

Development of a Predictive Equation to Estimate Strain at the Shoulder

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Abstract: Musculoskeletal Disorders of the shoulder have a significant impact. Few ergonomic/biomechanical analysis methods exist that include the shoulder, and no methods exist that focus on the shoulder exclusively. The objective of this research was to develop a predictive equation that can estimate relative risk of shoulder injury for a single-handed lifting task based on the location of a load from the sternal notch. Five male participants were recruited to perform a series of right-handed lifting tasks throughout the working range of the right arm at 8" intervals (forward/backward, left/right, and up/down) from the sternal notch. After each trial, participants rated their perceived exertion on a 10-point Borg scale. Experimental trials were modeled in AnyBody Musculoskeletal Modeling System and the glenohumeral reaction force output was used as input into a previously developed strain index equation for the shoulder. Regression methods were used to develop regression equations that accurately predicted the strain index results with distances from the sternal notch to the load as predictors. These four regression equations were used to calculate predicted values for each trial and analyzed using correlation with strain index values and exertion rating and RMSE between the predicted values and the strain index values. The resulting predictive equation had 8 terms with an $R^2=75.68\%$, correlation with strain index of $r=0.8783$, correlation with perceived exertion rated or $r=0.6244$, and $RMSE= 8.0029$.

Keywords: Musculoskeletal Modeling, Shoulder, Musculoskeletal Disorders

1. Introduction

1.1 Impact of Work-Related Musculoskeletal Disorders of the Shoulder

Workplace injuries and musculoskeletal disorders (MSDs) commonly affect the shoulders, resulting in considerable direct and indirect costs. According to data from the U.S. Bureau of Labor Statistics (2017), shoulder injuries represented 14.9% of all work-related musculoskeletal disorders in 2016. Despite being less common than musculoskeletal disorders of the low back and knee, injuries to the shoulder tend to be the most severe, requiring a median of 25 days away from work compared to 7 and 15 days for the low back and knees, respectively. Several analyses have been performed to determine the prevalence, costs, characteristics, and outcomes of Work-related MSDs in different states. An analysis of Washington State Worker's Compensation data from 1997-2005 revealed shoulder claims as having the highest per claim cost, with an average cost \$16,092 per claim and a median cost of \$1,111 per claim over 46,479 claims, resulting in a total claim cost of \$645 million (Silverstein and Adams, 2007). Similar analyses were performed with data from 2002-2010 (Anderson et al., 2015) and 2006-2015 (Howard and Adams, 2018) revealing an average per claim cost of \$60,298 over 29,046 claims and \$65,053 over 31,366 claims, respectively.

1.2 Current Analysis Methods

Due to the high medical costs, loss of productivity, and reduced quality of life due to shoulder MSDs, there is a drastic need for workplace job analysis to determine the risk for shoulder MSDs. Currently, very few methods exist that consider the shoulder. Rapid Upper Limb Assessment (RULA) is a qualitative task analysis tool where posture of the upper body, muscle use (repetitive vs. static load), and force/load are used to generate a grand score between 1 and 7 that is broken down into 3 risk categories (McAtamney et al. 1993). Since the posture determinations are approximate ranges and the other scores are based on easy to determine criteria (e.g. "Add 1 if trunk is twisting"), RULA requires no special equipment and only a

rudimentary knowledge of kinesiology making it very easy to apply. However, the grand score doesn't provide any information specific to the shoulder and only advises whether the task is acceptable or how urgently it needs to be addressed.

The Rapid Entire Body Assessment (REBA) tool functions similarly to RULA, but uses full body posture, force/load, and load coupling as criteria to generate a score between 1 and 15, divided into 5 risk categories (Hignett and McAtamney 2000). While REBA expands on RULA by including the lower body in the assessment, the method suffers the same drawbacks as and is no more useful than RULA for shoulder assessment.

