A Biomechanical Strain Index to Evaluate Shoulder Stress

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Abstract

Work-related forceful arm exertions are epidemiologically associated with musculoskeletal disorders (MSDs) of the shoulder. Previous studies have reported a significant stress-strain relationship for the shoulder complex during physically demanding exertions. However, a clear assessment method to evaluate the risk of injury to the shoulder complex during forceful arm exertions currently does not exist. The objective of this study was to develop and validate a new shoulder strain index. Specifically, the concept of the concavity compression mechanism which stabilizes the glenohumeral joint was used to develop the proposed strain index through the performance of a lab-based study. Human participants performed forceful arm exertions of varying magnitude in six orthogonal directions and reported their subjective perceived exertion rating. Reaction forces acting at the glenohumeral joint were estimated using a biomechanical model. The angular deviations of the resultant force vectors under different model configurations were used to estimate the strain index. A significant correlation of 0.70 was observed between strain index scores and ratings of perceived exertion (p<0.001) indicating that the proposed strain index can reasonably predict physical loading of the shoulder complex.

Keywords
Shoulder, stability, concavity compression, musculoskeletal disorders

1. Introduction

Musculoskeletal disorders (MSDs) are non-traumatic soft tissue disorders that can be caused and/or exacerbated by workplace exertions [1-3]. MSDs place a heavy burden on both employer and worker in terms of health and economic costs. In particular, MSDs of the shoulder are a major cause of morbidity and pain in the modern working population. In 2011, shoulder disorders were the second most prevalent type of MSD after the low back, but were the most severe requiring 21 median days away from work for recovery [4].

Previous epidemiological investigations have found evidence that several work-related exposures are associated with the development of shoulder disorders. These past studies have proposed that exposures such as awkward and prolonged sustained postures of the upper extremities, and repetitive and forceful arm exertions can lead to work-related shoulder disorders [1, 3, 5-7]. In particular, exposure to forceful arm exertions in pushing and pulling directions were associated with shoulder MSDs [1, 4, 8]. A significant dose-response relation between pushing and pulling exertions and shoulder complaints was also reported in a previous study [9].

The shoulder complex is the most mobile part of the human body with a range of motion covering nearly 65% of a sphere [10]. The high level of mobility of the shoulder complex allows a person to adopt a wide variety of postures and facilitates in the application of forces of varying magnitude in nearly any direction. However, in exchange for its high flexibility and force exertion capabilities, the shoulder sacrifices its inherent stability [11]. The glenohumeral joint is the main joint of the shoulder and provides much of the shoulder’s mobility. It functions as a ball-and-socket type joint where the rounded protrusion of the humerus of the upper arm fits together with the glenoid cavity, or the shoulder socket, of the scapula. The glenohumeral joint is characteristically unstable in that the humeral head is not fully encapsulated by the glenoid with only around 30% of the humeral head in contact with the glenoid in various shoulder postures [12]. Because of this, the glenohumeral joint is typically stabilized by the forces produced by the shoulder muscles that press the humeral head into the glenoid cavity through a mechanism called “concavity compression” and is destabilized by translational forces that push the humeral head away from the glenoid [13].
Forceful arm exertions which are commonly performed in the workplace can alter the compressive and translational forces acting on the glenohumeral joint. Such exertions, especially pushing and pulling, can potentially destabilize the glenohumeral joint with high translational forces and may place the shoulder at an increased risk for injury. Currently no method exists to evaluate strain experienced by the shoulder complex during forceful arm exertions that generate varying levels of concavity compression. Therefore, the purpose of this study was to develop and validate a new shoulder strain index to evaluate shoulder strain during work-related forceful arm exertions. Specifically, the concept of the concavity compression mechanism which stabilizes the glenohumeral joint was used to develop the proposed strain index through the performance of a lab-based study.

