Ergonomic Characteristics of Expert Masons

JuHyeong Ryu, A.M.ASCE[1]; Bennett Banting[2]; Eihab Abdel-Rahman[3]; and Carl T. Haas, F.ASCE[4]

Abstract: Masons are aided by ergonomic inventions such as tools, processes, and equipment, yet they are still subjected to performing physically demanding and hazardous tasks at the worksite. Experienced masons have a high level of job satisfaction; however, they also experience a high rate of attrition during their training phase and do not, on average, experience as long of a working life as nonconstruction workers. By analyzing expert masons' performance, in terms of body kinematics and load levels, during various masonry activities, guidelines for the training of a safer and more productive generation of masons can be formulated. This study investigated expert masons' performance and ergonomic characteristics during seven common masonry activities. Specifically, eight expert masons with over 20 years of experience laid out 16.6 kg concrete masonry units (CMUs) to construct a standard wall, a reinforced wall, a wall in constraint space (under ceiling), and the first course. They also utilized individual and collaborative lifts to build a five-course wall using 23 kg CMUs and collaborative lifts to build the same configuration using 35.2 kg CMUs. Inertial motion capture systems captured their motion, and a biomechanical analysis determined the load experienced by major body joints in each activity. The present study contributes to the body of knowledge by providing insights into expert masons' distinctive ergonomic characteristics in seven common masonry activities. Our findings open the door to providing apprentices with improved training based on those characteristics. We quantified the impact of optimized work configurations (working height for picking up and laying down material at about waist level) on minimizing musculoskeletal risks. A more significant impact on masons' safety, health, and productivity is expected by applying expert masons' biomechanical strategies in designing and/or redesigning work systems for a safer generation of masons. **DOI: 10.1061/(ASCE)CO.1943-7862.0002434.**

Author keywords: Construction management; Masonry; Ergonomics; Training; Motion capture system.

Introduction

Masonry work systems have experienced a surge in innovation due to advances in materials, design, and automation. Masons, on the other hand, remain at the center of these deceptively simple systems due to the highly unique nature of their work. Masons perform physically strenuous and demanding manual tasks on a daily basis, including repetitive heavy lifts and awkward postures that lead to work-related musculoskeletal disorders (WMSDs) (Hess et al. 2010; Wang et al. 2015). Continued exposure to WMSD risks is linked to workers' injury and loss of workdays as well as health and economic costs (Cheng et al. 2013; Gatti et al. 2014). Experienced masons have a high level of job satisfaction; however, they also experience a high rate of attrition during their training phase and do not, on average, experience as long of a working life as nonconstruction workers.

Among construction trades, masonry had the highest rate of overexertion injuries resulting in days away from work at 66.5 per 10,000 full-time equivalent workers in 2010, which was more than double the overall rate for the construction field at 28.5 per 10,000 full-time equivalent workers (CPWR 2013). Although the rate of overexertion injuries decreased to 33.4 per 10,000 full-time equivalent workers in 2015, the combined rate for brick and stone masons was still the third highest between 2015 and 2017 (CPWR 2019).

Manual block and brick lifting, which is an integral part of masonry work, requires frequent and deep bending of the trunk, hips, and knees to lift and lay down heavy loads (Hess et al. 2010; van der Molen et al. 2004). Hess et al. (2010) estimate that block masons manually lift at least 200 concrete masonry units (CMU) per day. Considering that a standard CMU (dimensions: $0.19 \times 0.19 \times 0.39$ m) weighs 16.6 kg (CCMPA 2013), masons can manually lift over 3,300 kg per workday. Masons also spend up to 53% of their working time in a bending posture to pick up materials at or below knee level and 38% of their working time in awkward postures (Boschman et al. 2011). As a consequence, masons recorded severe low back injuries at 22 per full-time equivalent worker compared to 16.2 for all industries (CPWR 2018), along with a high rate of injuries to upper extremities (Boschman et al. 2012; Hess et al. 2020).

Occupational safety and health research has shown that less-experienced workers, including masonry apprentices, suffer more from workplace injuries than experienced workers (CPWR 2018; Okun et al. 2016; Ryu et al. 2020a). Continued exposure to occupational risks at an earlier career stage leads to involuntary early retirement. Coupled with the aging worker population, those factors

[1]Assistant Professor, Dept. of Industrial and Management Systems Engineering, West Virginia Univ., 1306 Evansdale Dr., Morgantown, WV 26506 (corresponding author). ORCID: https://orcid.org/0000-0001-5836-9968. Email: juhyeong.ryu@mail.wvu.edu

[2]Director of Technical Services, Canada Masonry Design Centre, 360 Superior Blvd., Mississauga, ON, Canada L5T 2N7. Email: Bbanting@canadamasonrycentre.com

[3]Professor, Dept. of System Design Engineering, Univ. Waterloo, 200 University Ave. West, Waterloo, ON, Canada N2M 0A9. ORCID: https://orcid.org/0000-0002-3709-7593. Email: eihab@uwaterloo.ca

[4]Professor, Dept. of Civil and Environmental Engineering, Univ. of Waterloo, 200 University Ave. West, Waterloo, ON, Canada N2M 0A9. Email: chaas@uwaterloo.ca

Note. This manuscript was submitted on February 8, 2022; approved on August 23, 2022; published online on October 31, 2022. Discussion period open until March 31, 2023; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

are driving a shortage of skilled craft workers. On the other hand, the construction industry in Canada is experiencing increased labor demand, with more than 309,000 new workers expected to be recruited, trained, and retained over the next decade (BuildForce Canada 2021). The United States is experiencing a similar trend with demand for masons, specifically, expected to result in 24,600 new hiring per year over the next decade (BLS 2021).

Given the burden of occupational injuries and the corresponding increase in labor demand, adequate training for current and new-hire masons is important in order to prevent WMSDs as well as improve work efficiency (Hess et al. 2020; Teizer et al. 2013). Workers acquire their skills and techniques through different sources of craft training, e.g., apprenticeship programs, community colleges, and firm-sponsored training (Albers et al. 1997; Wang et al. 2008). However, most of the current training frameworks are insufficient in terms of providing knowledge about ergonomic hazards and hands-on ergonomic training (Hess et al. 2020; Okun et al. 2016).

Expert workers consistently demonstrate the superior performance of tasks within their domain of expertise compared to novices, simultaneously achieving higher safety, lower occupational injuries, and higher productivity (Alwasel et al. 2017; Ryu et al. 2020a). As they gain more experience, workers structure and develop a set of knowledge and skills necessary to carry out their tasks (Authier et al. 1995, 1996). Identifying and analyzing advantageous strategies developed by experts can guide the training of a safer and more productive generation of masons.

To objectively evaluate the ergonomic aspects of workers' performance, it is essential to collect and analyze data pertaining to worker postures and motions due to their association with joint loads and WMSDs (NIOSH 2014). Inertial motion capture (IMC) systems have enabled the collection of a broad range of accurate motion data within the construction industry (Chen et al. 2017; Valero et al. 2016). They feature a set of inertial measurement units (IMU); this is a sensor platform integrating 3D accelerometers, gyroscopes, and magnetometers, firmly attached to the body, allowing for direct motion data collection without interfering with ongoing worksite tasks. Researchers utilized motion data sets collected from IMC systems for various applications in the construction industry, including ergonomic assessments (Diraneyya et al. 2021; Nath 2017; Ryu et al. 2018, 2020a, b, c; Valero et al. 2016, 2017) and recognition of construction activities (Joshua and Varghese 2014; Ryu et al. 2016, 2019) and physical exertion (Zhang et al. 2019a, b).

Integrating accurately collected motion data from IMC systems with ergonomic evaluation tools enables us to evaluate work strategies objectively. In previous work (Alwasel et al. 2017; Ryu et al. 2020a), we conducted biomechanical analysis on the construction of a standard CMU wall and reported quantitative estimates of masons' joint loads grouped by different experience levels. We found that journeyperson masons with more than 20 years of experience adopt ergonomically safer and more productive working methods than less-experienced masons. Identifying those methods, therefore, present the potential to improve training programs by transferring those skills to apprentices. Furthermore, those ergonomic measures play an important role in workplace design with a view to improving safety by reducing the workers' joint loads.