The Liberty Mutual Manual Materials Handling Tables, also known as the Snook Tables, are a set of tables that can be referenced to estimate a maximum acceptable load/force for lifting/lowering, pushing/pulling, and carrying tasks based on task characteristics such as distance, repetitions, and load origin and destination (Snook & Ciriello, 1991). The Snook Tables are most useful when the load can be changed, since they advise the appropriate load based on task characteristics. If changing the load is not feasible, the Snook tables are less useful than other methods. Additionally, the Snook tables only cover a limited number of values for the distances. For instance, the tables for lifting tasks only account for hand distances of 7, 10, and 15 inches in front of the body.

Rodger's Muscle Fatigue Analysis is a full-body fatigue analysis tool that was developed around the hypothesis that fatigued muscles are more prone to inflammation and injury (Rodgers, 1991). The effort, duration, and frequency of motion of each of the seven major body regions (neck, shoulders, back, arms/elbow, wrist/hand/fingers, legs/knees, and ankle/feet/toes) during a task are rated from 1 to 4 based on given criteria. The criteria for the frequency and duration are the same for all body regions, but the effort criteria are different for each region. The ratings are strung together to form a 3-digit code that corresponds to a level of risk (low, moderate, high, very high) provided in a table. While this tool is simple to use and can be used to evaluate an individual body region, its analysis for each body region is very basic.

2. Methods

2.1 Approach

The objective of this research was to develop a predictive equation that can estimate shoulder strain based on the location of the load with respect to the body. Motion capture data of participants performing lifting tasks throughout the working range of the right arm were used to drive the movement of a musculoskeletal model (AnyBody Modeling System), which allowed the computation of the reaction forces of the shoulder. Reaction forces at the glenohumeral joint were calculated from AnyBody output for the experimental trials using a previously developed strain index. Regression methods were used to develop an equation that predicts the strain index values from the 3-dimensional distances from the sternal notch to the load that is lifted.

2.2 Strain Index

In previous research that aimed to estimate shoulder strain based on model outputs from AnyBody Modeling System, Chowdhury et al. (2018) developed and validated a strain index (Equation 1) based on the concept of the concavity-compression mechanism, i.e. that compressive force at the shoulder increase stability, translational forces decrease stability, and that translative forces that overcome the compressive forces can result in shoulder injury or dislocation. This strain index calculation requires an MVC reference to calculate R_{f-MVC} (Equation 2) and R_{t-MVC} (Equation 3).

$$SI = \left[\left(\frac{\sqrt{F_y^2 + F_z^2}}{R_{f-MVC}} * \frac{\tan^{-1}\left(\frac{F_y}{F_z}\right)}{45} \right) + \left(\frac{\sqrt{F_x^2 + F_z^2}}{R_{t-MVC}} * \frac{\tan^{-1}\left(\frac{F_x}{F_z}\right)}{45} \right) \right] * 100 \quad (1)$$

where,

F_x is anterioposterior force,
 F_y is inferosuperior force, and
 F_z is compression/distraction force.

$$R_{f-MVC} = \sqrt{F_y^2 + F_z^2} \quad (2)$$

where,

F_y is inferosuperior force from MVC reference trial, and
 F_z is compression/distraction force from MVC reference trial.

$$R_{t-MVC} = \sqrt{F_x^2 + F_z^2} \quad (3)$$

where,

F_x is anteroposterior force from MVC reference trial, and
 F_z is compression/distraction force from MVC reference trial.

2.3 Participants

Five healthy male participants were recruited with mean (\pm sd) age, height, and weight of 26.2 (\pm 5.8) years, 1.76 (\pm 0.04) meters, and 68.04 (\pm 8.49) kg, respectively. The height and weight data were utilized in the anthropometrical scaling of the musculoskeletal model. For inclusion in the study, potential participants were male, aged 18-40 years old, right-hand dominant and reported no musculoskeletal disorders that would affect their ability to perform the tasks or that could affect the results.

2.4 Equipment

Optical Motion Capture System (MX Series, Vicon Motion Systems, Oxford, UK): An eight-camera, infrared, optical motion capture system and accompanying software was used to track the three-dimensional location of 12mm retro-reflective markers attached to the participant.