2. Methodology

2.1. Approach

Human participants performed forceful push/pull arm exertions in six orthogonal directions using three different force levels. The experimental data was modeled using a biomechanical model of the shoulder complex to quantify the forces placed at the glenohumeral joint of the shoulder. The modeling analysis was performed under two conditions; one with muscles and the other without muscles. The resultant of the reaction forces obtained under the without model configuration takes into account only the forces caused by external loading and is always opposite to the direction of the external force application. On the other hand, the resultant of the reaction forces under the with muscle configuration must instead be redirected towards the shoulder by the shoulder muscles in order to improve the joint’s stability by enhancing the concavity compression (Figure 1). Thus, the change between the angular deviations of the resultant force vectors of these two conditions provides a direct assessment of the strain experienced by the shoulder complex during forceful arm exertions. The strain index, which indicates the amount of strain experienced by the shoulder during the exertions, was developed based on the angular vector deviations and magnitudes of the resultant forces between the with muscle and without muscle model configurations. This index was then validated using the ratings of perceived exertion recorded during the forceful arm exertions.

![Figure 1: Biomechanical model showing the resultant force vectors between two model configurations. Blue: without shoulder muscles; Red: with shoulder muscles.](image-url)

2.2. Participants

In this ongoing study, four male participants between the ages of 18 and 40 have been recruited to participate so far. Participants were excluded from the research if they had any type of musculoskeletal, degenerative, or neurological disorder or if they had a history of shoulder pain or any current pain. The Physical Activity Readiness Questionnaire (PAR-Q, Canadian Society for Exercise Physiology) was used to screen participants for cardiac and other health problems (e.g., dizziness, chest pain, and heart trouble). Participants who met the inclusion criteria were asked to
read and sign a consent form approved by the local Institutional Review Board. Mean (SD) age, height, and weight of participants was 24.8 (3.3) years, 178.3 (3.4) cm, and 73.0 (4.5) kg, respectively.

2.3. Equipment

2.3.1. Custom-built Force Exertion Device

This device consists of a wooden chair attached to a column and base assembly fitted with a bar-handle peripheral assembly (Figure 2). The chair is equipped with a four-point harness to secure participants in a standard sitting posture in order to prevent any upper body movement that would otherwise interfere with the data collection (Figure 2(a)). The column and base assembly sits directly in front of the chair and serves as an attachment point to the bar-handle assembly. The bar-handle consists of a small horizontal metal bar mounted to the sturdy, immobile base portion of the assembly. A D-handle is attached to this bar and is able to be adjusted along the bar’s length. The D-handle attachment consists of a small steel plate mounted onto its back that is screwed onto the face of a Force/Torque (F/T) sensor (Figure 2(b)). In addition to the bar-handle assembly, the base assembly also has an attached computer monitor that faces the participant. This monitor is able to display a real-time force exertion level graph that provides bio-feedback to the participants in order to help them maintain a target force exertion during the experiment (Figure 2(c)). Force data from the F/T sensor is acquired using a TeleMyo 2400R G2 receiver at a frequency of 1000 Hz (Noraxon USA Inc., Scottsdale, AZ). The MyoResearch XP analysis software (Noraxon USA Inc., Scottsdale, AZ) is used to display a real-time force exertion level graph to the participants.

![Figure 2: Force exertion device: (a) chair with four-point harness facing bar-handle assembly and computer monitor, (b) F/T sensor mounted with a handle and attached to bar, and (c) force level feedback screen.](image)

2.3.2. Biomechanical Model

The resultant reaction forces acting at the glenohumeral joint during forceful arm exertions was estimated using the AnyBody Modeling System™ (version 5.0, AnyBody Technology, Aalborg, Denmark). This is a full-body
biomechanical modeling system. Models are formulated using AnyBody’s AnyScript modeling language. The models consist of bones, joints, and muscle-tendon units based on real physiological properties. Joints are driven by experimentally obtained kinematic and kinetic data. Muscle and joint forces are computed by using inverse dynamics analysis.

2.4. Experimental Design
A two-factor replicated block design was used in this research. Factor 1, direction of force exertion, was treated at six levels: 1) anterior (+X), 2) superior (+Y), 3) lateral (+Z), 4) posterior (-X), 5) inferior (-Y), and 6) medial (-Z). Factor 2, force exertion level, was treated at three fixed levels: 1) 20 N, 2) 40 N, and 3) 60 N. These force exertion levels approximately represent low, medium, and high exertion demands and are obtained based on the findings of our preliminary study [14]. Each force exertion trial was approximately 20 seconds long: The first 5 seconds were used for force build up, followed by 10 seconds of constant force exertion, and the last 5 seconds were used to return to zero force exertion. Three replicates were collected for each experimental condition. In total, 54 experimental trials (6 direction × 3 force exertion levels × 3 replications) were collected from each individual participant and the trial order was completely randomized. A rest period of 45 to 60 seconds was provided between the experimental trials to mitigate fatigue.