In this context, this study investigates the performance and ergonomic characteristics of expert masons during seven common masonry activities. Specifically, eight journeyperson masons laid five courses of a standard wall, two courses in a reinforced wall, three courses within a constrained space, and the first course using standard-sized (20 cm hollow unit weighing 16.6 kg) CMUs. They utilized individual and collaborative lifts to build a five-course wall using heavy CMUs (30 cm hollow unit) weighing 23 kg and collaborative lifts to build a five-course wall using very heavy CMUs (30 cm semihollow unit) weighing 35.2 kg. All tasks were completed while wearing motion capture suits to quantitatively evaluate joint loads. Biomechanical analysis was carried out to evaluate their joint loads and study their work techniques.

Backgrounds

Manual Materials Handling Training

Manual material handling tasks, such as CMU lifting and carrying, are common in various industries, including construction. Especially combined with heavyweight, the manual handling or lift tasks significantly contribute to claims for WMSDs and their resultant cost (CPWR 2013). Indeed, in Ontario, Canada, alone, WMSDs are the leading cause of lost-time injuries, costing hundreds of millions of dollars due to worker absence and lost productivity (Ministry of Labour 2021).

To reduce exposure to risk factors associated with WMSDs, safety and ergonomic training have been considered a solution (Entzel et al. 2007; Lahiri et al. 2005); however, they are often underprioritized in worksites. For example, according to Choi (2012), 69% of construction companies in the United States had a lifting training program, and only 31% had an ergonomic program. Furthermore, while construction apprentices particularly require ergonomics training early in their careers to recognize and reduce the cumulative risk exposures leading to WMSDs, ergonomics training is insufficient in apprenticeship programs (Kincl et al. 2016).

One of the challenges with ergonomics training is the lack of transfer of learning to the work environment or other untrained tasks due to its less relevance to real-world work settings and insufficient integration of multidisciplinary knowledge (Clemes et al. 2010; Haslam et al. 2007). However, emphasizing expert work strategies in training programs can limit exposure to biomechanical risks (Gagnon 2003). Furthermore, previous studies that compared experts' and novices' work strategies have found that experts adopted different strategies, leading to higher safety, health, and productivity simultaneously (Authier et al. 1995, 1996; Ryu et al. 2020a, d, 2022). Therefore, ergonomics training reflecting experts' work strategies is essential because current ergonomics training programs have a limitation in transferring learning to workplaces and performing untrained tasks.

Expert Manual Material Handling Strategies

Given that experts' strategies are a significant indication for safer and more productive working methods, adopting them for ergonomics training programs and work interventions has significant potential, especially for apprentices, to prevent and reduce occupational injuries (Plamondon et al. 2010). To objectively determine the work strategies, biomechanical analysis has been considered a practical solution because it provides a quantitative evaluation of safer working methods by estimating body loads (Gagnon 2005; Ryu et al. 2020a).

Previous studies have been interested in comparing biomechanical differences (e.g., spinal moments acting on the L5/S1 vertebrae and shoulder moments) of different lifting movements during manual material handling tasks (Harari et al. 2019, 2020). Plamondon et al. (2010, 2012, 2014), and Gagnon (2003) particularly investigated an experience-based biomechanical analysis of manual handling strategies. They showed that estimated joint loads on the body segments provide a quantitative evaluation of safer working methods. However, experimentally validated studies were limited to laboratory environments under restrictive conditions.

To better understand the experts' biomechanical work strategies while heavy material handling tasks in masonry, it is critical to study comprehensive biomechanical analysis with actual masonry activities. Our previous studies (Ryu et al. 2020a), using an extended dataset of the current study, examined the difference in loads at major body joints among four different experience groups of masons while they completed a standard prebuilt CMU lead wall using 45 CMUs. The journeyperson group had significantly lower joint loads than the less-experienced masons, confirming a one-way analysis of variance (Ryu et al. 2020a). Yet, to the best of our knowledge, no work has been reported regarding the expert masons' biomechanical analysis of different masonry activities other than in laboratory settings. The present study investigates expert masons' performance and ergonomic characteristics by assessing body loads while carrying out seven actual masonry activities to identify their unique biomechanical work strategies.

Research Methods

The overall research framework of the current study is shown in Fig. 1. It consists of (1) IMC calibration, (2) data collection and processing, and (3) biomechanical analysis. To collect whole-body motion data, we used wearable IMC systems from journeypersons masons. After wearing the IMC system, each participant carried out a calibration step to determine the sensor-to-body alignment and body segment length. Then, their motion data were collected while completing seven masonry activities, and the following sections described the details of each activity. Finally, the 3D Static Strength Prediction Program (3DSSPP) was utilized to calculate the body loads, namely, net joint compression forces and moments.

Participants

Ontario's masons complete a 3-year masonry apprenticeship program consisting of 780 h of in-school and 4,880 h of on-the-job training and work experience. Graduates of this program may then apply to become certified journeypersons. Eight journeypersons with over 20 years of experience each were recruited to collect motion data at the Canada Masonry Design Centre in Mississauga, Ontario. The reported average participant stature and weight were 179.63 ± 4.78 cm and 90.84 ± 12.03 kg, respectively. The study and its protocols were reviewed and approved by the Institutional Review Board (IRB) at the University of Waterloo.

Experimental Setup

The journeypersons completed seven common masonry activities in two sessions over the same day. In the first session, individual masons carried out four activities using standard-sized CMUs (dimensions: $0.19 \times 0.19 \times 0.39$ m) weighing 16.6 kg:

- Activity 1: Laying the 2nd to 6th courses in a prebuilt lead wall (standard wall) using 45 CMUs, Fig. 2(a). The prebuilt wall consisted of 27 standard CMUs.
- Activity 2: Laying two courses of a reinforced wall (reinforced wall). Upon completion of Activity 1, seven units along the 6th course were removed by study personnel. Steel reinforcing bars were inserted into the cells of the 5th course CMUs. The reinforcement bars extended approximately 800 mm above the 5th-course level, Fig. 2(b). Participants laid the 6th and 7th courses, using 13 full and 2 half units to complete this activity. The study considered only the full units and excluded the half units from the analysis. This configuration represents a realistic maximum height a mason would be required to perform a lift over reinforcement bars.
- Activity 3: Laying three courses within a constrained space (constrained space). Following the completion of Activity 2, the reinforcement bars were removed, and a temporary ceiling was placed approximately 625 mm above the top of the 7th course, Fig. 2(c). Participants laid courses 8 through 10 using 20 full units and 2 half units to complete this activity. This setup simulates the final courses of an unreinforced partition wall built up to the underside of a floor slab. In this configuration, all CMUs being laid were above the shoulder/head height.
- Activity 4: Laying the first course in front of the prebuilt wall (first course). Participants laid seven standard CMUs directly on the floor to form the first course of a wall, Fig. 2(d).

Those CMU construction activities were chosen based on the recommendation of instructors and technical staff at the Ontario Masonry Training Centre (OMTC) and the Canada Masonry Design Centre (CMDC) as representative of standard activities as well as activities conditions where masons may encounter awkward postures or elevated risk exposure. To carry out these activities, the participants retrieved the CMUs from three piles placed approximately one meter away from the lead wall and used mixed mortar provided by helpers in two mortar trays located between the piles. Between activities, participants had a 15-min break, while helpers modified the wall configuration for the next activity, such as installing reinforcements or a temporary ceiling. After completing Activity 4, the participants had an hour break.

In the second session, participants completed three activities using two sizes of heavy CMUs:

- Activity 5: Individual masons laid the 2nd to 6th courses in a prebuilt lead wall using l5 full unit and 5 half units of 30 cm

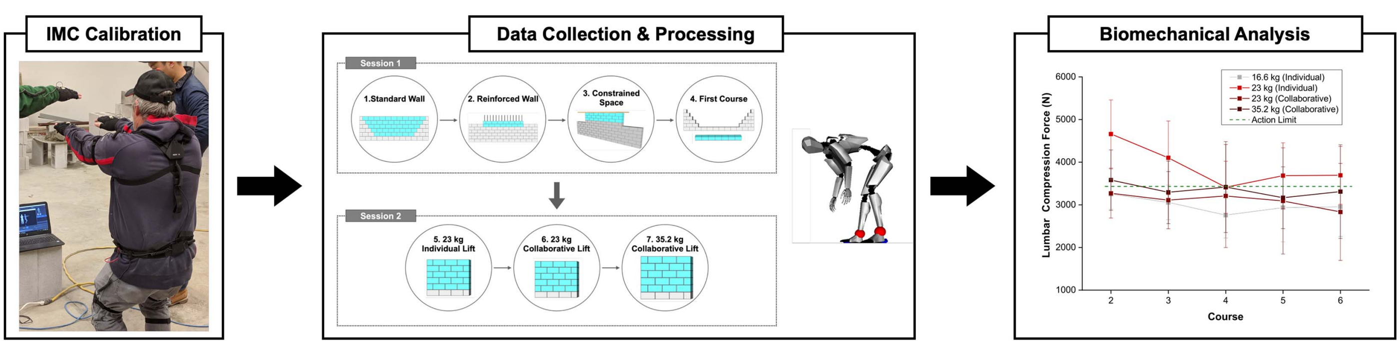

Fig. 1. Overall research framework.

