 and 387.52 lb,

respectively, at 50 dB, and 430.21 and 409.77 lb, respectively, at 100 dB (Table 2). Additionally, a very strong positive correlation was observed between the L4-L5 and L5-S1 regions of the lower back and noise levels, with correlation coefficients of 0.956 and 0.946, respectively (Fig. 6). A negative correlation with productivity also was found, with correlation coefficients of -0.712 and -0.591 , respectively (Fig. 6). Furthermore, the correlation between noise levels and productivity was strongly negative, with a correlation coefficient of -0.761 (Fig. 6).

Overall, this study offers valuable insights into the relationships among noise exposure levels, WMSDs, and productivity. However, several limitations must be acknowledged. First, although VR can reproduce the visual sequence and spatial structure of masonry work in a controlled environment, it does not fully capture the actual mass, contact resistance, and haptic feedback associated with handling physical bricks. In this study, the experiment was not intended to reproduce the absolute physiological loading or full musculoskeletal demand of field masonry work. Rather, it was designed to compare posture-related biomechanical responses across different noise conditions while holding task geometry, wall layout, and visual guidance constant. Because the VR environment did not include physical brick handling, certain responses such as actual muscle activation and joint loading may differ from those in real work settings. Accordingly, the biomechanical results should be interpreted as posture-derived comparative estimates under controlled VR conditions rather than as direct quantification of the absolute physiological stress experienced during actual masonry work.

Cleworth et al. (2012) reported that virtual height exposure produced changes in balance-related postural responses similar to those observed under real height conditions, and Hu et al. (2011) found that 80.4% of elbow angle differences between virtual and real task settings were within 10%. Similar observations have been reported in other virtual ergonomics studies. Rizzuto et al. (2019) found that wrist, elbow, and shoulder joint angles at end-state postures were virtually identical between real and virtual environments, with mean differences of less than 0.5° across all joints. Homayounpour et al. (2021) showed that posture estimation in VR was within 10° of motion capture measurements in 81% of seated pick and place events for neck and trunk angles, with cross-correlation coefficients above 0.88. In the construction domain, Dias Barkokebas and Li (2021) further supported the applicability of VR-based ergonomic assessment by reporting approximately 86% accuracy in RULA and 80% accuracy in REBA relative to a physical mockup. Pontonnier et al. (2013) further demonstrated that posture-based ergonomic indicators, including RULA scores, had fairly good correlations between VR and real environments, with a correlation coefficient of 0.76, indicating that the relative trends of such indicators in VR are consistent with those in real environments. This is because posture-based biomechanical outputs are strongly influenced by body configuration, working height, reach pattern, and overall task geometry, even when all real-world force conditions are not fully reproduced. Accordingly, when the task sequence, spatial layout, and visual guidance are kept consistent across conditions, a VR-based task can support relative comparison of posture-related biomechanical differences even if the absolute physiological loading of real masonry work is not fully reproduced. Future studies should incorporate field-representative loading and acoustic conditions (e.g., physical props, haptic interfaces, and on-site noise measurements) to strengthen the transferability of the observed patterns.

Second, although the experiment did not include a prolonged exposure condition, it was designed to isolate short-term posture-related biomechanical responses to noise intensity while minimizing the influence of cumulative fatigue. To control for potential

order effects, participants were randomly assigned to one of two groups, with noise levels presented either in increasing order from 50 to 100 dB or in the reverse order from 100 to 50 dB. In addition, each task lasted approximately 5 min, and rest periods were provided between conditions. These procedures were implemented because the purpose of the experiment was to compare immediate posture-related biomechanical and productivity responses across noise levels under controlled conditions, rather than to evaluate cumulative exposure effects over an entire work shift. Although the 85-dBA criterion is defined for occupational exposure over an entire work shift, it was used in this study only as a reference point for selecting a construction relevant noise range, based on previous reports of full-shift construction noise exposures near or above this level. Therefore the brief noise exposures used in the present experiment should be interpreted separately from the occupational full shift exposure framework. Accordingly, the present results reflect posture-related biomechanical and productivity responses under brief controlled exposures rather than cumulative exposure effects over an entire work shift. In addition, because established WMSD evidence emphasizes cumulative physical exposures such as forceful exertions, repetition, and sustained nonneutral postures (Bernard 1997; Panel on Musculoskeletal Disorders and Workplace 2001), the present findings should be interpreted as posture-derived indicators of short-term responses under controlled noise conditions rather than as direct evidence of long-term WMSD outcomes. Prolonged exposure may involve additional influences, such as accumulated fatigue, sustained cognitive demand, and adaptation over time, which remain important considerations for future longitudinal research (Carey and Balasubramaniam 2025; McNeer et al. 2016; Rahimimoghadam et al. 2023; Salihu et al. 2022; Woollacott and Shumway-Cook 2002).

