DEVELOPMENT AND IMPLEMENTATION OF AUTOMATED APPRENTICE ASSESSMENT TOOL FOR MANUAL HANDLING TASKS IN MASONRY

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ABSTRACT

Construction workers are at risk for musculoskeletal disorders (MSDs) due to the strenuous nature of their jobs, many of which require manual handling of heavy loads. Notably, masonry has one of the highest rates of overexertion and back injuries in construction. For the past several decades, the 'gold standard' for kinematic data collection in the field of biomechanics has been optoelectronic motion capture. However, this system has several drawbacks which prohibits its use in the field. Recent advancements in inertial measurement unit (IMU) technology have led to the development of data collection systems comparable to that of the aforementioned 'gold standard', thereby enabling the quantification of joint loads and forces on masons in the working environment. Previous research has shown that technique during manual handling tasks, such as lifting, can have a large impact on spinal loads. This paper focuses on further development of an automated risk assessment tool to measure and evaluate whole body motions and joint loads of masons while working on-site. The peak joint loads of expert masons while completing seven different masonry tasks are used to establish an upper limit for joint loads that would minimize muscle injury risk. A novel quantitative scoring system is proposed to make the tool to offer the users a simple interpretation of risk assessment. This tool is the first of its kind to propose an MSD risk scoring system based on realistic measurement of biomechanical loads onsite.

KEYWORDS: *biomechanics, ergonomics, musculoskeletal disorders, training*

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INTRODUCTION

Construction workers are at high risk for musculoskeletal disorders (MSDs) due to the strenuous nature of their jobs, many of which require manual handling of heavy loads [1]. Heavy loads, repetitive loads, and awkward postures, synonymous with current masonry practices, are all contributors to increased MSD risk [2-4]. Notably, masonry has one of the highest rates of overexertion and back injuries in construction [1]. This has negative repercussions for worker health and safety as well as their work quality and productivity [5].

Previous research has shown that technique during manual handling tasks, such as lifting, can have a large impact on spinal loads [6]. The comparison of expert and novice working techniques in masonry reveals that expert journeymen use distinct working strategies which can lead to both lower joint forces and increased productivity [7]. Furthermore, training based on expert work strategies has been shown to reduce exposures to biomechanical risks [8-9]. Despite frequency of injuries, MSD risks are often under-prioritized in terms of safety training. In the US construction industry, 91% of companies had a written safety program, but only 69% had a lifting program and only 34% had an ergonomics program [10].

To assess the internal physical demands on the human body, it is necessary to analyze the movements of (kinematics) and forces applied to (kinetics) the body during masonry. In the field of biomechanics, the 'gold standard' of the past several decades for collecting kinematic data has been optoelectronic motion capture [11]. This motion capture system uses cameras and reflective or light-emitting markers attached to the body to capture the movement of the body parts. However, it has several drawbacks which prohibit its use in the field, including high cost, low portability, additional labour and set-up and line-of-sight requirements [12]. Recent advancements in inertial measurement unit (IMU) technology has led to the development of data collection systems comparable to that of the gold standard, thereby enabling a practical, low-cost, accurate method to capture kinematics in complex working environments. Used in conjunction with dynamic modelling processes, the internal joint loads and forces experienced by masons can be calculated. These biomechanical exposures are then correlated with MSD risk [4].

This paper focuses on further development of an automated risk assessment tool to measure and evaluate whole body motions and joint loads of masons while working on-site. The peak joint loads of expert masons while completing seven different masonry tasks are used to establish an upper limit for joint loads to minimize muscle injury risk. Using the peak load profiles of expert masons enables the development of joint thresholds which are more evidence-based, practical and industry-specific to the masonry sector. A novel quantitative scoring system is proposed to make the tool more user friendly and easy to understand. This tool is the first of its kind to propose an MSD risk scoring system based on onsite measurement of biomechanical loads. It has the capacity to improve manual handling training by providing quantitative load metrics and estimates of risk, deployable as learning indicators. The automated assessment tool can also be used to provide insight into MSD risks associated with job and workstation design and can be leveraged to improve workplace ergonomics.