Custom Weight Support and Floor Grid: A custom built wooden structure was securely attached to the front of the hydraulic scissor lift (Figure 1). The structure was used to support a hanging weight at the desired height. Several pieces of foamboard were attached to create a foamboard platform that is 70 inches by 40 inches. The gridlines left-to-right were labeled 32R, 24R, 16R, 8R, 0, 8L, 16L, and 24L. The gridlines forward-to-back were labeled 0, 8, 16, and 24. Intervals of 8 inches provided a good compromise between number of trials each participant must perform and the resolution of the data.



Figure 1. Custom-built wooden structure to support hanging weight

2.5 Participant Preparation

A marker set including thirty-two 12mm retro-reflective markers was used in this research. Twenty-four of the markers were affixed to the skin of the participant at specific anatomical landmarks with double-sided tape. Four markers were attached to the shorts with double-sided tape. The final four markers are on a headband that was worn by the participant. Locations of each marker and their identifying label can be found in Table 1.

Table 1. List of 32 retro-reflective markers in the marker set and their location on the body.

Head		Pelvis	
RFHD/LFHD	Right/left side of forehead	RASI/LASI	Right/left anterior iliac spine
RBHD/LBHD	Right/left side of back of head	RPSI/LPSI	Right/left posterior iliac spine
Trunk			
C7	Spinous process of C7 vertebrae	STRN	Xiphoid process at base of sternum
CLAV	Sternal notch at top of sternum	T10	Spinous process of T10 vertebrae
RSHO/LSHO	Right/left acromion process of shoulders	RBAK/LBAK	Inferior angle of right/left scapula
Left/Right Arms			
RUPA/LUPA	Midpoint of right/left upper arm on lateral side	RWRA/LWRA	Radial styloid of right/left wrist
RLELB/LLELB	Lateral epicondyle of humerus at right/left elbow	RWRB/LWRB	Ulnar styloid of right/left wrist
RMELB/LMELB	Medial epicondyle of humerus at right/left elbow	RFIN/LFIN	5th MCP joint of right/left hand
RFRM/LFRM	Midpoint of right/left forearm	RTHB/LTHB	2nd MCP joint of right/left hand

2.6 Experimental Tasks

The participant stood upright with their arms down to their side at the instructed location on the floor grid. When signaled to begin, while keeping the trunk still, the participant grasped the weight with their right hand and gently lifted it just enough to support the mass of the weight and remove tension on the rope it was suspended from. Participants were instructed to remain as still as possible while supporting the weight. After supporting the weight for approximately 6 seconds, the participant gently lowered and released the weight. After releasing the weight, the participant was asked to rate their level of exertion on a 10-point Borg Scale. This procedure was followed for each of the locations that were within reach of the participant while maintaining a stable, upright trunk, resulting in approximately 80-90 trials per participant, depending on their height and reach. Trial order was determined by randomizing the order of the 5 heights, then randomizing the locations within that height. This was done instead of randomizing over all trials to avoid having to adjust the height of the weight between each trial. A one-minute rest period was provided between trials.

2.7 Data Processing

2.7.1 Musculoskeletal Modeling

Each experimental trial was processed in Vicon Nexus. While processing each trial in Nexus, a 5 second period in which the participant was supporting the weight was identified and start and end points were identified and recorded. The marker data was exported from Vicon Nexus in C3D file format, and modeled in AnyBody Modeling Software. The focus in this section of the research was on the span of time during each trial that the participant was supporting the weight, which was a static exertion. Reaction forces at the Glenohumeral joint were output in three orthogonal dimensions: compression/distraction (CD), anteroposterior (AP), and inferosuperior (IS). Compression/distraction force is the magnitude of the force perpendicularly inward or outward from the Glenohumeral joint. Anteroposterior and inferosuperior forces, considered translational forces, are the magnitude of the force in the forward/backward and upward/downward directions, respectively. Adding these three vectors gave the magnitude and direction of the resultant force at each frame.

