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SEMI-AUTOMATED WORK SYSTEM IN MASONRY WORK

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ABSTRACT

Despite being one of the oldest professions, the level of automation in masonry trade has lagged behind other industries such as automotive and manufacturing. Masons still manually perform physically strenuous and demanding tasks such as block lifting at worksites. As a result, masons experience significant overexertion and back injuries. In this study, we propose an automated-levelling pallet as an intervention to reduce block lifting demands. The pallet maintains constant pick-up height using a mechanical spring system. Then, we investigate the health and productivity impact of this intervention on lifting of concrete masonry units (CMUs), an integral component of masonry work. Wearable motion capture systems are utilized to analyze body joint loads. The results revealed that masons experienced a 40% reduction in lumbar compression force and a 10% increase in productivity. We discovered that the proposed intervention has an immense potential to contribute towards a safer and more productive work environment for masons.

KEYWORDS: *automation, human-robotic systems, health, safety, productivity*

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INTRODUCTION

Due to the physically strenuous and demanding tasks in the construction field, work-related musculoskeletal disorders (WMSDs) are widely reported as a substantial challenge in the construction industry [1-4]. In 2017, the Bureau of Labor Statistics recorded that the incidence rate of WMSDs for the U.S construction industry was 31.2 per 10,000 full-time workers [5].

Within construction trades, masonry had the highest rate of overexertion injuries and the second-highest rate of back injury among all construction sub-sectors [6]. This is due to masons frequently performing physically demanding and repetitive tasks that may exceed the safe limit. In particular, manual block and brick lifting, both being integral parts of masonry work, require masons to repeatedly perform deep bending of the trunk, hips, and knees in order to lift and lay down heavy loads [7,8]. Hess et al. [7] estimate that masons manually lift a minimum of 200 concrete masonry units (CMUs) per day; considering that the standard CMU (0.19 x 0.19 x 0.39m) weighs 16.6 kg [9], masons are calculated to manually lift over 3,300 kg per workday. Masons also spend a significant fraction of their working time in bending postures driven by the fact up to 53% of material pick up occur at or below knee level [1]. In fact, they spend and 38% of their working time in awkward postures [1]. Frequent handling of heavy materials in bent postures exposes masons to severe lower back risks, which in turn causes masons to have the second-highest back-injury rate across construction subsectors [6].

The adoption of full automation in the construction field is becoming an active area of research. Particularly, in masonry, new technologies such as bricklaying robots, SAM 100 [10], and the In-situ-Fabricator [11], are currently being introduced. Such masonry automation promises improvements to masons' health and productivity by substituting workers in physically demanding and repetitive tasks. However, full automation still poses a challenge in many situations because of limitations such as intrinsic dynamic changes in worksites, the need for continued worker interventions, and regulations. Therefore, the flexibility of a semi-automated work system where operators work in unison with machines and robots is an attractive alternative.

Semi-automated force-assist systems have the potential to mitigate workers' exposure to WMSD risks by directly reducing the amount of physically demanding tasks. For example, robotic arms that externally support the weight and maneuver tools at construction sites can offload physical demands from the operator to the mounting system, thereby reducing the associated risk [12]. Warszawski and Navon [13] also suggested that robotics can generate economic value by performing the most physically exhausting tasks (e.g., heavy lifting, reaching to the ceiling and/or floors) to reduce the costs of injuries and time loss. This in turn can leave the more complex finishing tasks for humans to complete.

As such, the integration of semi-automation into conventional work systems can reduce industrial injury risks, and further, have economic benefits by reducing injuries and promoting productivity [14]. However, in order to effectively integrate semi-automated work systems into conventional work processes, it is critical to quantitatively and objectively assess their value, especially in terms of health and productivity. This study proposes a self-leveling pallet as a force-assisted semi-automated work system that can reduce the lifting demands on masons whilst building a standard CMU wall. It also quantifies the health and productivity impact of introducing those pallets into masonry work.

