IMPROVING HEALTH AND PRODUCTIVITY OF CONSTRUCTION WORKERS: A NEW TOOLKIT

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ABSTRACT

An aging workforce and work related injuries are reducing the number of experienced workers in construction. The decrease in the number of workers is accompanied by increased musculoskeletal disorder (MSD) injury rates and insurance premiums for employers. Adoption of interventions to reduce the number of these injuries has had limited success. These interventions usually apply the same technique to all employees irrespective of their experience level. They have not significantly changed the extent of MSD injuries. Statistics show that the majority of injuries in construction happen to workers while in their training phase, those with less than five years of experience with the same employer. The presented work focuses on investigating whether and in what ways workers' experience plays a role in safety, productivity, and efficiency. Twenty-one workers were recruited at four experience levels ranging from novices to journeymen with more than five years of experience. Participants were asked to build a 12 x 6 block wall using standard Concrete Masonry Units (CMU). Body kinematics were collected using 17 Inertial Measurement Units (IMUs) attached to major body segments. Video cameras were setup to record workers' motion from three different positions. Biomechanical analysis was carried out to calculate the forces and moments in major body joints. It shows that low back moment and force levels increase with experience in the first three years with a peak at three years of experience, beyond which they decrease significantly. Moreover, productivity increases with experience, this increase is accompanied with reduced injury rates. These trends suggest that apprentices focus on productivity and efficiency at the cost of health and safety. Hence, they sustain injuries early in their careers. Further analysis will extract expert motion patterns in order to teach them to trainees to enhance the overall training process, improve health and safety, and increase productivity.

KEYWORDS: *ergonomics, masonry, safety, productivity*

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INTRODUCTION

Musculoskeletal injuries (MSIs), resulting from everyday work, are taxing the number of experienced workers in construction. In addition, the industry is dealing with an aging workforce. While the aging workforce is partly due to baby boomers, who started turning sixty-five years old in 2011, it is also due to the decline in the number of trained workers resulting from injuries and attrition[1], [2].

According to Kumar (2011), MSIs are the result of the interaction of morphological, genetic, biomechanical, and psychosocial factors[3]. Moreover, differential fatigue where muscles, under loading, will fatigue with different rates thereby altering the optimum way that the body adopts to perform motion. Furthermore, cumulative loading plays a major role in lowering the injury threshold leaving muscles more prone to injuries. Finally, overexertion of force, duration, and posture are also risk factors for MSIs.

Inspecting the aforementioned risk factors, we can predict that the number MSIs in construction is high due to the presence of all the risk factors on-site[4]. While this is true, it is also true in many other industries. Moreover, statistics show a higher rate of injuries in some subsectors than others. The rate of overexertion per 10,000 full time equivalent workers was 66.5 in 2013 for masons compared to 49.2 and 45.3 for concrete and drywall workers[5].

The problem associated with the MSIs is that construction, and other industries, rely on productivity. This drives the nature of work to be highly repetitive. While factors such as force levels can be managed through change in material or the design of new tools, the repetition decreases the muscles' threshold for injury, hence, making the body more prone to injury.

However, statistical data suggest that the rate of MSI decrease with the length of employment time, with the same employer, which means that workers are more prone to injuries as apprentices than as journeymen. Workers with 1 year of experience with the same employer suffered 37.5% of all MSIs reported in 2014 while workers with 1-5years of experience suffered 34.2% and 26.5% of all the injuries targeted workers with more than 5 years of experience[6].

It is important to note that the variation in the rates of injuries is not an indication of change of tasks since all workers with different experience levels are performing the same job. The variation in rates of injuries indicates that workers with more than five years of experience are performing the work in a different way. This led to their body not being exposed to MSIs' risk factors.

This indicates that without changing the work environment or tools, a safer more productive method of work can be extracted from the way expert workers move. Using this extracted motion, new apprentices can be trained to perform work in a safer and productive way.

This paper describes a five-year research program designed to address these issues. It also reports on the results of an experiment conducted to investigate the biomechanical load levels on masons' joint forces and moments and its relation to the masons' level of expertise.