2.7.2 Predictive Equation Development

Sets of predictors were developed based on 3-dimensional distances between the sternal notch (STRN) and the load, represented by the center of the right hand and wrist markers (RWRA, RWRB, RFIN, and RTHB). The list of tested predictors included squares, cubes, absolute values, and square roots two versions of the X, Y, and Z distances from the sternal notch to the load:

- 1) Three-Direction Predictors –
 - a. X-axis (+Forward,-Backward): Positive values are Forward, negative values are Backward;
 - b. Y-axis (+Right,-Left): Positive values are Right, negative values are Left; and
 - c. Z-axis (+Up,-Down): Positive values are Up, negative values are Down.

- 2) Six-Direction Predictors – Left, Right, Down, Up, Forward, Backward – Values are non-negative. Examples:
 - a. Load is 5 inches to the Left of the sternal notch, Left = 5, Right = 0;
 - b. Load is 8 inches Down from sternal notch, Up = 0, Down = 8;

Best sets regression was performed which each predictor set to determine which sets of these predictor sets should be given focus during the next steps. Multiple regression was used to narrow down to a short list of models utilizing these distance predictor sets that were best able to accurately predict the strain index values calculated from the musculoskeletal model output. After multiple iterations and attempts utilizing different combinations of the predictors, four regression equations resulted. Further analysis was performed on these four equations.

For each collected and modeled experimental trial, the glenohumeral forces from the model output were used to calculate the SI value. For each experimental trial, predicted values were calculated using each of the four regression equations. Correlation analysis was performed between the predicted values for each regression equation and both the strain index values and the perceived exertion rating. Additionally, RMSE was calculated between the predicted values and strain index values.

Table 2. Predicted R², terms, correlations and RMSE results for each of the regression equations.

Regression Equation	Predicted R ²	Terms	Correlations		RMSE
			Strain Index	Perceived Exertion	Composite Index
1	75.71%	16	0.8838	0.6235	7.8291
2	75.68%	8	0.8783	0.6244	8.0029
3	74.18%	9	0.8708	0.6138	8.2276
4	74.22%	8	0.8700	0.6109	8.2531

Regression Equation 1 had the highest Predicted R-Square (Table 2), the strongest correlation with the composite index values, and the lowest RMSE, while the strongest correlation with the perceived exertion values was found with Regression Equation 2. While Regression Equation 1 performs the best, the usability of the equation should also be considered. Since Regression Equation 2 performs nearly as well as Regression Equation 1 with only half as many terms, Regression Equation 2 will be accepted as the final predictive equation.

$$SI = 12.4 - (2.6\sqrt{D}) + (0.086F^2) + (0.029R^2) - (0.364U^2) + (0.2FL) - (0.21R\sqrt{U}) + (0.126R\sqrt{D}) + (1.85U^{3/2}) \quad (4)$$

where,

F = Distance forward (Inches)

R = Distance right (Inches)

L = Distance left (Inches)

U = Distance up (Inches)

D = Distance down (Inches)

3. Discussion and Conclusions

This research had several limitations. Sample sizes were small, which was necessary due to limited resources and the significant time requirements to collect and analyze the data for each participant. However, this was counteracted, to an extent, by each participant performing 80+ experimental trials. Males were only used due to the need to remove the shirt for placement of motion capture markers. Validation with females needs to be performed to confirm that the predictive equation is still accurate for females. Additionally, the tasks were performed with the right hand only, therefore this predictive equation is only relevant for one-handed lifting tasks performed with the right hand.

Finally, only a single weight was used in the experimental tasks. Therefore, the magnitude of the load could not be included as a factor in the predictive equation. Therefore, these predicted strain values should be considered relative risks values. In other words, when evaluating two different locations for a load in a task using the same weight, the predictive equation results can be compared, however if the load changes, it would be erroneous to compare the values.

In this research, a predictive equation was developed to estimate the relative strain on the shoulder based on the location of the load. Generally, the predictive equation agrees with existing knowledge on risk factors of shoulder disorders, i.e. as the load moves upward, especially above the shoulder, the risk becomes more severe. When the distance between the body and the load increases, the moment arm increases and therefore the strain increases. Strain also increased when reaching across the body. Peak strain occurred at a combination of these factors, when the load was above the shoulder, away from the body, and required reaching across the body.

4. References

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