RESEARCH METHODS

Manual handling of CMUs is an essential part of masonry tasks, it also exposes masons to cumulative musculoskeletal stress [15,16]. The self-leveling pallet is an automatic load leveler that utilizes a mechanical spring system to adjust its height according to the weight of materials placed on the pallet. This allows the pick-up height of the CMUs to remain at waist height as the number of CMUs, and the weight of the load, is decreased. The self-leveling pallet adopted in this study —manufactured by Southworth Products Corp. (Southworth, Portland, USA)— had a 2041.17 kg (4500 lb.) load capacity with a rotating platform that measures 1.11 m in diameter (Figure 1). It aims to reduce the height and reach distance while picking CMUs, thereby minimizing arm and lower back movements and reducing the task completion time.

Figure 1: The self-leveling pallet utilized in the experiment (Southworth, Portland, USA).

A controlled experiment was conducted to objectively evaluate the performance of the proposed semi-automated work system. Thirteen healthy male masons (aged 26.4 ± 6 years, stature 181.0 ± 4.7 cm, total body mass 88.5 ± 12.1 kg) were recruited from the Ontario Masonry Training Centre (Mississauga, Ontario). Ten of the participants were apprentices with 1 year of masonry experience, and the remaining three were apprentices with 3 years of masonry experience. The experiment received ethics approval from the Office of Research Ethics at the University of Waterloo.

Protocol

The study consisted of both control wall sessions and self-leveling pallet sessions. Participants took part in one session per day. On day one, they were randomly assigned to either the control wall session or the self-leveling pallet session, and on day two, they took part in the other session. Randomization was used to minimize the impact of a learning curve on the results. Each participant was tasked to complete a pre-built lead wall using 45 CSA – Type "A" CMUs weighing 16.6 kg with dimensions of 0.19 × 0.19 × 0.39 m [9]. The pre-built lead wall consisted of 27 CMUs of a 6-courses on which the participants laid down CMUs from the second to the sixth course.

During the control wall session, the materials were arranged to replicate a standard job site set up; the CMUs were stacked in three piles approximately one meter away from the pre-built lead wall, and mixed mortar was provided by helpers in two mortar boards placed between the stacked piles (Figure 2, left). Each pile consisted of 16 CMUs, which were stacked with 4 layers of 4 CMUs each.

In the self-leveling pallet session, the CMUs were placed on the pallet approximately one meter away from the lead wall with two mortar boards placed on either side of the pallet (Figure 2, right). CMUs were stacked on the pallet in stacks of 3 layers of 16 CMUs each.

The initial CMU pick-up (pile) height in the control wall session was 0.76 m. Participants picked up CMUs at lower levels as they proceeded with the experiment to a minimum of 0.19 m for the bottom layer. In the self-leveling pallet session, pick-up heights for each layer decreased in the following order: 1.05 m, 0.97 m, and 0.9 m.

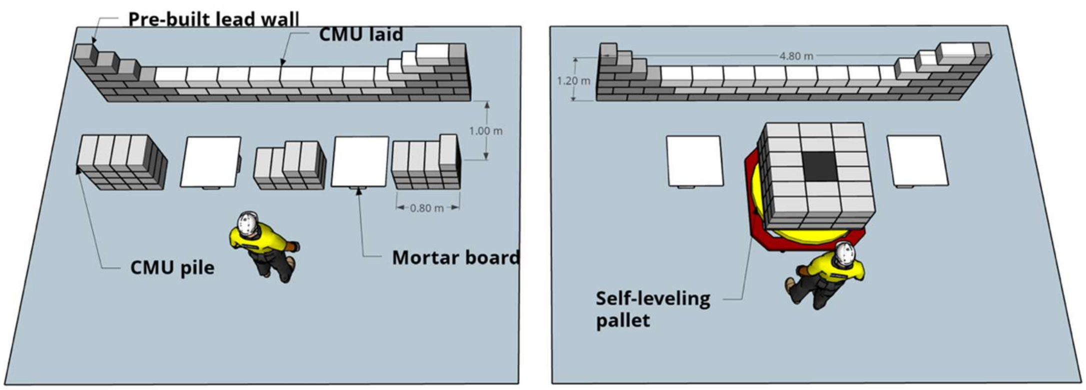

Figure 2: Layout of the experimental setup: conventional work setup (left) and semi-automated job setup (right).