Finally, although the study sample (e.g., young males aged 22–34 years) provided a controlled group for examining noise effects on posture and productivity, this sample selection may limit the generalizability of the findings to the broader construction workforce, which includes varied ages, sexes, and physical characteristics. Differences in age and gender can influence how noise affects posture, musculoskeletal loading, and productivity; for example, older workers often have lower strength and slower reactions, and those with occupational noise exposure have shown poorer postural control and greater instability (Bazoni et al. 2022). Gender-related differences in body size and strength distribution also can alter lifting posture and coordination, because men and women use distinct trunk motion patterns during lifting (Lindbeck and Kjellberg 2001). Future studies can include a more representative construction workforce to examine interaction effects between noise, demographic characteristics, and work performance.

From a practical perspective, the relationships among noise exposure levels, WMSDs, and productivity examined in this study offer potential strategies for reducing postural risks and enhancing productivity. First, with regard to the reduction of postural risks, the results demonstrated a very strong positive correlation between noise exposure levels and postural risks across the entire body. Specifically, the correlation coefficients between increased noise exposure levels and increased biomechanical stress in the L5-S1 and L4-L5 regions of the lower back, torso, hips, and knees were 0.946, 0.956, 0.917, 0.827, and 0.828, respectively (Fig. 6). These findings underscore the necessity of managing the acoustic working environment or using personal protective equipment to protect workers from high noise levels, thereby minimizing postural risks.

Among various body parts, the lower back experienced the most significant effects from noise exposure, with biomechanical stresses in the L4-L5 and L5-S1 regions measuring 401.77 and 387.52 lb, respectively, at 50 dB, and 430.21 and 409.77 lb, respectively, at

100 dB (Table 2). Additionally, the biomechanical risk to the lower back increased as the height of the task decreased, irrespective of the noise level (Table 4). These results suggest that improving the working height could serve as an effective strategy for reducing postural risks, particularly in the lower back. Second, in terms of productivity improvement, the results revealed negative correlations between noise levels, biomechanical risks at the lower back, and productivity. Specifically, the correlation coefficient between noise levels and productivity was -0.761 , and the correlation coefficients between productivity and the L5-S1 and L4-L5 regions of the lower back were -0.591 and -0.712 , respectively (Fig. 6). These findings indicate that strategies aimed at reducing postural risks, such as managing the acoustic environment and optimizing working height, also may support productivity improvement under noisy working conditions.

Conclusion

This study examined the associations among construction noise, posture-related biomechanical indicators, and productivity in the context of masonry tasks, with a specific focus on how noise associated postural changes relate to work performance. The analysis demonstrated that increased noise levels were associated with postural changes, particularly in the lower back (L5-S1 and L4-L5) and torso, with comparatively greater posture-related biomechanical changes observed in these regions. These patterns also were associated with lower productivity, as reflected in the strong positive correlations between noise levels and posture-related biomechanical indicators in core body regions, together with the negative correlation between torso-related biomechanical demand and productivity. Accordingly, the findings suggest that posture-related biomechanical indicators may be relevant to understanding the observed associations between noise exposure and productivity under controlled experimental conditions. These findings emphasize the importance of managing occupational noise not only as an auditory hazard but also as a factor associated with posture-related biomechanical demand and work output.