ASSESSMENT TOOL

An ergonomic assessment tool was created to capture biomechanical motion data from masons on-site and evaluate joint loads and muscle injury risk [13]. IMU sensors are worn by the participant while completing a task and the output from the IMU sensor system is processed by the assessment tool software. The participant is also filmed on video, to visualize the recorded movements, alongside the kinematic data. Additional information is inputted into the software program manually, such as the participants' height and weight, as well as the timestamps and hands associated with manual handling. After task completion by the participant the assessment tool uses inverse dynamics to estimate the net joint forces and moments, namely low back compression force and shear forces at the L4/L5 disc, shoulder, elbow, hip, knee and ankle. The tool generates a report, Figure 1, which identifies critical moments where the loads on the joints are particularly high and provides a video replay of the at-risk movement, a graph of the joint moment including those critical points, and a colour-coded stick figure to represent the risk at various joints in the body.

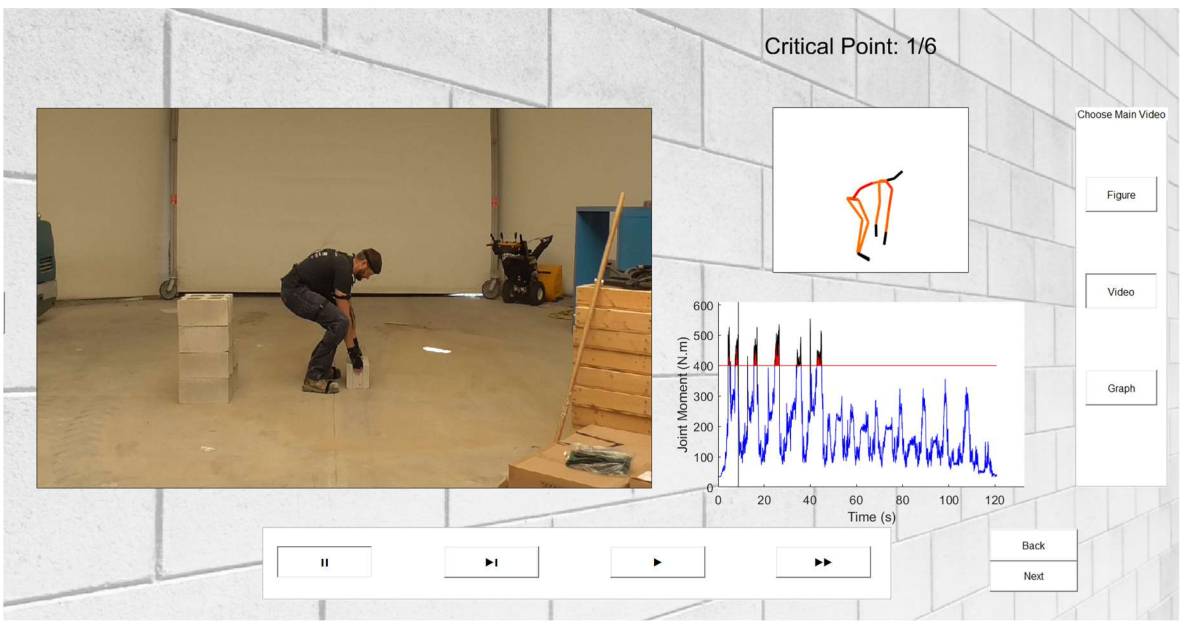

Figure 1: Graphical Interface of the Assessment Tool Critical Point Report

The automated assessment tool enables the evaluation of risk directly from estimated forces and moments measured while masons are working on-site. This is especially novel given that the majority of onsite assessment tools in the industry still rely on observational techniques of postures to estimate risk, e.g. RULA, REBA, and are not suited for manual materials handling tasks [14]. However, further improvements to the tool are still necessary. In the absence of established thresholds for joint moments and forces, the assessment tool used 80% of the peak force or moment to act as a threshold for defining critical points. The tool also reported the loads at the critical points in N or N•m, which without context, is not meaningful to masons without expertise in biomechanics.

METHODS

Data Collection & Processing

Participants completed seven different masonry tasks. The first four tasks consisted of laying the first course of a standard wall, building a standard wall from a pre-built lead wall, building a reinforced wall (rebar), and building a wall under a ceiling (in a constrained space), all using 20 cm hollow concrete masonry units (CMUs), weighing 16.6 kg. The last three tasks consisted of building a wall individually using 30 cm hollow 23 kg CMUs and building a wall while collaboratively lifting with another mason, using 30 cm hollow 23 kg CMUs and 30 cm semi-solid 35.2 kg CMUs. These seven tasks were chosen to represent the variety of physical demands in the masonry trade. Eight expert masons were recruited from the Ontario Masonry Training Centre (Mississauga, Ontario). The participants were all red-seal journeymen with 20 or more years of experience. All the experts were male masons, with an average height of 179.63 cm (±4.78) and an average weight of 90.8 kg (±12.03). Their average age (estimated based on years of experience and typical masonry career commencement) was over 40 years old.