Data collection & processing

A wireless motion capture suit, Perception Neuron from Noitom Ltd. [17], was used to collect whole-body kinematic data at a sampling rate of 125 Hz. The suit contains 17 IMUs, each consisting of a three-axis accelerometer, a three-axis gyroscope, and a three-axis magnetometer. In addition, all experiments were recorded using a camcorder to label and segment the data during the data processing phase. All participants reported that the motion capture suit was comfortable and did not interfere with their work.

We segmented the acquired data into individual 'lift' motion files, thereby obtaining 45 CMU motion files per session. Individual lifts were comprised of a motion sequence commencing with a participant picking up a CMU and ending with the participant fully placing it on the lead wall. The segmentation was accomplished based on the recorded video files.

Analysis

We carried out a biomechanical analysis to investigate the risk levels masons are exposed to while handling CMU. The biomechanical analysis package 3D Static Strength Prediction Program (3DSSPP) [18] was used to estimate the physical demands, spinal compression force and major body joint moments during each of the lifts. During both experimental sessions, the peak lumbar compression force and associated posture were determined for each lift and averaged by course height. The peak lumbar compression forces during pickup were also averaged and compared.

In a standard masonry work setting, masons are expected to complete a predetermined number of CMUs each day. As a result, productivity becomes an essential aspect of a mason's career. Within this investigation, productivity was calculated for all participants by recording the time taken to complete a lead wall using 45 CMUs. The average lift time was also determined and analyzed to further investigate participants' productivity.

RESULTS

Peak lumbar compression force was this study's primary focus, as it provides a direct representation of the physical demands on the back. In this section, the peak lumbar compression force was compared during the 1) whole lift and 2) pick-up phase only.

Figure 3 shows the average peak lumbar compression force among 13 participants at pick-up and over the whole lift. When using the self-leveling pallet, the average peak lumbar compression force was reduced by 20% during the whole lift and by 40% during pick-up phase only. NIOSH defines the 'action limit' (3433 N) as the threshold below which 99% of male workers and 75% of female workers have the strength capacity to perform the task with minimal risk [19,20]. While completing the task without the self-leveling pallet participants were exposed to lumbar compression forces close to the action limit during the whole lift. Using the self-leveling pallet resulted in substantially lower lumbar compression forces during the whole lift and the pick-up phase. Notably, with the self-levelling pallet participants were exposed to lumbar compression forces that were only ~50% of the action limit during the pick-up phase. An independent sample t-test determined that the differences in lumbar compression forces between the two work conditions were significant ($p < 0.05$).

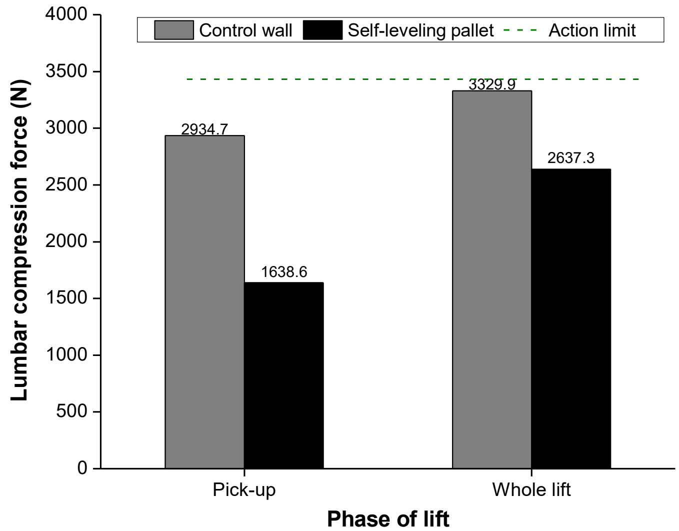

Figure 3: Peak lumbar compression force (N) during the whole lift and pick-up phase with and without the self-leveling pallet.

As the participants laid CMUs from the 2nd to the 6th course, their working postures varied according to course height. Specifically, participants bent their back significantly more while placing CMUs at the 2nd course than they did while placing CMUs at the 6th course. Figure 4 shows the peak lumbar compression forces during whole lifts averaged by course height. Due to significant differences in trunk flexion according to course height, participants experienced the highest lumber compression at the 2nd course for with and without the self-levelling pallet. However, when participants used the self-leveling pallet, lumbar compression forces decreased with increasing course heights. Particularly, the peak lumbar compression force with the self-levelling pallet at the 6th course is 37.9% lower than it is at the 2nd course. It is also lower by 38.5% than that encountered without the self-levelling pallet.