Overall, the findings support treating occupational noise not only as an auditory hazard but also as an operational constraint that can affect sustainable work output through posture-sensitive physical demands. Accordingly, the evidence can inform intervention prioritization and work planning in noisy operations, such as identifying task segments in which exposure management and administrative measures may be most valuable. Future research could build on these findings by conducting long-term studies in real-world construction environments to assess the sustained effects of noise on posture and productivity. Furthermore, investigating the effectiveness of specific ergonomic solutions designed to alleviate noise-induced postural strain would further enhance the practical contributions of this study in improving worker health and project efficiency within the construction industry.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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Author Contributions

JinHyeok Lee: Formal analysis; Investigation; Methodology; Writing – original draft. ChungBae Yoon: Formal analysis; Methodology; Writing – original draft. Hieu T. T. L. Pham: Formal analysis; Methodology; Writing – original draft. Juwon Hong: Formal analysis; Investigation; Writing – original draft. Jinwoo Choi: Formal analysis; Investigation; Writing – original draft. Taehoon Hong: Conceptualization; Supervision; Writing – review and editing. Dong-Eun Lee: Funding acquisition; Resources; Writing – review and editing. SangUk Han: Conceptualization; Methodology; Supervision; Validation; Writing – review and editing.

References

- Abatement, U. S. O. N. 1974. *Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety*. Washington, DC: US Government Printing Office.
- Abbas, A., J. Seo, S. Ahn, Y. Luo, M. J. Wyllie, G. Lee, and M. Billingham. 2023. “How immersive virtual reality safety training system features impact learning outcomes: An experimental study of forklift training.” *J. Manage. Eng.* 39 (1): 04022068. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0001101](https://doi.org/10.1061/(ASCE)ME.1943-5479.0001101).
- Abrey, M., and J. Smallwood. 2014. “The effects of unsatisfactory working conditions on productivity in the construction industry.” *Procedia Eng.* 85 (Jan): 3–9. <https://doi.org/10.1016/j.proeng.2014.10.522>.
- Aktuğ, S. S., R. F. Ahmed, and M. Dağ. 2019. “A case study of erbil steel company workers in terms of non-auditory effects of industrial noise on worker productivity.” *Siirt Üniversitesi Sosyal Bilimler Enstitüsü Dergisi* 7 (13): 21–41.
- Ali, A., S. M. Qutubuddin, S. S. Hebbal, and A. C. S. Kumar. 2012. “An ergonomic study of work related musculoskeletal disorders among the workers working in typical Indian saw mills.” *Int. J. Eng. Res. Dev.* 3 (9): 38–45.
- Altai, Z., C. F. Hayford, A. T. Phillips, J. Moran, X. Zhai, and B. X. Liew. 2024. “Lower limb joint loading during high-impact activities: implication for bone health.” *JBM R Plus* 8 (11): ziae119. <https://doi.org/10.1093/jbmrlp/ziae119>.
- Ann Arbor, M. 2017. *3D static strength prediction program: User's manual*. Ann Arbor, MI: Univ. of Michigan.
- Anton, D., M. Bray, J. A. Hess, D. L. Weeks, L. D. Kincl, and A. Vaughan. 2020. “Prevalence of work-related musculoskeletal pain in masonry apprentices.” *Ergonomics* 63 (9): 1194–1202. <https://doi.org/10.1080/00140139.2020.1772380>.
- Bashir, M. T., A. Khan, R. Alrowais, M. A. Sikandar, M. M. H. Khan, B. Zamin, and F. Farid. 2024. “Evaluating the impact of environmental noise pollution on construction worker productivity in Peshawar, Pakistan: Justifying enforcement of noise regulation policies in the construction sector.” *J. Infrastruct. Policy Dev.* 8 (9): 6384. <https://doi.org/10.24294/jipd.v8i9.6384>.
- Bazoni, J. A., L. L. de Moraes Marchiori, D. S. A. Ciquinato, V. C. Puzzi, C. Pereira, D. de Castro Teixeira, and K. C. Furlanetto. 2022. “Impact of occupational noise on the postural control of older adults.” *Res. Soc. Dev.* 11 (16): e144111636336. <https://doi.org/10.33448/rsd-v11i16.36336>.
- Bernard, B. P., ed. 1997. *Musculoskeletal disorders and workplace factors: A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back*. Cincinnati: US Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.