Fig. 2. Experimental configuration: (a) standard wall; (b) reinforced wall; (c) constrained space; (d) first course; (e) individual heavy (23 kg) CMU lift; and (f) collaborative heavy (23 kg) CMU lift.

hollow CMUs weighing 23 kg and measuring $0.29 \times 0.19 \times 0.39$ m (individual heavy CMU lift), Fig. 2(e).

- Activity 6: Two masons collaboratively completed the same activity using the same 23 kg CMUs (collaborative heavy CMU lift), Fig. 2(f).
- Activity 7: Two masons collaboratively completed the same activity using 30 cm semisolid CMUs weighing 35.2 kg and measuring $0.29 \times 0.19 \times 0.39$ m (collaborative very heavy CMU lift).

The wall constructed in the second session contained artificial leads for the masons to use for their string line, as shown in Figs. 2(e and f). Considering the heavy and very heavy CMUs size and the lead wall width, the CMUs were placed in one pile approximately one meter away from the lead wall with one mortar board placed next to it. We found that these did not interfere with participants' movement or work methods during the experiment. Furthermore, the selected activities are most likely to daily encounter their workplaces, thereby minimizing the learning curve during the experiments.

Data Collection and Processing

Participants were equipped with a wireless motion capture suit, Perception Neuron (Noitom Ltd. 2017), to acquire whole-body motion data. The accuracy of the joint kinematics estimates obtained from this motion capture system was found comparable to that of the gold standard, optical motion capture systems. (Robert-Lachaine et al. 2020) found that the motion capture system had an acceptable error, under 5 degrees. Using a wireless and portable system, data collection did not appear to hinder or affect the participants' work techniques. The suit consists of 17 IMUs, and each of which is composed of a three-axis accelerometer, three-axis gyroscope, and three-axis magnetometer. Using elastic straps, the IMUs were secured to the head, back, shoulders, upper and lower arms, hands, thighs, legs, and feet.

Before the start of the experiment, all participants completed a calibration procedure (T-pose, A-pose, and S-pose) to establish the sensor-to-body alignment and body dimensions as directed by the motion capture software, Axis Neuron (Noitom Ltd. 2017). After calibration, the software samples data at a frequency of 125 Hz to reconstruct 3D human skeletal models. The system implements a Kalman filter followed by a proprietary algorithm to counteract sensor drift. For the purposes of segmentation and data processing, each session was recorded with a camcorder.

The manual block handling task is an integral part of masonry activities. Masons are frequently exposed to cumulative musculoskeletal injuries due to executing heavy CMU lifting (Ryu et al. 2020a). Therefore, this study primarily investigates the levels of risks in CMU lifting. We segmented the raw motion data file into individual CMU lifts. Each lift started at the moment a participant lifts a CMU and ended when the participant fully placed it in the wall. The number of segments varied according to activity, with the first course activity comprising seven lifts, the standard wall comprising 45 lifts, the reinforced wall comprising 13 lifts, and the constrained space activity comprising 20 Lifts. For the three activities in the second session, 15 lifts (23 and 35.2 kg CMUs) were segmented. Other actions undertaken during the experiment, such as spreading mortar and positioning the unit once laid, were not included in the analysis. For collaborative lifts, data for each mason were considered individually.

The data obtained from the motion capture suits were extracted as Biovision Hierarchy (BVH) files and segmented into local rotations and translations of 26 major body joints with respect to a root body joint, namely, the hip (Meredith and Maddock 2001). Next, using local transformation matrices based on the hierarchical kinematic structure of the human body, the global position (3D coordinates) of the body joint centers were computed in BVH Viewer (Lv 2006) and exported as a.txt file for each lift.

Biomechanical Analysis

Occupational biomechanics is commonly used to investigate the causes of workplace injury, especially concerning overexertion of the musculoskeletal systems (Chaffin 2009). This field devises biomechanical models and deploys them to quantify and analyze forces and moments on the human body during manual tasks in the workplace.

Software packages are commonly used to estimate the internal loads from biomechanical datasets describing the whole-body 3D motions (Seo et al. 2015). Our study used 3DSSPP to estimate joint loads, namely, net compression forces and moments, using a static biomechanical model (Center for Ergonomics at the University of Michigan 2016). To run 3DSSPP biomechanical analysis, the joint center positions (.txt files) obtained were converted using a MATLAB code to 'joint location files (.loc)' formatted following a hierarchical description of body joint center locations. Combining the participants' anthropometric parameters (stature and weight) with those joint location files, along with the external forces (CMU weight) they experience, 3DSSPP calculated compression force in the lumbar joint at the L4/L5 disc level and the joint moments in the elbow, shoulder, L5/S1 disc, hip, and knee joints.

Results

This study treats the motion sequence as a set of quasi-static postures. While this is a standard practice in ergonomic analysis, it neglects the inertial forces that develop during body motions. The analysis aim is to find the 'most critical posture', where peak force or moment is registered for a given joint, in each lift. The peak joint loads are then averaged across activity type and course height for all subjects and relevant lifts. Those averages are then compared across activity types and course heights. Therefore, the averages of the peak joint loads (i.e., most critical working postures) are investigated for each category.

Standard Weight CMUs

The first four activities employing standard weight CMUs span wall course heights from 1 to 10. Fig. 3 shows the peak lumbar compression force at each course height covered by these activities, namely, first course (F. 1), standard wall courses (S. 2-6), reinforced wall courses (R. 6-7), and constrained space courses (C. 8-10). The green dashed line represents the action limit (a load threshold of 3433 N) defined by NIOSH (1981). The journeyperson masons having over 20 years of work experience were found to maintain lumbar compression forces below the action limit, except when they completed the first course activity where they exceed that to reach 3893.4 N. Further, it was found that the subjects experienced similar or lower compression forces in the higher courses of the reinforced wall and constrained space to those of the standard wall.

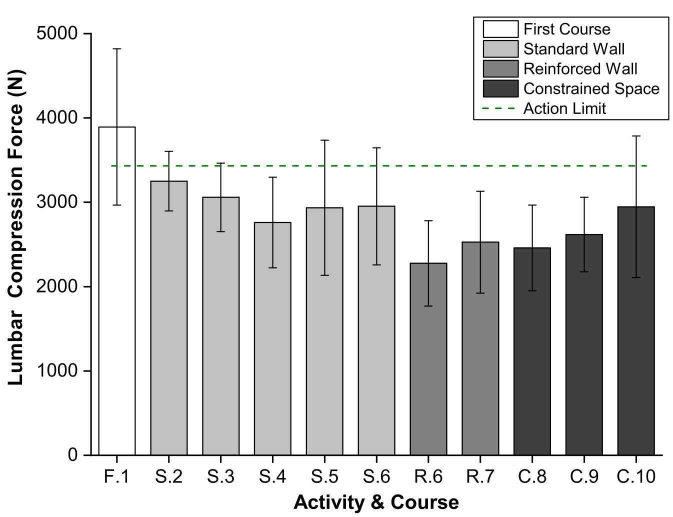

Fig. 3. Average peak lumbar compression force by activity and course.

The activities carried out in this session represent the extreme possibilities of CMU construction, where masons are most likely to encounter their workplaces. Participants, therefore, were familiar with performing the given activities, thereby minimizing the learning curve during the experiments. In addition, the lumbar compression forces were primarily affected by back bending postures and CMU weights. For example, while conducting the first course activity was the fourth order of the experiment, its average peak lumbar compression force was the highest among the other three activities in the first session.

The average peak moments of the shoulder, elbow, hip, and knee joint for each course are shown in Fig. 4. Shoulder moments were consistently higher than elbow moments. Both shoulders and elbow moments increased gradually with course level. In contrast, the lower limb joint (hip and knee) moments remained relatively constant, demonstrating no correlation with the activities or course levels except that the hips experienced elevated joint moments in the first two courses. This corresponds to the hip-hinged and squatting postures journeyperson masons adopted to lay CMUs at those courses.