Motion data was captured at a sampling rate of 125 Hz using wireless inertial measurement unit (IMU) suits from Perception Neuron (Noitom, USA). The motion suit had 17 IMUs attached to the head, neck, pelvis, shoulders, upper and lower arms, thighs, legs, hands, and feet. Data from the IMUs were processed by Axis Neuron software, which reconstructed skeletal models. Body segment location and orientation data was then exported as Biovision Hierarchy (BVH) files. An inverse dynamic model developed by the research group was used to calculate the joint loads.

Data Analysis

The motion data collected from the eight masons was used to estimate the peak joint loads representative of expert movement in masonry. The peak joint forces or moments per task, was averaged across all tasks (and left and right joints, where applicable) to calculate the average loads within masonry at each of the joints. The average peak loads were then used to establish a threshold for MSD risk, accounting for a wide variety of masonry tasks and physical demands.

Since all the expert motion data came from male participants, a ratio was used to determine equivalent thresholds for female masons. Lifting strength of females was reported to be between 60-76% of male lifting strength on average [15] with both overall strength and back strength reported as roughly two thirds of their male counterparts [16-17]. The values range differ slightly between lower body strength and upper body strength [16, 18] but based on overall strength ratios in the literature, the female thresholds were set to 66% of the male force or moment equivalent for all joints.

RESULTS & DISCUSSION

Expert masons experienced the greatest peak L4/L5 compression and shear forces when completing the heavy individual wall build with 23 kg CMUs, followed by the collaborative lifting (2-person lifts) wall build with 36 kg CMUs, Figure 2. For six of the seven masonry tasks analysed

(85.7%), the L4/L5 compression forces exceeded loading threshold recommended by the National Institute of Occupational Safety and Health (NIOSH), namely the action limit set to 3433 N, by 256.6-1768.2 N (7.47-51.51%) [19]. Furthermore, four of the seven tasks (57%) exceeded the recommended shear action limit for lifts over 100 lifts/day by 111.0-417.9 N (22.6-85.2%) [20]. It should be noted however, that these values represent peak forces rather than average forces. Peak forces and moments were used as thresholds to account for the individual variability and the range of values around the mean to better establish an upper limit for risk.

The peak expert forces were used for the threshold and scoring system instead of the widely used NIOSH and shear limit values due to their specific applicability to the masonry industry. Some researchers have criticized the NIOSH values for lack of sex or age specificity, and lack of epidemiological and biomechanical evidence [21]. The NIOSH thresholds may be more conservative due to their lack of sex specificity. Additionally, 20-year-old males have been reported to have an average low back compression strength of approximately 8000 N, while 40-year-old males have an average low back compression strength of approximately 6700 N, both of which are above the NIOSH action limit and maximum permissible limit [22]. Non-sex specificity is a major shortcoming especially when data has shown a significant disparity between the sexes [15-18]. This is a flaw in practice that our software is correcting by setting thresholds and scores based on the subject's sex. This is especially pertinent, given that the masonry sector is overwhelming male-dominated [23]. Additionally, use of expert motion data better tailors the thresholds to realistic load exposures and practical application within the masonry industry.