2.5. Experimental Data Collection
Upon arriving at the laboratory, participants were provided with a tour of the experimental set-up. Equipment, data collection procedures, and specifics of the experimental tasks were explained to the participants and their signatures were obtained on a consent form approved by the local Institutional Review Board. A set of anthropometric measures such as height, weight, and age were then recorded for each participant for later use in the biomechanical analysis. Participants were then seated and secured into the wooden chair of the force exertion device using the four-point harness. The position of the D-handle was adjusted such that the participant could grasp it using an 80°- 90° flexed elbow joint and a 5°- 10° flexed shoulder joint. Next, they were instructed on how to perform the forceful arm exertion tasks and were allowed to practice in order to familiarize themselves with the nature of the exertion. After they felt comfortable in performing the exertions, the maximum force exertion ability in the six previously mentioned directions were measured for each participant to make sure that they had sufficient strength to conduct the experimental trials. Following the above preparatory steps, participants then performed forceful arm exertions along six directions at three force levels. After the completion of each exertion, the participant was asked to numerically rate their perceived exertion using Borg’s CR-10 scale. The Borg CR-10 scale contains two columns, one for subjective categories ranging from “nothing at all” to “extremely strong” and the other for numerical ratios ranging on a scale of 0 to 10 that are associated with the different categories [15].

2.6. Data Processing and Analysis
A biomechanical model was used to quantify the loading placed on the shoulder complex. This model is part of the model repository provided by AnyBody Technology as part of their AnyBody Modeling System™. The model consists of 118 muscle fascicles and defines the three main shoulder complex joints: the glenohumeral joint, the acromioclavicular joint, and the sternoclavicular joint. The muscle forces required to generate motion or sustain body posture are computed using inverse-dynamic methods by solving a multi-body dynamics problem. The muscle recruitment in the inverse dynamics process is solved using a min/max optimization procedure within which the objective function is to minimize the maximal normalized muscle force subject to equilibrium constraints and lower bounds on force (i.e., all forces must be in the “pull” direction) [16]. The model was scaled for each participant based on their individual anthropometrical data. The outcomes of the biomechanical analysis include the reaction forces acting on the shoulder complex in the three anatomical directions (distraction (medial-lateral), inferior-superior, and anterior-posterior). The reaction forces acting at the primary shoulder joint, the glenohumeral joint, were obtained by running the model under two different model configurations: without muscles and with muscles.

2.6.1. Strain Index Calculation
Reaction forces in the distraction direction help improve the concavity compression of the glenohumeral joint [13, 17, 18]. Therefore, the angular vector deviation and magnitude of the resultant force vectors in the distraction (medial-lateral) direction were used to develop the proposed strain index. To estimate the angular vector deviation in the distraction direction, the force vector for the resultant of the reaction forces was mirrored onto a two dimensional plane representing the frontal body plane (Figure 3).
Figures 3: Angle definitions graphed in the frontal plane used in the calculation of the strain index. Blue: without muscle condition; Red: with muscle condition.

Angles $\beta$ and $\beta'$ correspond to the angles the resultant force vector makes with the Y-axis for the without muscle configuration and with muscle configuration, respectively (Equation (1)).

$$\beta = \tan^{-1} \left( \frac{F_z}{F_y} \right)$$  

(1)

The strain index was estimated using changes in the orientation and magnitude of the resultant forces between the with muscle and without muscle model configurations using the following equation (2):

$$Strain \text{ Index} = A_1 + \frac{(M' - M)}{(M' - M)_{max}}$$  

(2)

Where,

$$A_1 = \left( \frac{(|\beta| + |\beta'|)}{180^\circ} \right)$$

$$M = \sqrt{fx^2 + fy^2 + fz^2}; f_x, f_y, \text{ and } f_z \text{ are reaction forces at the glenohumeral joint under the without muscle condition}$$

$$M' = \sqrt{(f'x'^2 + f'y'^2 + f'z'^2)}; f'_x, f'_y, \text{ and } f'_z \text{ are reaction forces at the glenohumeral joint under the with muscle condition}$$

Note that the angular deviation ($A_1$) and changes in the magnitude ($M$ and $M'$) are normalized to standardize these values to change between 0-1 and the resulting strain index to change between 0 to 2 (0 – low or no strain, 2 – high strain).