The lift completion time was found to vary depending on activity type and course height. We compare the averaged lift completion time per course in Fig. 5. The standard wall was completed most efficiently at 3.06 s per CMU, while the reinforced wall and constrained space took significantly more time, 5.92 and 5.56 s, respectively. Interestingly, the time per lift increases with course height in reinforced walls and constrained spaces. However, this phenomenon was not the case for the standard walls with lift completion remaining stable.

Heavy Weight CMUs

Fig. 6 compares the average peak lumbar compression force during lay down of courses two to six of a prebuilt wall while individually lifting standard (16.6 kg) and heavy (23 kg) CMUs and collaboratively (two-person) lifting heavy (23 kg) and very heavy (35.2 kg) CMUs. The subjects experienced the highest lumbar compression force (3915.74 N) when they handled heavy (23 kg) CMUs individually. This was approximately 14% in excess of the action limit. The difference in the lumbar compression force between collaborative lifts of 23 kg and 35.2 kg CMUs was small despite a 50% difference in their weight.

Comparing the peak lumbar compression forces averaged by course shows that lifting heavier CMUs results in higher lumbar compression forces, Fig. 7. It also shows that the force variation with course height was similar for individual lifts of standard (16.6 kg) and heavy (23 kg) CMUs. Likewise, the force variation with course height for the collaborative lifts was similar for heavy (23 kg) and very heavy (35.2 kg) CMUs. While the compression force due to collaborative lifts decreased with course height, the compression force due to individual lifts reached a minimum at or below waist level (course 4). Moreover, the lumbar compression forces, during placement of CMUs at the fourth course, were below the action limit across all three CMU weights and similar to that when individually placing standard (16.6 kg) CMUs at the 2nd course.

The shoulder and elbow joint moments increased with course height, Fig. 8, irrespective of CMU size for individual and collaborative lifts. In contrast, knee and hip joint moments were relatively

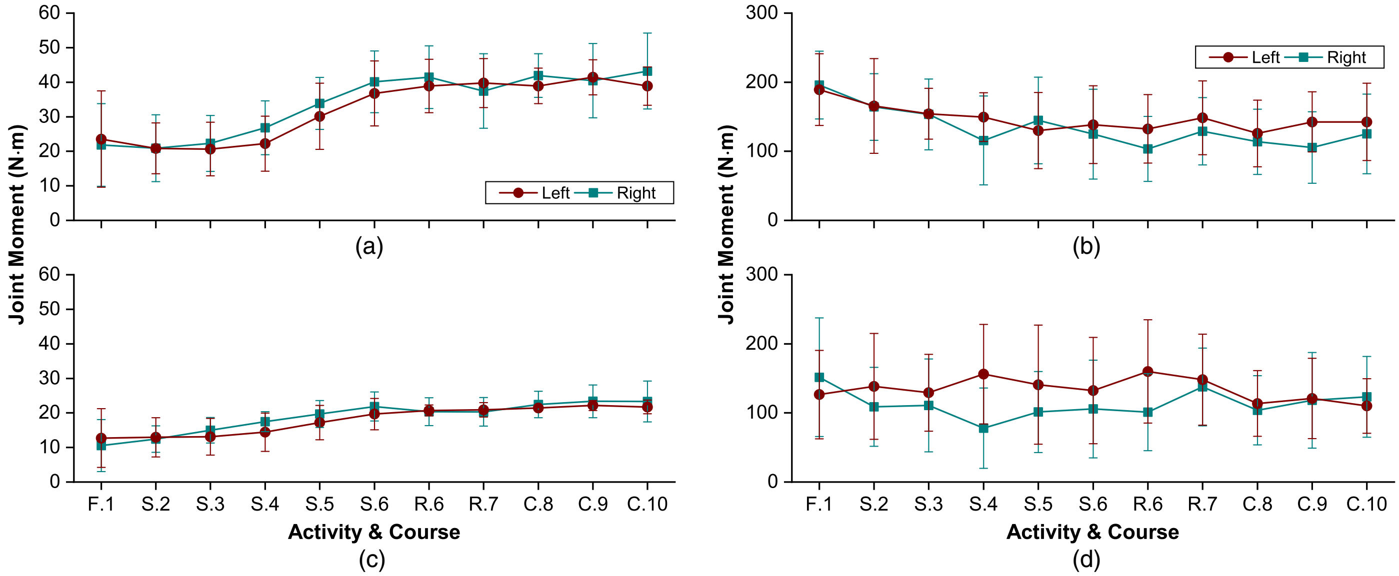

Fig. 4. Average peak joint moment for the: (a) shoulder; (b) elbow; (c) hip; and (d) knee joints.

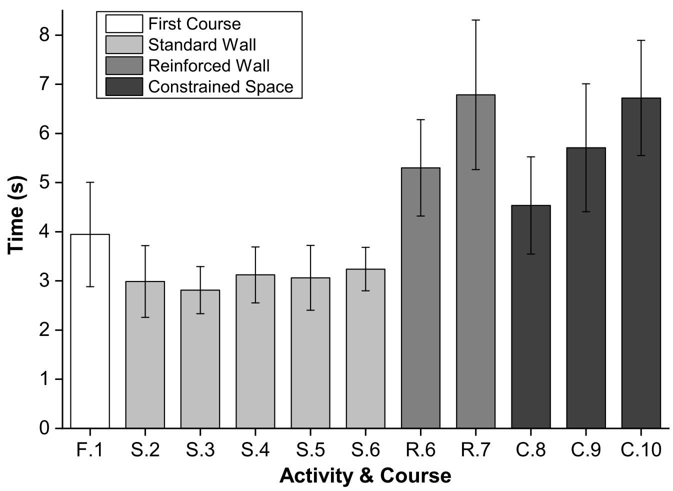

Fig. 5. Completion time per CMU lift averaged by activity and course.

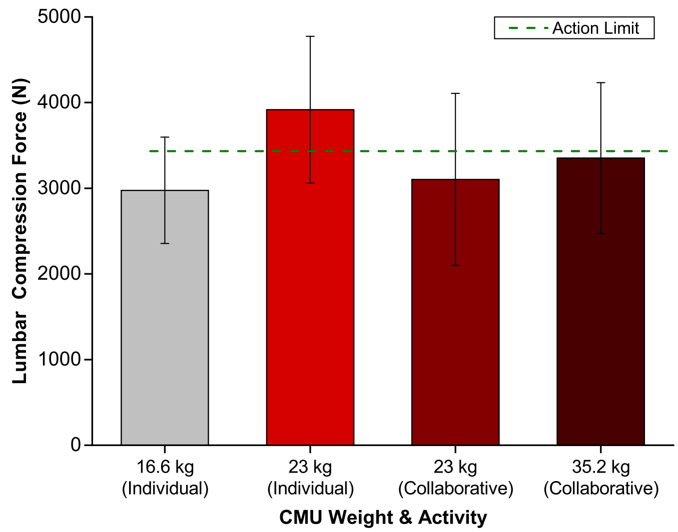

Fig. 6. Average peak lumbar compression forces by CMU weight.

unaffected by course height. Upper and lower limb joint moments were highest for individual lifts of heavy (23 kg) CMUs.

The lift completion times averaged by course for individual and collaborative lifts of the three CMU sizes are shown in Fig. 9. Participants spent the most time (5.36 s) and the least time (3.06 s) individually lifting heavy (23 kg) and standard (16.6 kg) CMUs, respectively. Collaborative lifts of heavy (23 kg) and very heavy (35.2 kg) CMUs resulted in similar completion times. The completion time of collaborative heavy (23 kg) CMU lifts varied among the courses, while that of very heavy (35.2 kg) CMU lifts remained constant. Participants carried out the heavy CMU lifts before the very heavy CMU lifts. This variation might be an artifact of a learning curve while the two participants synchronized their lift techniques.

Lift Technique

Journeyperson masons varied their CMU lift techniques depending on the activities they carried out. In this study, we define a mixed lift as one that involves stretches of one-handed and two-handed lifting, such as a midpoint switch between one and two-handed lifting or between a dominant and nondominant hand. Table 1 summarizes the percentage of each lift technique used in each of the seven activities. One-handed lifts were primarily used in laying the first course and during collaborative lifts. Expert masons opted for two-handed or mixed lifts in higher courses completed, individually including the reinforced wall and constrained space.