OBJECTIVES
It is apparent that a unique window of opportunity for innovation in masonry systems is upon us. The availability of low-cost, high mobility motion suits and small wireless accelerometers, electro goniometers, and optical encoders allows us now to study the motions of masons onsite without interfering with their ability to work or their productivity. Augmenting these measurement systems with analytical methods and software tools allows us to: quantify the loads workers' body segments experience as they go about their tasks, measure their productivity in aggregate and their productivity in individual tasks and sub-tasks, and learn the techniques they develop to reduce loads and their impact on body tissue as they gain experience and the techniques they develop as they gain experience to increase productivity and avoid bottlenecks.

Further, we will study masonry works systems to quantify simultaneously their ability to reduce loads on worker body segments, reduce effort (energy expenditure), and increase productivity. This study allows us to give objective advice to workers and management on the best techniques to protect workers against short and long-term MSDs, to increase productivity, and to assess the cost-benefit of introducing existing and new masonry systems to worksites. The key objectives for the five-year research program are to:

1. Study masons with varying experience and involve them in innovating and evaluating new potential solutions. Early analysis has shown that master masons typically exhibit lower loading levels of critical areas, such as the lower back. We hypothesis that this is due to "Good Form": practices subconsciously developed through extensive experience.
2. Examine our hypothesis that "good form" and "bad form" exist, and if so, how can it used for redesign of masonry systems and training of apprentices.
3. Develop methods and tools through which Good Form can be identified, communicated to and learned by others.
4. Test the hypothesis that good form correlates with lower MSD risks and higher productivity. To some extent, this is heuristically 'known', for example it is known that less bending is better form. However, masonry requires complex movements that are not easily reducible to such simplifications.
5. Identify which sensors, sensor suites, and sensor data fusion methods are most effective for acquiring biomechanical data in true work conditions, such as construction sites. Our experience with IMU suits, wrist mounted monitors, exoskeleton mounted optical encoders, goniometers, and video cameras forms an initial knowledge base for addressing this objective.
6. Apply biomechanical analysis approaches to calculate the loads carried by body segments and joints as well as estimate energy expenditure during construction tasks in order to identify features relevant to good masonry form.
7. Apply accepted construction productivity analysis methods, such as the activity analysis, to assess aggregate, task and sub-task productivity under work system variations.

8. Identify through statistical analysis which factors in the variations analyzed are most related to practices that reduce MSD risk.
9. Identify through statistical analysis which factors in the variations analyzed are most related to improved labor productivity and to improved multi-factor productivity.
10. Apply the knowledge gained through this research to develop guidelines for masonry work systems that maximize productivity while minimizing MSD and safety risks.
11. Develop general principles that can be applied to masonry training courses to help masons acquire the knowledge and skills to proactively reduce their own risk of MSDs and increase their productivity.
12. Determine which variations of work processes, tools, equipment, robotic systems, and masonry unit design have potential to improve masonry productivity while at the same time reduce MSD risk factors and masons energy expenditures.
13. Configure these masonry work systems variations into subsystems for analysis, such as delivery sub-systems, staging sub-systems, and force-assist subsystems.

METHODOLOGY

Twenty-one masons with varying level of expertise ranging from novice to more than 5 years of experience in masonry work were recruited for this study. Since the apprenticeship program is 3 years long, the experiment recruited participant within the program in addition to masons who completed the program. The participants were asked to build a 12x6 block wall using standard concrete masonry units (CMUs). A lead wall, shown in figure 1, was built prior to starting the task, hence, each participant laid 45 blocks.

Instrumentation

Biomechanical analysis calls for measurement of kinematics (human body motion data). Thus, a ‘motion suite’ comprised of 17 inertial measurement units (IMUs), each consisting of a tri-axial accelerometer, a tri-axial gyroscope, and a tri-axial magnetometer, was used to measure body segment motions. Two camcorders were used to record the sessions for purposes of data synchronization.

Figure 1: Participant and a lead wall.

RESULTS

Using the Static Strength Prediction Program (3D SSPP) to analyze the data collected provides a vast amount of in-depth biomechanical information. The results are divided into two sets: joint moments and joint compression forces. In this paper, only results relevant to the major body joints, namely low back, elbow, shoulder, hip and knees joints, are described. These joints are highlighted in figure 2. These are the joints typically considered in biomechanical analysis of the human body [7], [8]. Specifically, the magnitudes of joint moments and forces are used to study the effects of experience while the normalized joint moments and compression forces are used to study the effects of course height.