- Borz, S. A., N. Talagai, M. Cheța, D. Chiriloiu, A. V. Gavilanes Montoya, D. D. Castillo Vizuete, and M. V. Marcu. 2019. “Physical strain, exposure to noise and postural assessment in motor-manual felling of willow short rotation coppice: Results of a preliminary study.” *Croatian J. For. Eng.: J. Theory Appl. For. Eng.* 40 (2): 377–388. <https://doi.org/10.5552/crojfe.2019.550>.
- Burns, J., C. Forde, and S. Dockrell. 2017. “Energy expenditure of standing compared to sitting while conducting office tasks.” *Hum. Factors* 59 (7): 1078–1087. <https://doi.org/10.1177/0018720817719167>.
- Buyuksalih, I., S. Bayburt, G. Buyuksalih, A. Baskaraca, H. Karim, and A. A. Rahman. 2017. “3D modelling and visualization based on the unity game engine—advantages and challenges.” *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.* 4 (Nov): 161–166. <https://doi.org/10.5194/isprs-annals-IV-4-W4-161-2017>.
- Carey, S., and R. Balasubramaniam. 2025. “Influence of cognitive demand and auditory noise on postural dynamics.” *Exp. Brain Res.* 243 (2): 54. <https://doi.org/10.1007/s00221-025-06998-w>.
- Carty, P., M. R. Cooper, A. Barr, R. L. Neitzel, J. Balmes, and D. Rempel. 2017. “The effects of bit wear on respirable silica dust, noise and productivity: A hammer drill bench study.” *Ann. Work Expo Health* 61 (6): 700–710. <https://doi.org/10.1093/annweh/wxx041>.
- Chaffin, D. B., G. B. Andersson, and B. J. Martin. 2006. *Occupational biomechanics*. Hoboken, NJ: Wiley.
- Chaharaghran, F., S. Tabatabaei, and S. Rostamzadeh. 2022. “The impact of noise exposure and work posture on job stress in a food company.” *Work* 73 (4): 1227–1234. <https://doi.org/10.3233/WOR-210872>.
- Cheța, M., M. V. Marcu, and S. A. Borz. 2018. “Workload, exposure to noise, and risk of musculoskeletal disorders: A case study of motor-manual tree felling and processing in poplar clear cuts.” *Forests* 9 (6): 300. <https://doi.org/10.3390/f9060300>.
- Cleworth, T. W., B. C. Horslen, and M. G. Carpenter. 2012. “Influence of real and virtual heights on standing balance.” *Gait Posture* 36 (2): 172–176. <https://doi.org/10.1016/j.gaitpost.2012.02.010>.
- Cohen, I., Y. Huang, J. Chen, J. Benesty, J. Benesty, J. Chen, Y. Huang, and I. Cohen. 2009. “Pearson correlation coefficient.” In *Noise reduction in speech processing*, 1–4. Berlin: Springer.
- Daneshmandi, H., A. R. Choobineh, H. Ghaem, M. Alhamd, and A. Fakherpour. 2017. “The effect of musculoskeletal problems on fatigue and productivity of office personnel: A cross-sectional study.” *J. Prev. Med. Hyg.* 58 (3): E252–E258. <https://doi.org/10.15167/2421-4248/jpmh2017.58.3.785>.
- Das, B. 2020. “Effects of awkward posture on work-related musculoskeletal disorders (WMSDs) among sawmill workers in India.” *J. Occup. Health Epidemiol.* 9 (3): 158–166. <https://doi.org/10.29252/johe.9.3.158>.
- Dias Barkokebas, R., and X. Li. 2021. “Use of virtual reality to assess the ergonomic risk of industrialized construction tasks.” *J. Constr. Eng. Manage.* 147 (3): 04020183. [https://doi.org/10.1061/\(ASCE\)CO.1943-7862.0001997](https://doi.org/10.1061/(ASCE)CO.1943-7862.0001997).
- Entzel, P., J. Albers, and L. Welch. 2007. “Best practices for preventing musculoskeletal disorders in masonry: Stakeholder perspectives.” *Appl. Ergon.* 38 (5): 557–566. <https://doi.org/10.1016/j.apergo.2006.08.004>.
- Faber, G., I. Kingma, P. Kuijter, H. Van der Molen, M. Hoozemans, M. Frings-Dresen, and J. Van Dieën. 2009. “Working height, block mass and one-vs. two-handed block handling: The contribution to low back and shoulder loading during masonry work.” *Ergonomics* 52 (9): 1104–1118. <https://doi.org/10.1080/00140130902915947>.
- Fang, H.-S., S. Xie, Y.-W. Tai, and C. Lu. 2017. “RMPE: Regional multi-person pose estimation.” In *Proc., IEEE Int. Conf. on Computer Vision*, 2334–2343. New York: IEEE.
- Fernández, M. D., S. Quintana, N. Chavarría, and J. A. Ballesteros. 2009. “Noise exposure of workers of the construction sector.” *Appl. Acoust.* 70 (5): 753–760. <https://doi.org/10.1016/j.apacoust.2008.07.014>.
- Habibi, E., H. Dehghan, S. E. Dehkordy, and M. R. Maracy. 2013. “Evaluation of the effect of noise on the rate of errors and speed of work by the ergonomic test of two-hand co-ordination.” *Int. J. Prev. Med.* 4 (5): 538–545.
- Hess, J. A., L. Kincl, T. Amasay, and P. Wolfe. 2010. “Ergonomic evaluation of masons laying concrete masonry units and autoclaved aerated