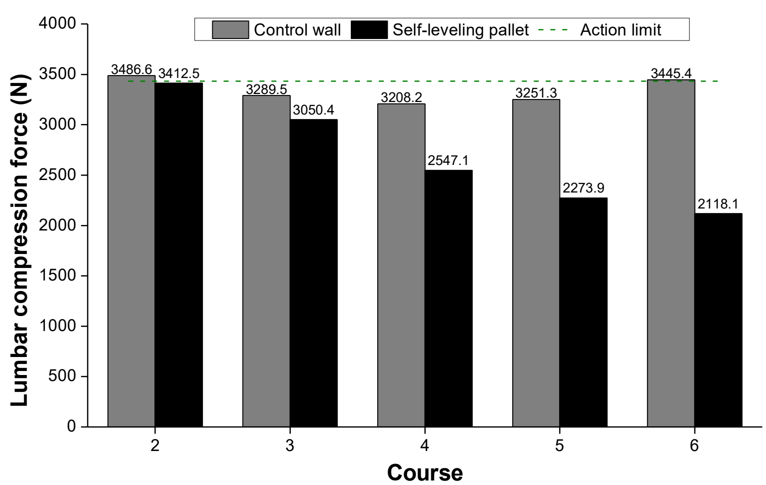

Figure 4: Peak lumbar compression force (N) during whole lifts averaged by course with and without the self-leveling pallet.

The difference in lumbar load due to the use of the self-leveling pallet was most significant during the CMU pick-up phase. Figure 5 illustrates this variation by comparing the average lumbar compression forces during the pick-up phase of lifts ending at courses 2-6. In the control wall session, the CMUs were picked up from a decreasing height as participants took the CMUs from stacked piles to build the wall. As a result, the lumbar compression force increased as they worked on higher courses. In contrast, by using the self-levelling pallet, participants maintained similar CMU pick-up heights regardless of the course; this ensured that their lumbar loads remained consistent throughout.

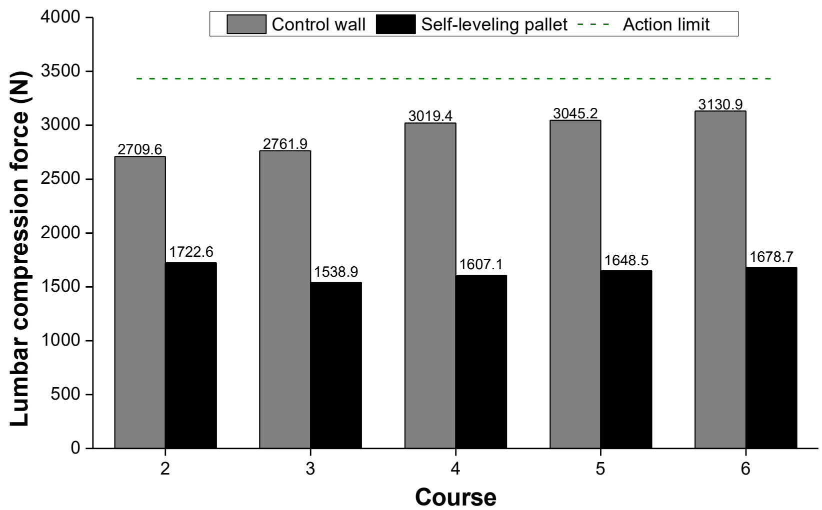

Figure 5: Peak lumbar compression force (N) during the pick-up phase averaged by the course where the lift was terminated with and without the self-leveling pallet

In both experimental sessions, the lead walls were completed with the same number of CMUs. However, the completion time with the self-leveling pallet was on average 10% faster than that without, eleven of the thirteen participants completed the self-leveling pallet session in a similar or shorter duration than the control wall. Since the self-leveling pallet only affected the participants' CMU lifts and did not affect other activities (e.g., spreading mortar), the average time it took to complete a whole lift was compared under both conditions. We found that lifts were completed approximately 22% faster with the self-leveling pallet than they were under the original conditions (Figure 6). This result indicates that masons moved CMUs over shorter paths, resulting in shorter completion times.