Discussion

Masons are at a high risk of WMSDs and frequently face involuntary early retirement following a lifetime of repetitive strain, heavy lifting, and awkward postures. By analyzing expert masons' performance, in terms of body kinematics and load levels during various masonry activities, we can formulate guidelines for the training

J. Constr. Eng. Manage., 2023, 149(1): 04022150

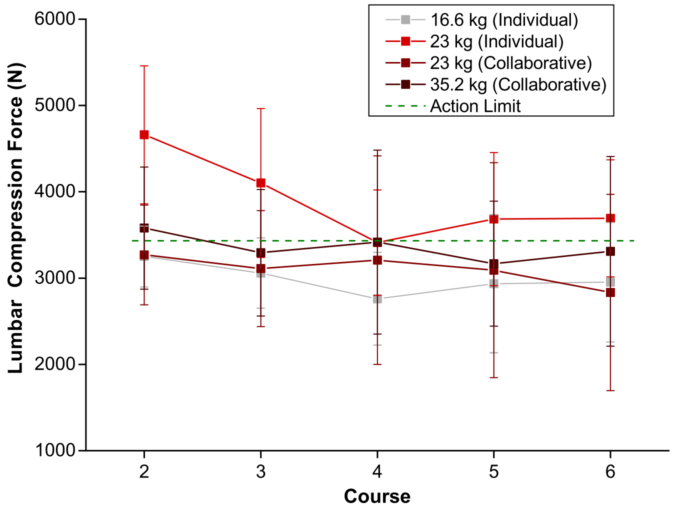

Fig. 7. Lumbar compression force for Lifts of standard, heavy, and very heavy CMUs averaged by course.

of a safer and more productive generation of masons. Toward that end, this study carried out a biomechanical analysis of eight expert masons during seven common masonry activities with three types of CMUs.

We found that the most critical body joints were those of the lower back (L4/L5 disc level) and upper limbs (shoulders and elbows). Repetitive strains at these joints may lead to low back pain (Adams et al. 2006), rotator cuff injuries (Steele et al. 2014), and other injuries requiring days away from work or, in severe cases, leading to retirement. The location of the critical joint was dependent on activity. Variations in the net moments of lower limb joints (hips and knees) were negligible across the activities and course heights examined in this work. They increased with CMU weights, particularly for individual lifts of heavy (23 kg) CMUs but remained within safe limits at all times.

In laying standard walls, lumbar compression forces were more critical than upper limb joint moments. Assuming safer postures, where masons maintain a straight back and hold the CMU closer to the body center, helps to keep those forces within the safe (action) limit (NIOSH 1981) regardless of course height.

The weight of heavy (23 kg) CMUs is equal to the recommended weight limit for individual lifts established by NIOSH (Waters et al. 1993). However, the average peak lumbar compression force for individual lifts of heavy (23 kg) CMUs was 15% higher than the NIOSH action limit, thus posing increased risks of lower back pain (Waters et al. 1993). On the other hand, the lumbar compression forces resulting from individual lifts of standard (16.6 kg) CMUs were below the action limit for all course heights.

Individual lifts of standard (16.6 kg) and heavy (23 kg) CMUs generated the highest lumbar compression force at the 2nd course and the lowest force at the 4th course. The height of the 2nd course is 40 cm from the floor. Placement of CMUs at this height requires significant back bending, resulting in elevated lumbar compression forces regardless of the CMU weight. On the other hand, the height of the 4th course is approximately 80 cm, corresponding to the waist level for 50-percentile males. Participants maintained a straight-back posture while slightly bending their knees when placing CMUs at the 4th course. This posture enabled them to hold even the heavy (23 kg) CMUs close to the center of the body. As a result, they experienced the lowest lumbar compression force at the 4th course. In fact, the lumbar compression force during individual heavy (23 kg) CMU lifts at the 4th course (3411 N) was below the action limit and similar to the force during the laying of standard (16.6 kg) CMU at the 2nd course (3298 N).

The lumbar compression force trends for collaborative lifts of heavy and very heavy CMUs (23 and 35.2 kg) were similar to each other but dissimilar to those of individual lifts. This is expected since body loads are a function of body posture and the relative position of the CMU with respect to the body. In individual lifts, participants maintained a symmetric posture with respect to the CMUs. In collaborative lifts, participants frequently adopted asymmetric body postures that limited their ability to control the position of the CMU relative to their body.

The shoulder joints were at higher risk than the lower back in reinforced wall and constrained space activities. In these activities, masons had to raise the CMUs above their shoulders or over their heads. Maintaining a straight back in this case was not challenging, but it did not protect the shoulder and elbow joints from exposure to the strains of awkward lifts. The exposure of the shoulders and elbows to ergonomic risk in these activities increases with course height as the net joint moments and lift completion time increase.

Further analysis reveals a monotonic increase in shoulder moments with CMU weight for individual (16.6 kg and 23 kg CMUs) and collaborative (23 kg and 35.2 kg CMUs) lifts. Heavier CMUs also led to higher upper limb moments in the standard wall activity, particularly when laying higher 5th and 6th courses. The increment was more pronounced in shoulder moments than elbow moments, particularly for heavier CMUs. To lay CMUs on these courses, masons have to extend their arms, resulting in large moment arms on their shoulders.

Expert masons were able to effectively distribute loads between the collateral joints of the upper limb (shoulder and elbow joints) during individual lifts. This is reflected in the fact that the trends of joint moments were identical across the two CMUs weights used for individual lifts. No obvious pattern emerges in the lightly loaded lower limb joints (hips and knees) where coordination is less critical. Similarly, no patterns emerge in load distribution between the upper limb joints in collaborative lifts. The left-side upper limb joints appear to carry higher loads than the right-side upper limb joints. Expert masons mostly adopted a one-handed lift technique during collaborative lifts, Table 1. Six out of eight participants in this study were right-handed. Elevated left-side joint loads may indicate the lower efficiency of lifts they performed with the left upper limb. Load coordination between the collateral joints in two-handed lifts and loads experienced by the carrying and free sides in one-handed lifts may merit further investigation.

Standard wall lifts were the most efficient with an average lift completion time of 3.06 s. Reinforced wall lifts at an average time of 5.92 s and constrained space lifts with an average time of 5.56 s were the least efficient due to the physical demands and awkward posture they require. While the CMU lift completion time varied by a maximum of 3 s, the cumulative time added with 200 CMUs laid per day per mason can be costly. Further studies on the relationship between cumulative joint loads and activity type are required.

The completion time of individual heavy (23 kg) CMU lifts was approximately 28% higher than the collaborative lift of the same CMU. However, when laying at the 4th course, the completion time differences between the two lifts were reduced to 13%. This shows that an appropriate masonry work system that maintains the laying height at about the waist will not only reduce the significant occupational injury risks associated with the individual laying of heavy CMUs but will also increase work efficiency.