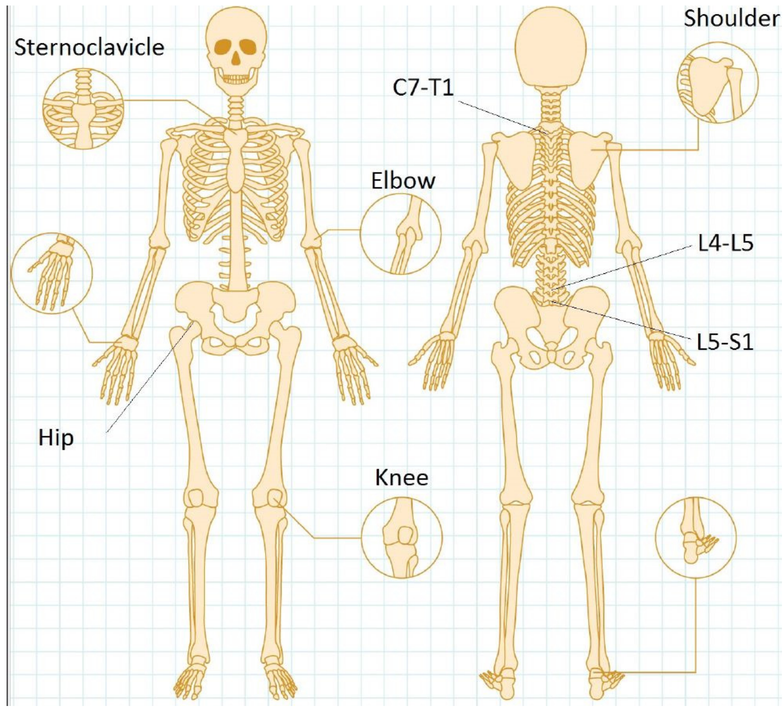

Figure 2: Major body joints (Designed by Freepik)

Joint forces and moments allow for quantification of load levels at each joint. Comparing these forces and moments to epidemiologically and biomechanically verified limits set by National Institute for Occupational Safety and Health (NIOSH) allow for risk assessment [9]–[11].

Lower back (L4-L5) joint compression forces are shown in figure 3, the curves represent the average compression force for each experience group as a function of course height. At the first course, the group with three years of experience showed high values of compression with an average of 6000 N. The three remaining groups showed relatively similar values. As they are laying the second course, all groups showed lower values of compression force compared to first course. However, the drop in the 3 years of experience group was significantly higher than the other group, 20% compared to 10%. The third course had the lowest values of compression across all groups, moreover, the three years group showed lower forces compared to one year group. Gradual increase from this minimum is observed across all groups for the fourth and fifth course. Lower back (L5-S1) joint compression forces show similar patterns to those observed for L4-L5 but at a reduced level.

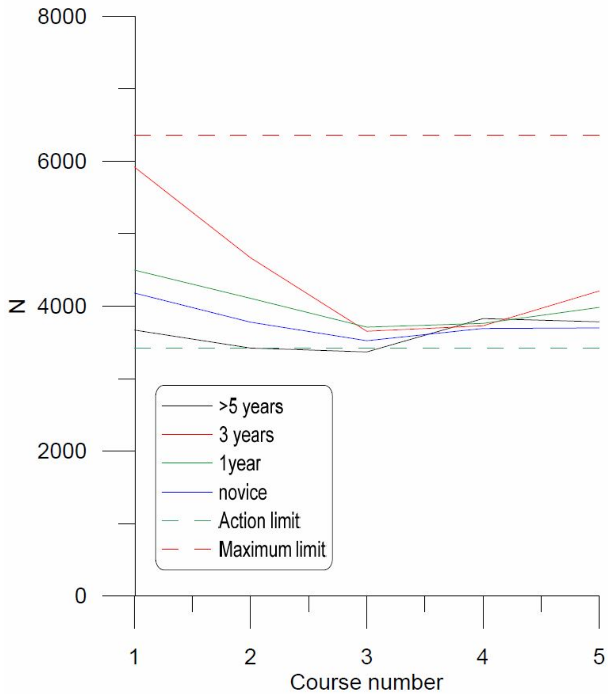

Figure 3: Low back joint compression force

The four groups L4-L5 joint compression forces are shown in figure 4 normalized with respect to each group's average for all blocks. This representation provides an indication of the forces exerted for each course height compared to average exerted force. The first course required from 100-130% above average. On the other hand, the second and third courses required compression forces below average. The same force level pattern is seen in the L5-S1 joint.