- concrete." *Appl. Ergon.* 41 (3): 477–483. <https://doi.org/10.1016/j.apergo.2009.10.003>.
- Hockey, G. R. J. 1997. "Compensatory control in the regulation of human performance under stress and high workload: A cognitive-energetical framework." *Biol. Psychol.* 45 (1–3): 73–93. [https://doi.org/10.1016/S0301-0511\(96\)05223-4](https://doi.org/10.1016/S0301-0511(96)05223-4).
- Homayounpour, M., D. Butter, S. Vasta, and A. Merryweather. 2021. "Validation of an inverse kinematic VR manikin in seated tasks: Application in ergonomics training." In *Proc., Congress of the Int. Ergonomics Association*, 367–373. Cham, Switzerland: Springer.
- Hong, J., J. Choi, J. Lee, S. Cho, T. Hong, S. Han, H. S. Park, and D.-E. Lee. 2023. "Virtual reality-based analysis of the effect of construction noise exposure on masonry work productivity." *Autom. Constr.* 150 (Jun): 104844. <https://doi.org/10.1016/j.autcon.2023.104844>.
- House, R. A., J. T. Sauvé, and D. Jiang. 2010. "Noise-induced hearing loss in construction workers being assessed for hand-arm vibration syndrome." *Can. J. Public Health* 101 (May): 226–229. <https://doi.org/10.1007/BF03404378>.
- Hu, B., L. Ma, W. Zhang, G. Salvendy, D. Chablat, and F. Bennis. 2011. "Predicting real-world ergonomic measurements by simulation in a virtual environment." *Int. J. Ind. Ergon.* 41 (1): 64–71. <https://doi.org/10.1016/j.ergon.2010.10.001>.
- Jung, S. W., J.-H. Lee, K.-J. Lee, and H.-R. Kim. 2019. "Association between occupational physicochemical exposures and headache/eye-strain symptoms among Korean indoor/outdoor construction workers." *Saf. Health Work* 10 (4): 437–444. <https://doi.org/10.1016/j.shaw.2019.09.004>.
- Juntunen, J., J. Ylikoski, M. Ojala, E. Matikainen, M. Ylikoski, and E. Vaheri. 1987. "Postural body sway and exposure to high-energy impulse noise." *Lancet* 330 (8553): 261–264. [https://doi.org/10.1016/S0140-6736\(87\)90840-3](https://doi.org/10.1016/S0140-6736(87)90840-3).
- Kachlan, A., S. A. Lavender, and C. Sommerich. 2025. "The effects of cognitive load and task precision restrictions on trunk and shoulder kinematics in a manual material handling task." *Int. J. Ind. Ergon.* 109 (Sep): 103795. <https://doi.org/10.1016/j.ergon.2025.103795>.
- Kerns, E., E. A. Masterson, C. L. Themann, and G. M. Calvert. 2018. "Cardiovascular conditions, hearing difficulty, and occupational noise exposure within US industries and occupations." *Am. J. Ind. Med.* 61 (6): 477–491. <https://doi.org/10.1002/ajim.22833>.
- Koushki, P., N. Kartam, and N. Al-Mutairi. 2004. "Workers' perceptions and awareness of noise pollution at construction sites in Kuwait." *Civ. Eng. Environ. Syst.* 21 (2): 127–136. <https://doi.org/10.1080/10286600310001642839>.