2.6.2. Statistical Analysis

The ability of the strain index to predict strain experienced by the shoulder complex during forceful arm exertions was evaluated by performing a correlation analysis between the strain index scores and the ratings of perceived
exertion. Additionally, ANOVA models were used to analyze the effects of direction of force exertion and force exertion level on the strain index. Significant effects were further evaluated by conducting comparison between means using Tukey’s Honestly Significant Difference (HSD) all-pairwise comparison test. The significance of correlation analysis and the ANOVA models was tested at p <0.05. Minitab 16 statistical analysis software (Minitab Inc., PA, USA) was used to perform the analysis.

3. Results
A significant correlation of 0.7 was observed between the calculated strain index scores and the ratings of perceived exertion (p<0.001) (Figure 4). The strain index scores were significantly affected by the direction of force exertion (p<0.001). The maximum strain index score (1.72) was observed for an exertion performed in the lateral (+Z) direction. The lowest strain index score (0.40) was tied between an exertion performed in the posterior (-X) direction and another in the inferior (-Y) direction. In general however, higher strain index scores occurred for forceful arm exertions performed in the lateral (+Z) direction while the lowest scores were typically seen in the posterior (-X) direction. Post hoc analysis showed that forceful exertions in the lateral (+Z) and posterior (-X) directions were significantly different from the other directions. Strain index scores were also significantly affected by the force exertion level (p<0.001); the strain index increased as the force exertion level increased.

![Figure 4: Strain index values and perceived exertion ratings by exertion direction and force exertion level. Error bars represent one standard deviation.](image)

4. Discussion & Conclusions
The proposed shoulder strain index is based on the concept of the concavity compression mechanism, i.e., during forceful arm exertions, the shoulder stabilizer muscles compress or pull the upper arm (head of the humerus) into the shoulder socket (glenoid) by counteracting the forces generated by external loading. A high strain index corresponds to the high work demand placed on the shoulder muscles to improve the concavity compression.

The highest strain index was observed for exertions performed in the lateral (+Z) direction. For these exertions, the resultant distraction forces due to “external loading only” (without muscle condition) are directed laterally outward from the shoulder (Figure 5). The forces generated by the shoulder muscles re-direct the resultant distraction forces inside the shoulder socket to improve stability through the concavity compression of the glenohumeral joint. The shoulder muscles have to work hard under duress to achieve this change in orientation of the resultant distraction forces, resulting in high strain indexes and perceived exertion ratings. On the other hand, for exertions performed in
the posterior (-X) direction, the resultant distraction forces due to “external loading only” (without muscle condition) are already directed inside the shoulder socket (Figure 5) and therefore require minimum contribution by the forces generated by the shoulder muscles to improve the concavity compression of the glenohumeral joint, resulting in low strain indexes and perceived exertion ratings.

Several limitations should be considered while interpreting and translating findings of this study to real workplace situations. First, standardized static exertions performed in a seated posture were used in the estimation of the proposed strain index. The duration of the exertions was kept relatively short in order to reduce the risk of injury or discomfort to the participant. Exertions performed in the workplace are typically dynamic in nature and may involve the use of complex upper extremity postures. Second, only young male participants with little manual material handling experience were tested in this study. Experienced individuals as well as females may exhibit different force exertion strategies and ratings of perceived exertion. Third, the estimation of the proposed strain index requires use of AnyBody or a similar type of biomechanical modeling system. This may pose difficulty in using the proposed strain index in practice if modelling systems are not available. Future studies should look at larger, more diverse populations and different types of physical exertions (dynamic, repetitive, non-neutral upper extremity postures, etc.). Additionally, the strain index quantification methods should be further simplified for possible field application.

Overall, the results of this study indicate that the proposed strain index can reasonably predict the physical loading taking place on the shoulder during forceful arm exertions and may have the potential as a new method for the evaluation of the physical risk factors associated with work-related exertions.
References