Productivity is measured as the number of laid blocks per minute. The build quality was visually assessed at the end of each session, all walls were in an acceptable state by the end of the task. Novice group laid an average of 0.67 block per minute. The one-year experienced apprentices laid an average of 0.99 blocks per minute. Apprentices with three years of experience laid an average of 1.23 blocks per minute. Journeymen laid 1.8 blocks per minute. An association between experience and productivity is apparent from these results, as blocks laid per minute increase with experience.

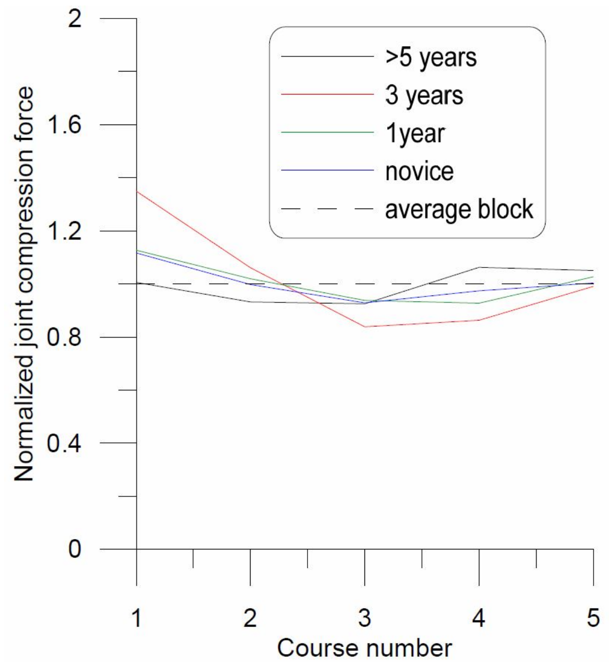

Figure 4: Low back Normalized joint compression forces

DISCUSSION

An initial goal of this effort is to determine the critical joints in the body for masonry tasks. Trunk analysis resulted in the tracking of four parameters, two compression forces and two joint moments. The results revealed that two of these parameters are enough to analyze trunk loads. It was found that the L5-S1 and L4-L5 joints experience the same force profile; however, the L4-L5 joint experiences higher compression forces. Thus, it is safe to use L4-L5 joint compression force to analyze low back forces. Similarly, the Sternoclavicular and L5-S1 joints moments exhibited the same behavior; however, the L5-S1 joint experienced higher moments, thus it can be used to analyze low back joint moment. Limb joints demonstrated differences among joints along the same dynamical link, such as shoulder and elbow. Moreover, differences were found between the dominant and non-dominant sides of the joint. Hence, all limb joints must be analyzed.

NIOSH equation for the design and evaluation of manual lifting tasks [10] recommends that the maximum carried load should not exceed 23kg because it will generate a disk compression force over the safe action limit (AL) set at 3.4kN. Compression forces lower than the action limit can be carried with low risk of injury by 99% of men and 75% of women [11]. However, only 1% of women and 25% of men are capable of carrying loads above the maximum permissible limit (MPL) of 6.4kN. The range between AL and MPL is considered a high-risk zone for low back injuries, hence, workers should minimize the time spent in this region, if avoiding it prove unrealistic.

In the case of masonry, carried loads are lower than 23kg; however, the average low back compression forces shown in figure 3 indicate that workers consistently experience forces in excess of AL, which is in agreement with Faber et al [12]. Although the compression forces do not exceed MPL, the risk of developing low back injuries is significant. Chaffin et al. [13] conclude that high stresses must be avoided in low back because they increase the risk of disk degeneration and that repetitive work at lower stresses is a potential hazard. Masonry work is repetitive, hence, lowering the stresses on the low back must be an objective to decrease the incidence rates of injury. In conclusion, while the loads carried by masons are safe, material handling techniques are not.