- Kristiansen, J., S. P. Lund, R. Persson, H. Shibuya, P. M. Nielsen, and M. Scholz. 2014. "A study of classroom acoustics and school teachers' noise exposure, voice load and speaking time during teaching, and the effects on vocal and mental fatigue development." *Int. Arch. Occup. Environ. Health* 87 (8): 851–860. <https://doi.org/10.1007/s00420-014-0927-8>.
- Lee, S. C., J. H. Kim, and J. Y. Hong. 2019. "Characterizing perceived aspects of adverse impact of noise on construction managers on construction sites." *Build. Environ.* 152 (Apr): 17–27. <https://doi.org/10.1016/j.buildenv.2019.02.005>.
- Leensen, M., J. Van Duivenbooden, and W. Dreschler. 2011. "A retrospective analysis of noise-induced hearing loss in the Dutch construction industry." *Int. Arch. Occup. Environ. Health* 84 (5): 577–590. <https://doi.org/10.1007/s00420-010-0606-3>.
- Lewkowski, K., I. W. Li, L. Fritschi, W. Williams, and J. S. Heyworth. 2018. "A systematic review of full-shift, noise exposure levels among construction workers: Are we improving?" *Ann. Work Expo Health* 62 (7): 771–782. <https://doi.org/10.1093/annweh/wxy051>.
- Li, K., and X. Zhang. 2009. "Can relative strength between the back and knees differentiate lifting strategy?" *Hum. Factors* 51 (6): 785–796. <https://doi.org/10.1177/0018720809360801>.
- Li, X., Z. Song, T. Wang, Y. Zheng, and X. Ning. 2016. "Health impacts of construction noise on workers: A quantitative assessment model based on exposure measurement." *J. Cleaner Prod.* 135 (Nov): 721–731. <https://doi.org/10.1016/j.jclepro.2016.06.100>.
- Lindbeck, L., and K. Kjellberg. 2001. "Gender differences in lifting technique." *Ergonomics* 44 (2): 202–214. <https://doi.org/10.1080/00140130120142>.
- Ljungberg, J., G. Neely, and R. Lundström. 2004. "Cognitive performance and subjective experience during combined exposures to whole-body vibration and noise." *Int. Arch. Occup. Environ. Health* 77 (3): 217–221. <https://doi.org/10.1007/s00420-003-0497-7>.
- Luijsterburg, P. A., P. M. Bongers, and E. M. de Vroome. 2005. "A new bricklayers' method for use in the construction industry." *Scand. J. Work Environ. Health* 31 (5): 394–400. <https://doi.org/10.5271/sjweh.923>.
- Luo, Y., Q. Yang, J. Seo, and S. Ahn. 2024. "Theoretical framework for utilizing eye-tracking data to understand the cognitive mechanism of situational awareness in construction hazard recognition." *J. Manage. Eng.* 40 (4): 04024027. <https://doi.org/10.1061/JMENEAM.ENG-5905>.
- Luttmann, A., M. Jäger, and W. Laurig. 1991. "Task analysis and electromyography for bricklaying at different wall heights." *Int. J. Ind. Ergon.* 8 (3): 247–260. [https://doi.org/10.1016/0169-8141\(91\)90036-L](https://doi.org/10.1016/0169-8141(91)90036-L).
- Marras, W. S., S. A. Lavender, S. E. Leurgans, F. A. Fathallah, S. A. Ferguson, W. Gary Allread, and S. L. Rajulu. 1995. "Biomechanical risk factors for occupationally related low back disorders." *Ergonomics* 38 (2): 377–410. <https://doi.org/10.1080/00140139508925111>.