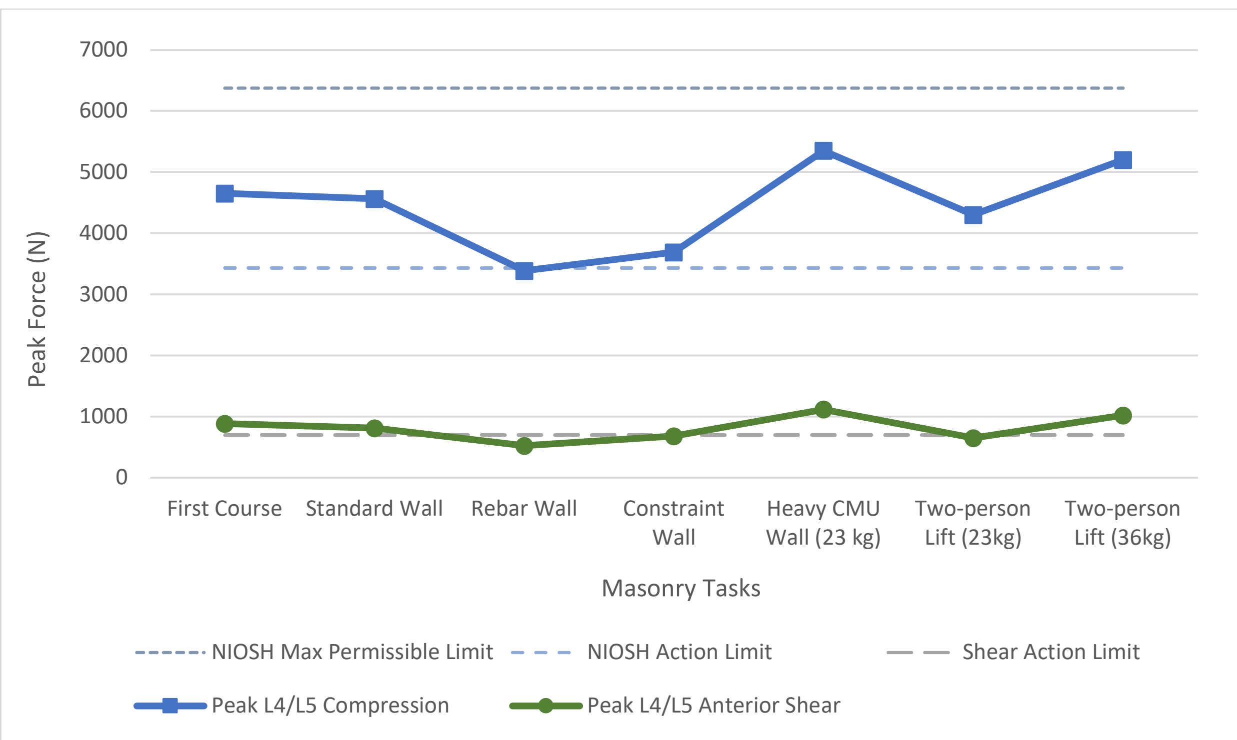

Figure 2: Peak Low Back Forces Across Masonry Tasks

Experts experienced higher peak moments on the lower body compared to the upper body, Figure 3. For the lower body, the standard wall task resulted in the highest moments, while for the upper body, the heavy individual wall builds with the 23 kg CMU and the collaborative lifting wall build with the 36 kg CMU resulted in the highest moments. The lower body joints all experienced peak moments within a range of 186.9-374.5 N•m with the ankle joint consistently experiencing the highest moments throughout the seven tasks. For the upper body, the joint moments all fell within a range of 4.5-55.2 Nm, with the shoulders consistently experiencing the highest moments. This falls in line with previous research that indicated the shoulders are the second leading body part affected by MSDs in construction [24]. There is a lack of clear, practical, moment-based exposure thresholds for these joints in the literature.