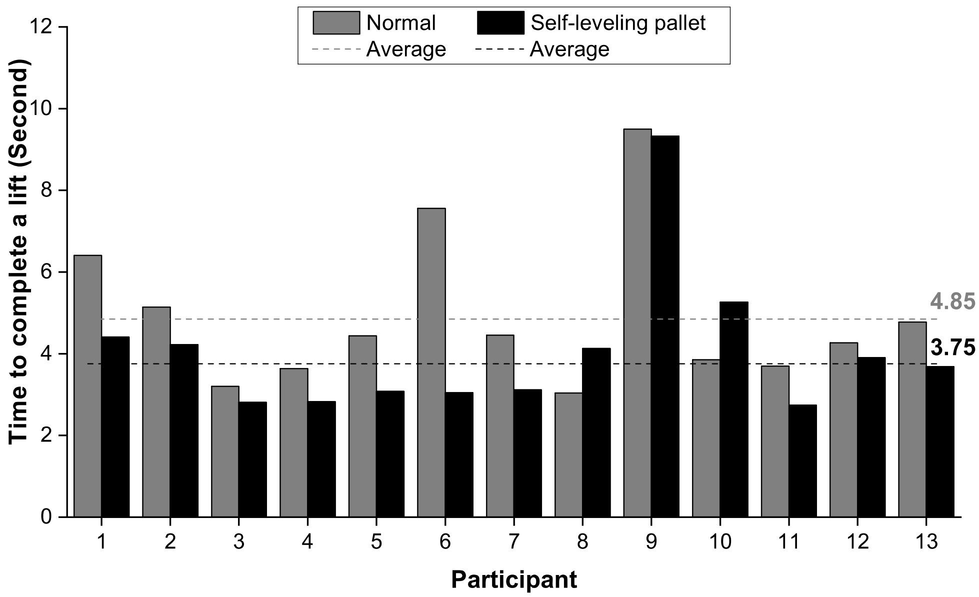

Figure 5: Averaged time for a single lift with and without the self-leveling pallet

DISCUSSION AND CONCLUSION

By combining wearable motion capture suits with biomechanical analysis tools, this study evaluated the impact of semi-automated work systems on the health and productivity of masons. Specifically, this study was carried out to assess the use of a self-leveling pallet in masonry tasks. Thirteen participants used 45 CMUs to complete a standard wall under two conditions: traditional and semi-automated workstations. The participants' lumbar compression forces and productivity were assessed and compared in each experimental condition through biomechanical and productivity analyses.

The results of the current study show the proposed methodology provides an objective (quantitative) evaluation of semi-automation, namely a 40% reduction in lumbar compression force, a 22% increase in lift speed, and 10 % improvement in labor productivity. It, therefore, offers a quantitative evaluation of the semi-automated work system's contribution to reducing exposure to WMSD risk factors associated with lower back injuries and increase in CMU pick-up speed. This evaluation process provides the quantitative data needed to conduct an objective cost-benefit analysis to determine the potential benefits of ergonomic interventions [21,22].

Until construction sites are fully automated, collaboration among robots, machines, and workers is inevitable. As such, semi-automation is a viable alternative for the near future. A recent surge in the popularity of exoskeletons has integrated this form of technology in the construction industry, including robotic exoskeletons (FRACO) being designed to augment masons' physical capabilities. As the popularity of these systems expand and are adopted onto worksites, management increasingly needs resources to systematically evaluate their impact on health and productivity. Consequently, the approaches proposed in this study will help bridge the gap between traditional and fully automated work systems.

The study emphasizes the importance of assessing not only the productivity increments resulting from the implementation of a semi-automated work system, but also and equal as important their impact on workers' health. Due to a lack of awareness or expertise, ergonomic principles are often overlooked during workplace design or planning of upcoming projects, such as the installation of semi-automated work system [23-25]. The introduction of robotics and automation into a workplace may introduce new risks, if human factors and ergonomics principles are not integrated into the design, work processes, and operation and maintenance requirements [26]. This study takes a proactive approach to the evaluation of both health and productivity of semi-automated work systems, thus filling this gap.

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