- McKnight, P. E., and J. Najab. 2010. "Kruskal-wallis test." In *The corsini encyclopedia of psychology*. Hoboken, NJ: Wiley.
- McNeer, R. R., C. L. Bennett, and R. Dudaryk. 2016. "Intraoperative noise increases perceived task load and fatigue in anesthesiology residents: A simulation-based study." *Anesth. Analg.* 122 (2): 512–525. <https://doi.org/10.1213/ANE.0000000000001067>.
- Minino, R., A. Romano, E. Troisi Lopez, M. Liparoti, P. Sorrentino, and A. Fratini. 2023. "The effects of vibratory and acoustic stimulations on postural control in healthy people: A systematic review." *Ann. Biomed. Eng.* 51 (4): 643–659. <https://doi.org/10.1007/s10439-023-03136-x>.
- Moore, B. C. 2014. "Development and current status of the 'Cambridge' loudness models." *Trends Hear.* 18 (Sep): 2331216514550620. <https://doi.org/10.1177/2331216514550620>.
- Moosavi, M. S., P. Raimbaud, C. Guillet, and F. Mérienne. 2024. "Enhancing weight perception in virtual reality: an analysis of kinematic features." *Virtual Reality* 28 (2): 72. <https://doi.org/10.1007/s10055-024-00948-7>.
- Mustapha, Z., B. B. Akomah, and J. Baiden. 2022. "Impact of work-related musculoskeletal disorders among construction workers in Ghana." *Balt. J. Real Estate Econ. Constr. Manage.* 10 (1): 129–139. <https://doi.org/10.2478/bjreem-2022-0009>.
- Neitzel, R., N. S. Seixas, J. Camp, and M. Yost. 1999. "An assessment of occupational noise exposures in four construction trades." *Am. Ind. Hyg. Assoc. J.* 60 (6): 807–817. <https://doi.org/10.1080/00028899908984506>.
- Neitzel, R. L., B. Stover, and N. S. Seixas. 2011. "Longitudinal assessment of noise exposure in a cohort of construction workers." *Ann. Occup. Hyg.* 55 (8): 906–916. <https://doi.org/10.1093/annhyg/mer050>.
- Palikhe, S., M. Yirong, B. Y. Choi, and D.-E. Lee. 2020. "Analysis of musculoskeletal disorders and muscle stresses on construction workers' awkward postures using simulation." *Sustainability* 12 (14): 5693. <https://doi.org/10.3390/su12145693>.
- Panel on Musculoskeletal Disorders, and Workplace. 2001. *Musculoskeletal disorders and the workplace: Low back and upper extremities*. Washington, DC: National Academies Press.
- Paquet, V. L., L. Punnett, and B. Buchholz. 2001. "Validity of fixed-interval observations for postural assessment in construction work." *Appl. Ergon.* 32 (3): 215–224. [https://doi.org/10.1016/S0003-6870\(01\)00002-3](https://doi.org/10.1016/S0003-6870(01)00002-3).
- Park, S., S. Seong, Y. Ahn, and H. Kim. 2023. "Real-time fatigue evaluation using ecological momentary assessment and smartwatch data: An observational field study on construction workers." *J. Manage. Eng.* 39 (3): 04023008. <https://doi.org/10.1061/JMENEAM.ENG-4953>.
- Pavlo, D., C. Feichtenhofer, D. Grangier, and M. Auli. 2019. "3D human pose estimation in video with temporal convolutions and