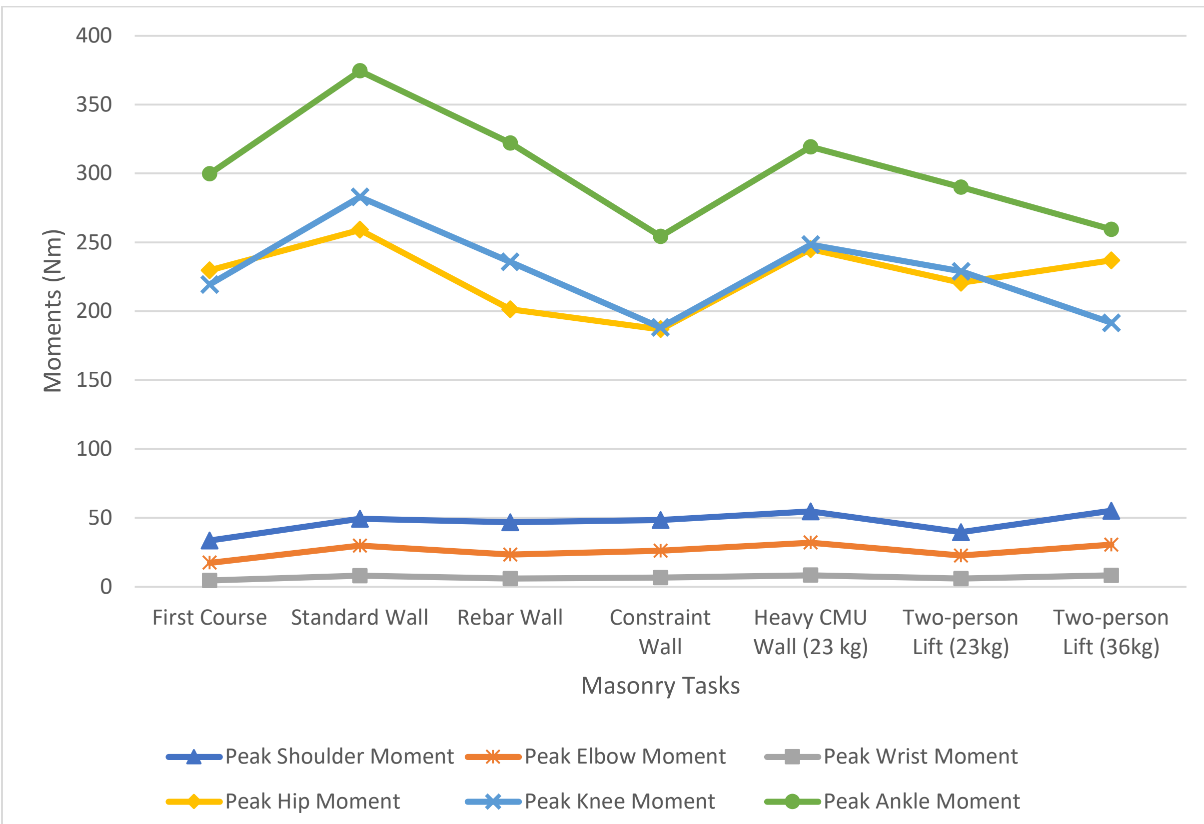

Figure 3: Peak Upper and Lower Body Joint Moments Across Masonry Tasks

For implementation within the automated assessment tool, the peak forces were averaged across all seven masonry tasks. Additionally, equivalent female forces and moments were calculated for each of the joint thresholds to provide sex-specific thresholds. The final values of the thresholds are depicted in Figure 4. A NIOSH-like framework was implemented with the action limit (AL) and maximum permissible limit (MPL) thresholds underlying the scoring system [19]. The peak expert loads were adopted as action limits and twice the peak expert loads were established as the maximum permissible limits. Forces or moments below the AL are considered low risk; forces or moments above the AL but below the MPL are moderate to high risk; and forces or moments above the MPL represent very high risk to the exposed individual.