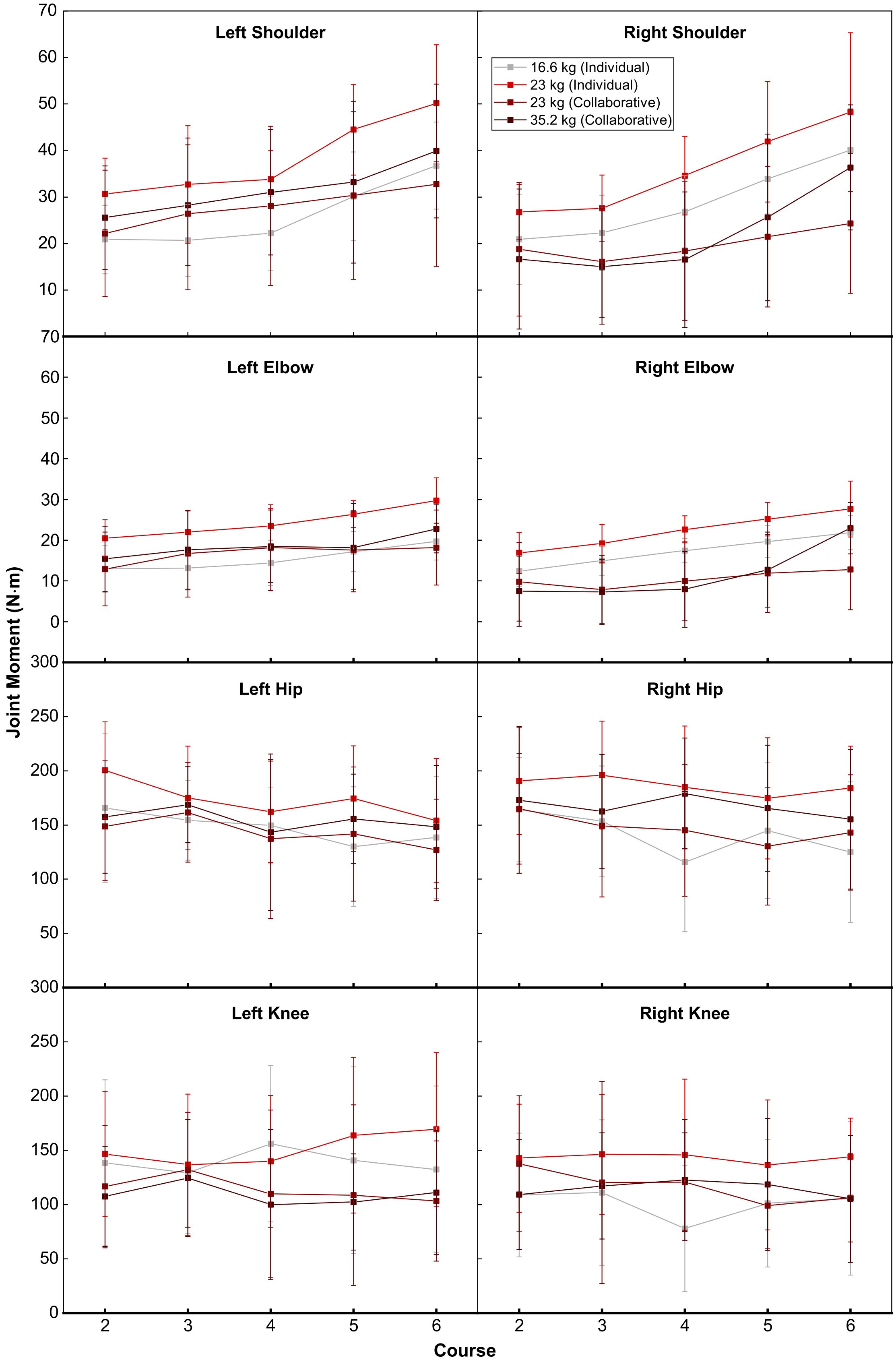

Fig. 8. Average peak moment for the shoulder, elbow, hip, and knee joints during individual and collaborative lifts of standard, heavy, and very heavy CMUs.

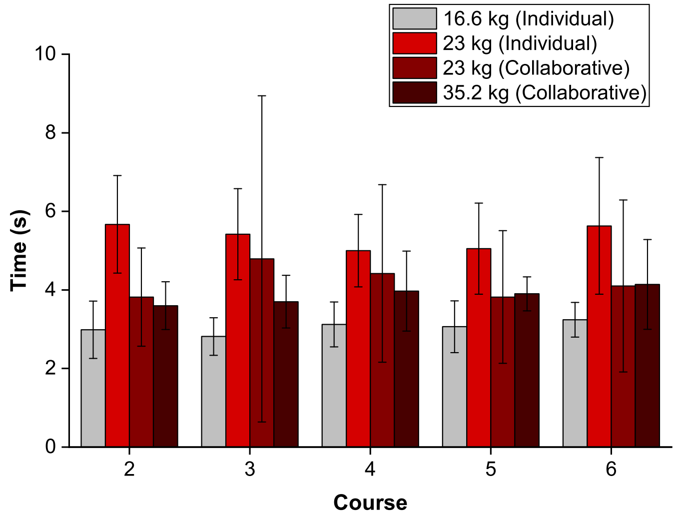

Fig. 9. Completion time per CMU lift averaged by course for the three CMU sizes.

Table 1. Lift technique by masonry activity

Task	Usage (%) One-handed lift	Two-handed lift	Mixed lift
First course	64.81	27.78	7.41
Standard wall	8.36	70.47	21.17
Constrained space	0.00	83.67	16.33
Reinforced wall	0.00	58.91	41.09
Individual lift (23 kg)	0.00	78.33	21.67
Collaborative lift (23 kg)	64.71	25.00	10.29
Collaborative lift (35.2 kg)	56.20	35.54	8.26

The adoption of robots and exoskeletons in construction is an active research area. Bricklaying robots, MULE (Construction Robotics 2021) and in-situ-fabricator (Giftthaler et al. 2017), as well as a robotic exoskeleton, such as Fraco (2021), are currently being introduced in masonry. By taking over physically difficult and repetitive tasks or augmenting physical capabilities, masonry robots promise to enhance masons' safety, health, and productivity. However, such robots and exoskeletons are still challenging due to constraints such as inherent dynamic changes in the work environment, the necessity for work interventions, and regulations (Ryu et al. 2020c). As a result, trained masonry workers in worksites are inevitable until such automation and robotics are fully implemented in masonry. In addition, semiautomation, where workers collaborate with robots and machines, is a feasible alternative. Analyzing and reflecting on expert masons' work methods and techniques before adopting such technologies as a work intervention would be critical to masons' safety, health, and productivity. Therefore, the identified experts' biomechanical work strategies may play an important role in (1) establishing improved training guidelines for novice and apprentice masons; and (2) optimizing work configuration to minimize musculoskeletal injury risks.

The experimental design of this study imposed certain limitations on its results and conclusions. First, participants completed the experiment in a training environment, which may promote different postures and productivity patterns than at a worksite. Additionally, the number of participants in the current experiment was rather small, and they were all male. Future studies should seek to increase the number of subjects and recruit female expert masons to improve the representation of the mason population. Furthermore, masons who adopted mixed lifts as opposed to one-handed or two-handed lifts have more complex motion patterns and body loads. The inclusion of those lifts in our results confounds the analysis of load coordination between the upper limbs and the comparison of loads between the carrying and free sides. The participants carried out the series of activities in a predetermined order, from Activity 1 to 7. This may result in order effects, where participants' movements are affected by the order of their activities. Fatigue may have influenced their movement patterns in performing later activities. To counteract this effect, sufficient breaks were provided. However, future studies should consider random counterbalancing in which the order of activities is randomly assigned for each participant to control for order effects.

In biomechanical analysis, the scope of this study was limited to the investigation of ergonomic risk levels during the task of CMU lift. Other actions undertaken during the experiment, such as spreading mortar and positioning the unit once laid, were not included in the analysis. Although CMU lift represents significant ergonomic risks in masonry work, including physically demanding and repetitive movements, future studies should also evaluate the ergonomic risks of other masonry actions. Also, the CMU weight was assumed to be split equally between the right and left hands for individual two-handed lifts and between both participants in collaborative lifts. As a result, we cannot draw conclusions about loads on the dominant versus nondominant upper limbs or sharing of load between partners in collaborative construction.

Conclusions

This study investigated the expert masons' performance and ergonomic characteristics in carrying out seven masonry activities to determine the associated risks. Expert masons constructed a standard wall, a reinforced wall, a wall in a constrained space, and a first course using standard CMUs weighing 16.6 kg. After completing the four activities, they constructed a wall individually using heavy (23 kg) CMUs, and two masons collaboratively constructed a wall using the same CMUs and very heavy CMUs weighing 35.2 kg. Their joint loads were assessed by utilizing a motion capture system to measure their motions and carry out a biomechanical analysis of those motions.

The critical joints were dependent on the activity, but the most critical body joints were at the lower back (L4/L5 disc level) and upper limbs (shoulder and elbows). Laying CMUs at the first course and the second course required the expert masons to bend their backs excessively, resulting in significant lumbar compression forces. Reinforced wall and constrained space activities and laying CMUs on the 5th and 6th courses of the standard wall allowed the expert masons to straighten their back, but they had to raise their shoulder to the shoulder level or even above the head level. Consequently, the critical joint was switched from the lower back to the shoulders. The findings of this study also suggest a configuration of optimized working height to minimize musculoskeletal stress. Although the heavy (23 kg) CMU is 40% more in weight and volume than standard (16.6 kg) CMUs, expert masons experienced joint loads similar to handling standard CMUs when laying down individually at the 4th course, which is at about waist level. Therefore, it is proposed that the optimal working height for tasks involving manual heavy material lifting is at about waist level.

This study presents a comprehensive understanding of the expert masons' ergonomic characteristics through biomechanical analysis of seven common masonry activities where masons encounter awkward postures or elevated injury risks. To the best of our knowledge, the present study is one of the first attempts to investigate expert masons' biomechanical strategies across different types of CMU lift activities. The methods and findings described herein contribute to identifying expert masons' safe and productive work strategies that they develop as they gain experience. Our findings open the door to providing apprentices with improved training materials based on expert masons' ergonomic characteristics. Given that a significant number of industrial workers often perform heavy manual material handling tasks, the findings described in this study suggest an approach that can be applied to training programs in other high WMSD-risk trades. Furthermore, it provides objective ergonomic measures to guide workplace and process design.

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.