- semi-supervised training." In *Proc., IEEE/CVF Conf. on Computer Vision and Pattern Recognition*, 7753–7762. New York: IEEE.
- Pontonnier, C., A. Samani, M. Badawi, P. Madeleine, and G. Dumont. 2013. "Assessing the ability of a vr-based assembly task simulation to evaluate physical risk factors." *IEEE Trans. Vis. Comput. Graphics* 20 (5): 664–674. <https://doi.org/10.1109/TVCG.2013.252>.
- Rahimimoghadam, S., S. Javan, S. Yari, A. Kheyrikhah, and M. Nourmohamadi. 2023. "Evaluation of exposure to noise and vibration and its effect on work-related fatigue." *Asian Pacific J. Environ. Cancer* 6 (1): 163–168. <https://doi.org/10.31557/apjec.2023.6.1.163-168>.
- Rizzuto, M. A., M. W. Sonne, N. Vignais, and P. J. Keir. 2019. "Evaluation of a virtual reality head mounted display as a tool for posture assessment in digital human modelling software." *Appl. Ergon.* 79 (Sep): 1–8. <https://doi.org/10.1016/j.apergo.2019.04.001>.
- Rwamamara, R., and P. Simonsson. 2009. "Health and safety in concrete casting processes." In Vol. 2 of *Proc., Annual ARCOM Conf.: 07/09/2009-09/09/2009*, edited by A. R. J. Dainty, 1253–1262. Reading, UK: Association of Researchers in Construction Management.
- Safety and Health. 1972. *Criteria for a recommended standard: Occupational exposure to noise*. Cincinnati: US Dept. of Health, Education, and Welfare, Health Services and Mental.
- Salihi, A. T., K. D. Hill, and S. Jaberzadeh. 2022. "Effect of cognitive task complexity on dual task postural stability: A systematic review and meta-analysis." *Exp. Brain Res.* 240 (3): 703–731. <https://doi.org/10.1007/s00221-021-06299-y>.
- Seixas, N., R. Neitzel, L. Sheppard, and B. Goldman. 2005. "Alternative metrics for noise exposure among construction workers." *Ann. Occup. Hyg.* 49 (6): 493–502. <https://doi.org/10.1093/annhyg/mei009>.
- Shah, S., and N. Nanavati. 2024. "Impact of cognitive tasks on postural stability in young and older adults." *Egypt. J. Otolaryngol.* 40 (1): 182. <https://doi.org/10.1186/s43163-024-00739-6>.
- Shin, Y., D. Choi, H. Park, M. Lee, T. Hong, and C. Koo. 2024. "Impact of heat stress on individual cognitive states: Utilizing EEG metrics in immersive VR-based construction safety training." *J. Manage. Eng.* 40 (6): 04024057. <https://doi.org/10.1061/JMENEA.MEENG-6076>.
- Stürmer, T., S. Luessenhoop, A. Neth, M. Soyka, W. Karmaus, R. Toussaint, T. R. Liebs, and U. Rehder. 1997. "Construction work and low back disorder: Preliminary findings of the Hamburg construction worker study." *Spine* 22 (21): 2558–2563. <https://doi.org/10.1097/00007632-199711010-00018>.
- Szalma, J. L., and P. A. Hancock. 2011. "Noise effects on human performance: a meta-analytic synthesis." *Psychol. Bull.* 137 (4): 682. <https://doi.org/10.1037/a0023987>.
- Tadele, G. 2020. *Assessment of ergonomics risk factors and occupational injuries in building construction workers in Bahir Dar city*. Bahir Dar, Ethiopia: Bahir Dar Univ.
- Turnbull, P. R., and J. R. Phillips. 2017. "Ocular effects of virtual reality headset wear in young adults." *Sci. Rep.* 7 (1): 16172. <https://doi.org/10.1038/s41598-017-16320-6>.
- US Bureau of Labor Statistics. 2023. *Table R5. Annualized incidence rates for nonfatal occupational injuries and illnesses involving days away from work, restricted activity, or job transfer (DART), days away from work (DAFW), and days of restricted work activity, or job transfer (DJTR) per 10,000 full-time workers by industry and selected nature of injury or illness*. Survey of Occupational Injuries and Illnesses, Calendar Year 2021–2022 Survey Results. Washington, DC: US Department of Labor.
- Winter, D. A. 2009. *Biomechanics and motor control of human movement*. Hoboken, NJ: Wiley.
- Woollacott, M., and A. Shumway-Cook. 2002. "Attention and the control of posture and gait: A review of an emerging area of research." *Gait Posture* 16 (1): 1–14. [https://doi.org/10.1016/S0966-6362\(01\)00156-4](https://doi.org/10.1016/S0966-6362(01)00156-4).
- Xu, S., M. Sun, Y. Kong, W. Fang, and P. X. Zou. 2024. "VR-based technologies: Improving safety training effectiveness for a heterogeneous workforce from a physiological perspective." *J. Manage. Eng.* 40 (5): 04024032. <https://doi.org/10.1061/JMENEA.MEENG-6016>.