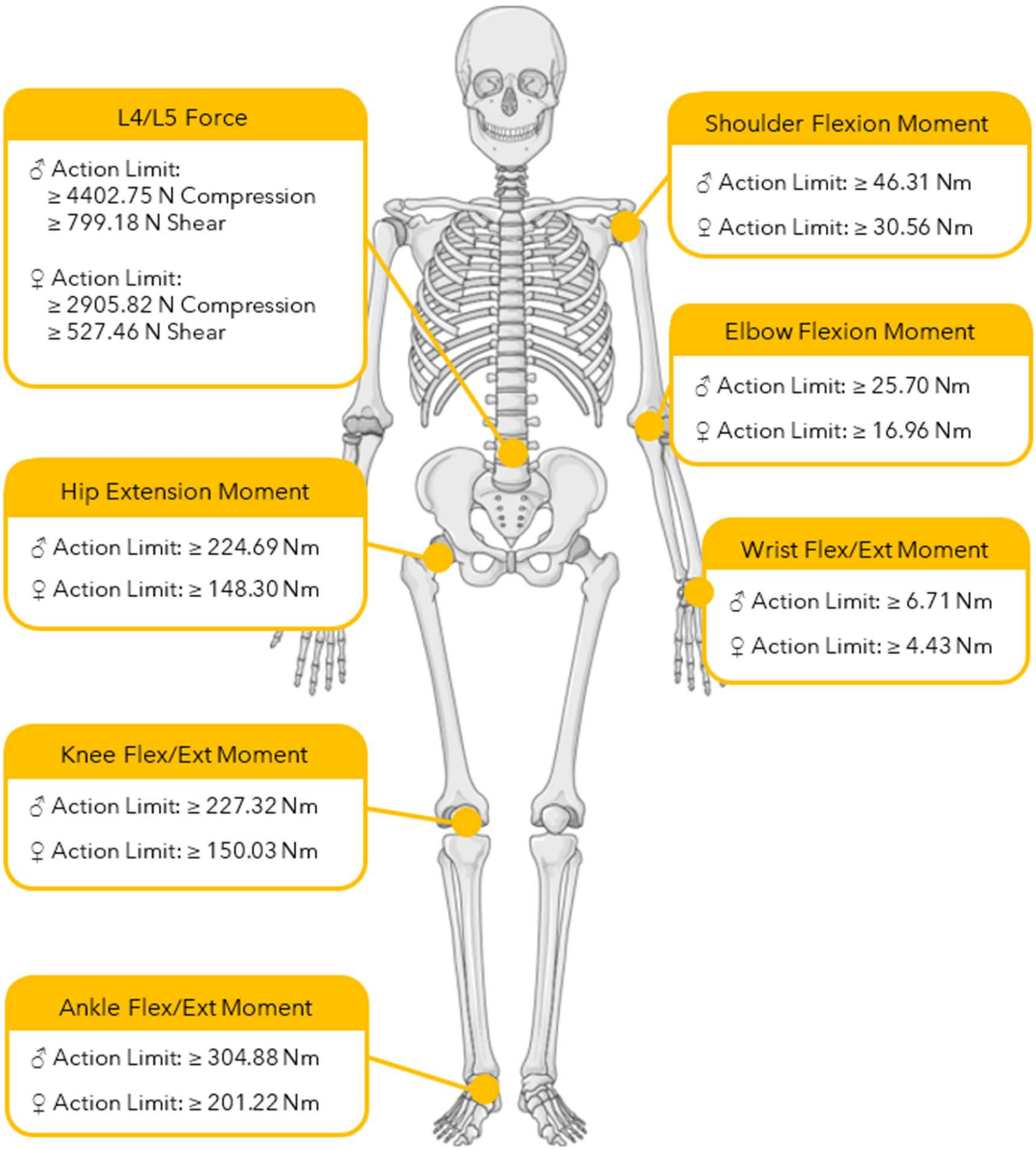

Figure 4: Male and Female Joint Load Thresholds Implemented in the Assessment Tool

SCORING SYSTEM

The joint score (S_J) is calculated as the ratio of the joint load (moment in N•m or force in N) to the respective action limit (moment in N•m or force in N).

$$S_J = [Joint\ Load/Action\ Limit] \times 100 \quad (1)$$

The whole-body score (S_{WB}) is the weighted sum of the joint scores (S_J) for all the joints in the body.

$$S_{WB} = [\textstyle\sum_A (Joint\ Load/Action\ Limit) \times 1 + \sum_B (Joint\ Load/Action\ Limit) \times 0.5] \times [100/9] \quad (2)$$

where joint group A (L4/L5 compression and shear forces, as well as the left and right shoulder flexion moments) are fully weighted to reflect greater contribution to the risk score than joint group B (all other joints, namely left and right elbow, wrist, hip, knee, and ankle, flexion/extension moments) which are half weighted. The whole-body score is weighted to prioritize exposure at the low back and the shoulders based on past evidence of increased risk for these joints in construction [24]. The sum is then multiplied by a factor to produce a final numeric score. The scores are then contextualized for risk as depicted in Figure 5.