Acknowledgments

The authors would like to acknowledge the Ontario Masonry Training Centre (OMTC) and the Canada Masonry Design Centre (CMDC) in Mississauga in Ontario, Canada, for their considerable help in data collection. The work presented in this paper was supported financially by the Canadian Concrete Masonry Producers Association (CCMPA), CMDC, and the Natural Sciences and Engineering Research Council of Canada (NSERC) (CRDPJ 494786-16).

References

Adams, M. A., K. Burton, and N. Bogduk. 2006. Vol. 55 of *The biomechanics of back pain*. Amsterdam, Netherlands: Elsevier.

Albers, J. T., Y. Li, G. Lemasters, S. Sprague, R. Stinson, and A. Bhattacharya. 1997. "An ergonomic education and evaluation program for apprentice carpenters." *Am. J. Ind. Med.* 32 (6): 641–647. https://doi.org/10.1002/(SICI)1097-0274(199712)32:6<641::AID-AJIM10>3.0.CO;2-1.

Alwasel, A., E. M. Abdel-Rahman, C. T. Haas, and S. Lee. 2017. "Experience, productivity, and musculoskeletal injury among masonry workers." *J. Constr. Eng. Manage.* 143 (6): 05017003. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001308.

Authier, M., M. Gagnon, and M. Lortie. 1995. "Handling techniques: The influence of weight and height for experts and novices." *Int. J. Occup. Saf. Ergon.* 1 (3): 262–275. https://doi.org/10.1080/10803548.1995.11076324.

Authier, M., M. Lortie, and M. Gagnon. 1996. "Manual handling techniques: Comparing novices and experts." *Int. J. Ind. Ergon.* 17 (5): 419–429. https://doi.org/10.1016/0169-8141(95)00005-4.

Boschman, J. S., H. F. van der Molen, J. K. Sluiter, and M. H. Frings-Dresen. 2011. "Occupational demands and health effects for bricklayers and construction supervisors: A systematic review." *Am. J. Ind. Med.* 54 (1): 55–77. https://doi.org/10.1002/ajim.20899.

Boschman, J. S., H. F. van der Molen, J. K. Sluiter, and M. H. Frings-Dresen. 2012. "Musculoskeletal disorders among construction workers: A one-year follow-up study." *BMC Musculoskelet Disord.* 13 (1): 196. https://doi.org/10.1186/1471-2474-13-196.

BuildForce Canada. 2021. "Forecast summary reports: Construction & maintenance looking forwards, highlights 2021–2030." Accessed November 10, 2021. https://www.buildforce.ca/en/lmi/forecast-summary-reports.

BLS (Bureau of Labor Statistics). 2021. "Occupational outlook handbook: Masonry workers." Accessed November 10, 2021. https://www.bls.gov/ooh/construction-and-extraction/brickmasons-blockmasons-and-stonemasons.htm/.

CCMPA (Canadian Concrete Masonry Producers Association). 2013. "Metric technical manual (Section 4. Physical properties)." Accessed September 11, 2019. http://ccmpa.ca/wp-content/uploads/2012/02/Final2013Sec4.pdf.

Center for Ergonomics at the University of Michigan. 2016. "3D static strength prediction program (3DSSPP v7.0)." Accessed September 17, 2019. http://c4e.engin.umich.edu/tools-services/3dsspp-software/2016.

Chaffin, D. B. 2009. "The evolving role of biomechanics in prevention of overexertion injuries." *Ergonomics* 52 (1): 3–14. https://doi.org/10.1080/00140130802479812.

Chen, J. Y., J. Qiu, and C. B. Ahn. 2017. "Construction worker's awkward posture recognition through supervised motion tensor decomposition." *Autom. Constr.* 77 (May): 67–81. https://doi.org/10.1016/j.autcon.2017.01.020.

Cheng, T., G. C. Migliaccio, J. Teizer, and U. C. Gatti. 2013. "Data fusion of real-time location sensing and physiological status monitoring for ergonomics analysis of construction workers." *J. Comput. Civ. Eng.* 27 (3): 320–335. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000222.

Choi, S. D. 2012. "A study of trade-specific occupational ergonomics considerations in the US construction industry." *Work* 42 (2): 215–222. https://doi.org/10.3233/WOR-2012-1344.

Clemes, S. A., C. O. Haslam, and R. A. Haslam. 2010. "What constitutes effective manual handling training? A systematic review." *Occup. Med.* 60 (2): 101–107. https://doi.org/10.1093/occmed/kqp127.

Construction Robotics. 2021. "MULE." Accessed January 15, 2022. https://www.construction-robotics.com/mule/.

CPWR (Center for Construction Research and Training). 2013. "The construction chart book: The U.S. construction industry and its workers." Accessed February 17, 2020. https://www.cpwr.com/sites/default/files/publications/5th-Edition-Chart-Book-Final.pdf.

CPWR (Center for Construction Research and Training). 2018. "The construction chart book: The U.S. construction industry and its workers." Accessed February 17, 2020. https://www.cpwr.com/sites/default/files/publications/5th%20Edition%20Chart%20Book%20Final.pdf.

CPWR (Center for Construction Research and Training). 2019. "Trends of musculoskeletal disorders and interventions in the construction industry (quarterly data report)." Accessed February 17, 2020. https://www.cpwr.com/sites/default/files/publications/Quarter3-QDR-2019.pdf.

Diraneyya, M. M., J. Ryu, E. Abdel-Rahman, and C. T. Haas. 2021. "Inertial motion capture-based whole-body inverse dynamics." *Sensors (Basel)* 21 (21): 7353. https://doi.org/10.3390/s21217353.

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.

Fraco. 2021. "Exoskeleton information sheet." Accessed January 15, 2022. https://www.fraco.com/en/documents/Fraco_Exoskeleton.pdf.

Gagnon, M. 2003. "The efficacy of training for three manual handling strategies based on the observation of expert and novice workers." *Clin. Biomech.* 18 (7): 601–611. https://doi.org/10.1016/S0268-0033(03)00076-7.

Gagnon, M. 2005. "Ergonomic identification and biomechanical evaluation of workers' strategies and their validation in a training situation: Summary of research." *Clin. Biomech.* 20 (6): 569–580. https://doi.org/10.1016/j.clinbiomech.2005.03.007.

Gatti, U. C., S. Schneider, and G. C. Migliaccio. 2014. "Physiological condition monitoring of construction workers." *Autom. Constr.* 44 (Aug): 227–233. https://doi.org/10.1016/j.autcon.2014.04.013.

Giftthaler, M., T. Sandy, K. Dörfler, I. Brooks, M. Buckingham, G. Rey, M. Kohler, F. Gramazio, and J. Buchli. 2017. "Mobile robotic fabrication at 1: 1 scale: The in situ fabricator." *Constr. Rob.* 1 (1–4): 3–14. https://doi.org/10.1007/s41693-017-0003-5.

Harari, Y., A. Bechar, and R. Riemer. 2020. "Workers' biomechanical loads and kinematics during multiple-task manual material handling."

Appl. Ergon. 83 (Feb): 102985. https://doi.org/10.1016/j.apergo.2019.102985.

Harari, Y., R. Riemer, and A. Bechar. 2019. "Differences in spinal moments, kinematics and pace during single-task and combined manual material handling jobs." *Appl. Ergon.* 81 (Nov): 102871. https://doi.org/10.1016/j.apergo.2019.06.002.

Haslam, C., S. Clemes, H. McDermott, K. Shaw, C. Williams, and R. Haslam. 2007. *Manual handling training: Investigation of current practices and development of guidelines*. Loughborough, UK: Loughborough Univ.

Hess, J., M. Weinstein, and L. Welch. 2010. "Ergonomic best practices in masonry: Regional differences, benefits, barriers, and recommendations for dissemination." *J. Occup. Environ. Hyg.* 7 (8): 446–455. https://doi.org/10.1080/15459624.2010.484795.

Hess, J. A., L. Kincl, D. L. Weeks, A. Vaughan, and D. Anton. 2020. "Safety voice for ergonomics (SAVE): Evaluation of a masonry apprenticeship training program." *Appl. Ergon.* 86 (Jul): 103083. https://doi.org/10.1016/j.apergo.2020.103083.

Joshua, L., and K. Varghese. 2014. "Automated recognition of construction labour activity using accelerometers in field situations." *Int. J. Productivity Perform. Manage.* 63 (7): 841–862. https://doi.org/10.1108/IJPPM-05-2013-0099.