Comparing the four experience groups in figure 3, journeymen past the five years experience mark seem to adopt safer techniques and achieve the lowest compression forces and joint moments. In agreement with Plamondon et al. [14], [15], novice workers experience similar low back joint compression forces and moments to those of journeymen. On the other hand, apprentices with three years of experience undergo elevated joint compression forces and moments compared to other groups. We note that lower joint moments indicate lower energy expenditure to complete a task.

As expected journeymen laid more blocks per minute than all other groups, followed by three-year apprentices. However, as the experience increases, figure 5, the increase in productivity is accompanied by an increase in three other parameters: the number of injuries reported, with the same employer, and low back joint compression force and moment. While the increase in production is a desired outcome, the other three facotrs are not. Ideally, it is desirable that apprentices gain proficiency, safety, and productivity over the course of their training while lowering joint loads and injury rates. However, this is not currently the case.

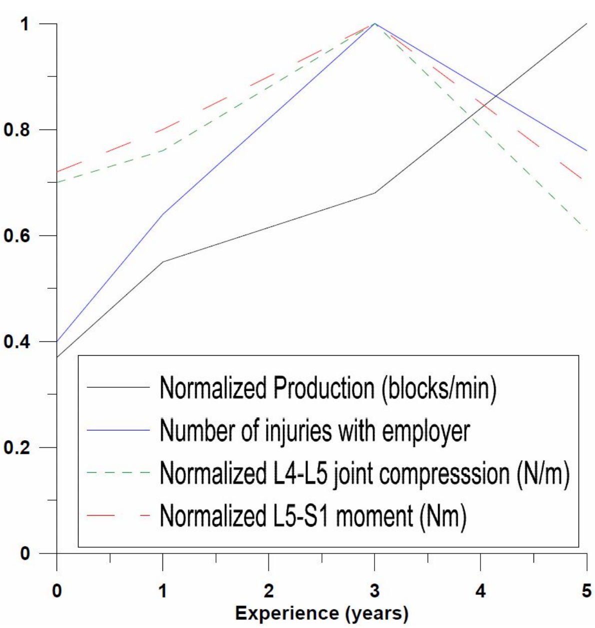

Figure 5: Productivity, injuries, and low back joint force and moment as functions of experience

CONCLUSION AND FUTURE WORK

A controlled experiment involving the building a 12 x 6 blocks wall was carried out to examine the relationships among masons' experience, safety, and productivity. Twenty-one participants distributed in four groups with different experience levels ranging from novice to more than five years of masonry work took part of the study. A combined biomechanical-productivity analysis was conducted to evaluate stresses on masons' major body joints and to assess productivity.

Results show that experience has a significant effect on productivity as journeymen laid more than twice the blocks per minute as novice masons. Novice and experienced journeymen bear lower joint forces and moments compared to one and three-years experience groups. Moreover, joint compression forces and moments were the lowest in journeymen group. Journeymen appear to develop a technique which allow them to be more productive and safe compared to other groups. The three-years experience group sustained the highest joint compression forces and moments. This correlates well with the Bureau of labor statistics [6] finding that workers with three-years experience with the same employer sustained the highest injury rate.

Unlike less experienced groups, journeymen appear to adopt a method of work that maintains similar joint forces and moments across all course heights. Furthermore, the analysis on the effect of course height showed that working on the third course, approximately hip level, generated the least joint forces and moments among all experience groups. This suggests that improvements can be made in bricklaying systems to reduce stresses experienced by masons.

Comparing the performance of masons at all four experience levels suggests that workers who learn to manipulate blocks in an ergonomically safe and productive manner by the five years experience mark enjoy a long-term career. On the other hand, during their first five years, workers gain proficiency and productivity at the cost of safety leading to increased injury rates and lower retention rates.

There is potential for training apprentices to excel in all three aspects: proficiency, productivity, and ergonomic safety. This will help improve workers' welfare and retention rates. More studies are needed to develop those training methods and to extend the use of combined safety-productivity analysis in masonry and other trades. Furthermore, it is recommended to recruit more participant with a view to improving the confidence level of the results. More masons are currently being recruited and improved results reflecting higher confidence levels will be presented at the symposium.

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