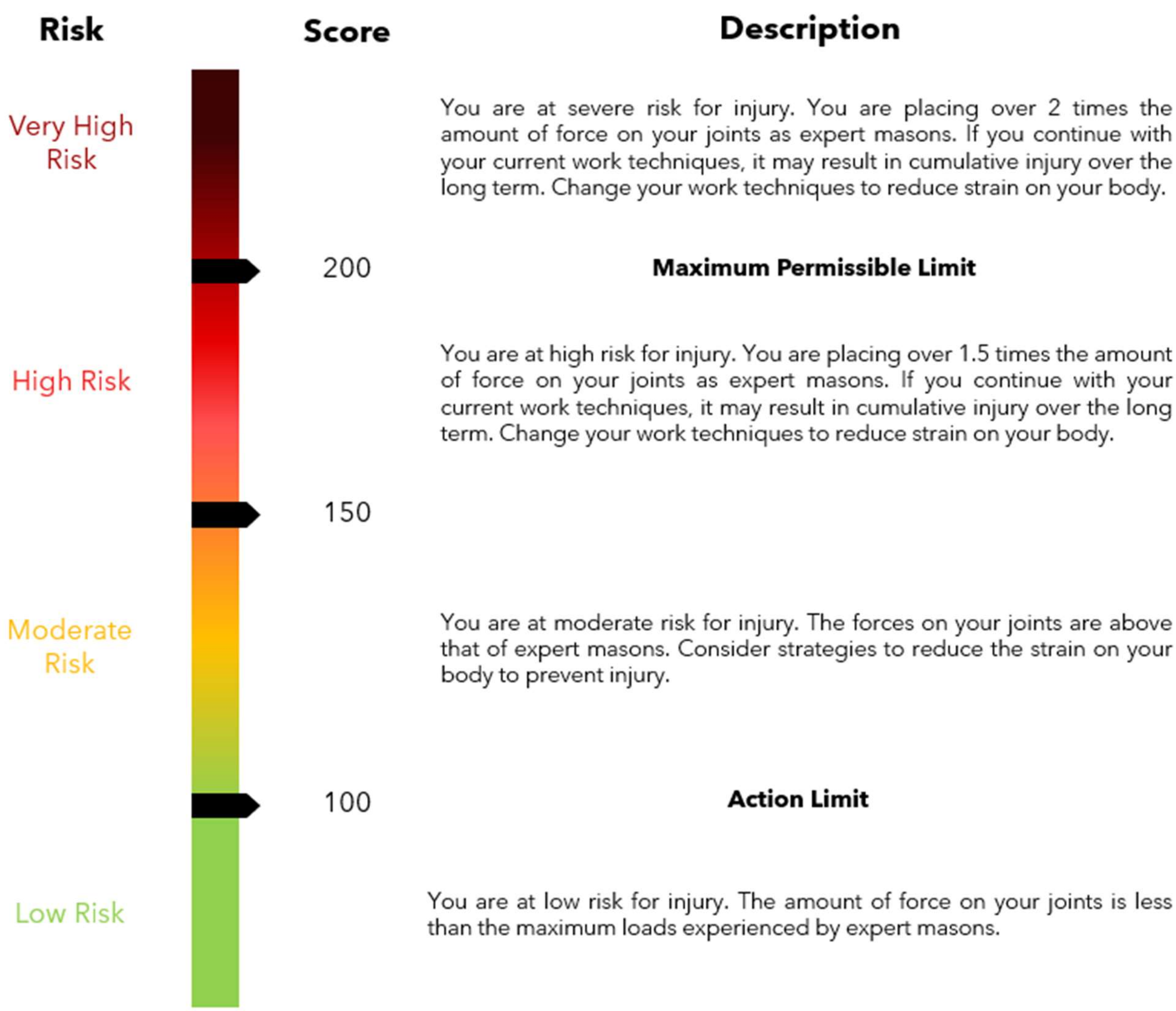

Figure 5: Scoring System

APPLICATION

These thresholds and scoring system will be implemented into the automated assessment tool as the new criteria for critical point identification. The critical points will be based on individual joints scores S_J larger than 100; joint loads that exceed their respective action limit. Alongside individual joint scores, the whole body score S_{WB} will also be provided. This tool is designed to be used within a larger manual handling training program for masonry apprentices, where assessment is only one component. While the current assessment tool can estimate joint loads and MSD risk, future work will identify at-risk movements, and provide recommendations to improve movement techniques and reduce MSD risk. The assessment component will then act as a learning indicator to depict potential progress or improvements over the course of the training program.

CONCLUSIONS & RECOMMENDATIONS

Masons face high physical demands and thus are more susceptible to MSDs. Onsite assessment of these physical loads is difficult for practitioners and typically results in the use of observational based methods. There is a lack of established risk thresholds for moments at joints besides the low back. This automated assessment tool is the first to propose an industry-specific biomechanical scoring system based on the onsite measurement of joint loads and grounded in expert motion data. The methodology used to develop the thresholds and scoring system can be applied to other construction trades and manual handling tasks in other industries. Limitations of the tool includes a lack of female mason representation in the data collection, resulting in a reliance on ratios from the literature to establish threshold values. Additionally, neck flexion and extension moments were absent from the developed thresholds. Furthermore, the scoring system is not supported by epidemiological data and future research needs to investigate the validity of the scoring system for the assessment of MSD risk, and further refine the scoring system. Future development of the tool will eliminate estimations of ground reaction forces as an input into the inverse model, as well as integrate postural feedback and training recommendations to improve apprentices' lifting techniques.

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