Kincl, L. D., D. Anton, J. A. Hess, and D. L. Weeks. 2016. "Safety voice for ergonomics (SAVE) project: Protocol for a workplace cluster-randomized controlled trial to reduce musculoskeletal disorders in masonry apprentices." *BMC Public Health* 16 (1): 362. https://doi.org/10.1186/s12889-016-2989-x.

Lahiri, S., P. Markkanen, and C. Levenstein. 2005. "The cost effectiveness of occupational health interventions: Preventing occupational back pain." *Am. J. Ind. Med.* 48 (6): 515–529. https://doi.org/10.1002/ajim.20193.

Lv, F. 2006. "BvhViewer (version 1.0)." Accessed October 1, 2018. http://vipbase.net/bvhviewer.

Meredith, M., and S. Maddock. 2001. "Motion capture file formats explained." Accessed July 20, 2019. http://www.dcs.shef.ac.uk/intranet/research/public/resmes/CS0111.pdf.

Ministry of Labour. 2021. "Ergonomics in the workplace." Accessed January 15, 2022. https://www.ontario.ca/page/ergonomics-workplace#section-1.

Nath, N. 2017. "Construction ergonomic risk and productivity assessment using mobile technology and machine learning." M.S. thesis, Dept. of Technology and Construction Management, Missouri State Univ. https://bearworks.missouristate.edu/cgi/viewcontent.cgi?article=4167&context=theses.

NIOSH (National Institute for Occupational Safety and Health). 1981. *Work practices guide for manual lifting*. Cincinnati: US Dept. of Health and Human Services.

NIOSH (National Institute for Occupational Safety and Health). 2014. *Observation-based posture assessment: Review of current practice and recommendations for improvement*. Cincinnati: US Dept. of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Noitom Ltd. 2017. "Perception neuron." Accessed September 17, 2019. https://neuronmocap.com/.

Okun, A. H., R. J. Guerin, and P. A. Schulte. 2016. "Foundational workplace safety and health competencies for the emerging workforce." *J. Saf. Res.* 59 (Dec): 43–51. https://doi.org/10.1016/j.jsr.2016.09.004.

Plamondon, A., A. Delisle, S. Bellefeuille, D. Denis, D. Gagnon, C. Lariviere, and I. M. R. Group. 2014. "Lifting strategies of expert and novice workers during a repetitive palletizing task." *Appl. Ergon.* 45 (3): 471–481. https://doi.org/10.1016/j.apergo.2013.06.008.

Plamondon, A., D. Denis, A. Delisle, C. Lariviere, E. Salazar, and IRSST MMH Research Group. 2010. "Biomechanical differences between expert and novice workers in a manual material handling task." *Ergonomics* 53 (10): 1239–1253. https://doi.org/10.1080/00140139.2010.513746.

Plamondon, A., C. Lariviere, A. Delisle, D. Denis, and D. Gagnon. 2012. "Relative importance of expertise, lifting height and weight lifted on posture and lumbar external loading during a transfer task in manual material handling." *Ergonomics* 55 (1): 87–102. https://doi.org/10.1080/00140139.2011.634031.

Robert-Lachaine, X., H. Mecheri, A. Muller, C. Larue, and A. Plamondon. 2020. "Validation of a low-cost inertial motion capture system for whole-body motion analysis." *J. Biomech.* 99 (Jan): 109520. https://doi.org/10.1016/j.jbiomech.2019.109520.

Ryu, J., A. Alwasel, C. T. Haas, and E. Abdel-Rahman. 2020a. "Analysis of relationships between body load and training, work methods, and work rate: Overcoming the novice mason's risk hump." *J. Constr. Eng. Manage.* 146 (8): 04020097. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001889.

Ryu, J., M. M. Diraneyya, C. T. Haas, and E. Abdel-Rahman. 2020b. "Analysis of the limits of automated rule-based ergonomic assessment in bricklaying." *J. Constr. Eng. Manage.* 147 (2): 04020163. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001978.

Ryu, J., T. McFarland, B. Banting, C. T. Haas, and E. Abdel-Rahman. 2020c. "Health and productivity impact of semi-automated work systems in construction." *Autom. Constr.* 120 (Dec): 103396. https://doi.org/10.1016/j.autcon.2020.103396.

Ryu, J., T. McFarland, C. T. Haas, and E. Abdel-Rahman. 2020d. "Automatic clustering of proper working posture." In *Proc., EG-ICE 2020 Workshop on Intelligent Computing in Engineering*, 106–114. Berlin: Universitätsverlag der TU Berlin. https://doi.org/10.14279/depositonce-9977.

Ryu, J., T. McFarland, C. T. Haas, and E. Abdel-Rahman. 2022. "Automatic clustering of proper working postures for phases of movement." *Autom. Constr.* 138 (Jun): 104223. https://doi.org/10.1016/j.autcon.2022.104223.

Ryu, J., J. Seo, H. Jebelli, and S. Lee. 2019. "Automated action recognition using an accelerometer-embedded wristband-type activity tracker." *J. Constr. Eng. Manage.* 145 (1): 04018114. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001579.

Ryu, J., J. Seo, M. Y. Liu, S. Lee, and C. T. Haas. 2016. "Action recognition using a wristband-type activity tracker: Case study of masonry work." In *Proc., Construction research congress 2016: Old and new construction technologies converge in historic San Juan*, 790–799. Reston, VA: ASCE.

Ryu, J., L. Zhang, C. T. Haas, and E. Abdel-Rahman. 2018. "Motion data based construction worker training support tool: Case study of masonry work. Paper presented at the ISARC." In *Proc., Int. Symp. on Automation and Robotics in Construction*. Pittsburgh: International Association for Automation and Robotics in Construction.

Seo, J., S. Han, S. Lee, and H. Kim. 2015. "Computer vision techniques for construction safety and health monitoring." *Adv. Eng. Inf.* 29 (2): 239–251. https://doi.org/10.1016/j.aei.2015.02.001.

Steele, T., A. Merryweather, and D. Bloswick. 2014. "Manual material handling guidelines for the shoulder: Biomechanical support for the Liberty Mutual Tables as developed by Snook and Ciriello." *Int. J. Ind. Ergon.* 44 (2): 275–280. https://doi.org/10.1016/j.ergon.2013.10.008.

Teizer, J., T. Cheng, and Y. H. Fang. 2013. "Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity." *Autom. Constr.* 35 (Nov): 53–68. https://doi.org/10.1016/j.autcon.2013.03.004.

Valero, E., A. Sivanathan, F. Bosche, and M. Abdel-Wahab. 2016. "Musculoskeletal disorders in construction: A review and a novel system for activity tracking with body area network." *Appl. Ergon.* 54 (May): 120–130. https://doi.org/10.1016/j.apergo.2015.11.020.

Valero, E., A. Sivanathan, F. Bosche, and M. Abdel-Wahab. 2017. "Analysis of construction trade worker body motions using a wearable and wireless motion sensor network." *Autom. Constr.* 83 (Nov): 48–55. https://doi.org/10.1016/j.autcon.2017.08.001.

van der Molen, H. F., S. Veenstra, J. Sluiter, and M. Frings-Dresen. 2004. "World at work: Bricklayers and bricklayers' assistants." *Occup. Environ. Med.* 61 (1): 89–93. https://doi.org/10.1136/oem.2002.001750.

Wang, D., F. Dai, and X. P. Ning. 2015. "Risk assessment of work-related musculoskeletal disorders in construction: State-of-the-art review." *J. Constr. Eng. Manage.* 141 (6): 04015008. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000979.

Wang, Y., P. M. Goodrum, C. T. Haas, and R. W. Glover. 2008. "Craft training issues in American industrial and commercial construction."

J. Constr. Eng. Manage. 134 (10): 795–803. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:10(795).

Waters, T. R., V. Putz-Anderson, A. Garg, and L. J. Fine. 1993. "Revised NIOSH equation for the design and evaluation of manual lifting tasks." *Ergonomics* 36 (7): 749–776. https://doi.org/10.1080/00140139308967940.

Zhang, L., M. Diraneyya, J. Ryu, C. Haas, and E. Abdel-Rahman. 2019a. "Automated monitoring of physical fatigue using Jerk. Paper presented at the ISARC." In *Proc., Int. Symp. on Automation and Robotics in Construction*. Pittsburgh: International Association for Automation and Robotics in Construction.

Zhang, L. C., M. M. Diraneyya, J. Ryu, C. T. Haas, and E. M. Abdel-Rahman. 2019b. "Jerk as an indicator of physical exertion and fatigue." *Autom. Constr.* 104 (Aug): 120–128. https://doi.org/10.1016/j.autcon.2019.04.016.