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Evaluation of shoulder strain during multi-directional forceful arm exertions

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Abstract.
BACKGROUND: Forceful exertions of the arm/shoulder are common during material handling and many other industrial tasks. Determination of how the risk of shoulder injury changes in conjunction with direction of force exertion could provide useful guidance on the design of workplaces and tasks.
OBJECTIVE: This research was conducted to determine how direction of force exertion and muscle recruitment algorithm effect shoulder strain computed by musculoskeletal modeling.
METHODS: Musculoskeletal modeling software was used to perform simulations of static force exertions of the right upper limb. A series of 36 force exertions in directions at 30° intervals in the transverse, sagital, and frontal planes were performed using three muscle recruitment optimization algorithms. A previously validated strain index equation was used to calculate risk injury for each force exertion based on the magnitude and direction of the resultant glenohumeral force.
RESULTS: Generally, highest strain values were found in the downward, backward, and leftward direction and lowest strain values were found in the upward, forward, and rightward direction, or, in other words, during force exertions opposing forces in those directions.
CONCLUSIONS: When designing workplace tasks that involve forceful exertions of the shoulder, pulling and downward pushing exertions should be given preference over pushing and lifting exertions.

Keywords: Musculoskeletal modeling, static force exertions, shoulder strain

1. Introduction

According to the Bureau of Labor Statistics, musculoskeletal disorders (MSD) accounted for almost 31% of occupational injuries requiring missed days of work in 2015 [1]. Musculoskeletal disorders are developed from the various factors including: arm exertions, repetitive motions, awkward body positions, and vibrations [2–4]. Specifically in shoulder MSDs, evidence shows a strong correlation with repetitive motions [3,5], forceful arm exertions [6,7], and awkward positioning [8]. Finding the direction of the forces contributing to these factors is helpful to deducing the amount of MSDs caused by occupational work.

The three major bones that make up the shoulder are the clavicle, humerus, and scapula. The clavicle is a long rounded bone connecting between the shoulder and the sternum at the center of the body.

The humerus is the upper arm bone composed of several parts including the head of the humerus, which fits into the scapula, creating a ball-and-socket joint between the two. This joint, the glenohumeral,

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allows the arm to rotate freely. The scapula is a triangular flat bone connecting between the clavicle and humerus. The lateral portion of the scapula is comprised of the glenoid cavity, which connects with the humerus head.

The interaction between the head of the humerus and the glenoid cavity create the concavity compression mechanism. More specifically concavity compression is the stability obtained between the compression of the humerus head into the concave glenoid fossa [9]. A net compressive force is created through the concavity compression mechanism that acts against the translational forces created from a load compressed on the shoulder [10]. Different tasks will carry a different load creating different translational and compressive forces. Certain tasks can exert large translations reaction forces that cause the humeral head to be pushed away from the center of the glenoid concavity and cause the shoulder to become unstable [11]. The combination of load applied to the glenohumeral joint and the direction of the resulting compressive force can allow a task to be categorized in terms of possible risk of injury to the human. A clear correlation between the stress-strain of the shoulder and physically demanding tasks exists [12].

The directions of the compressive and translation reaction forces can be measured using the inverse tangent function. The direction of the forces should be taken with respect to the medial-lateral direction because of the anatomy of the humerus head and glenoid cavity. In addition, it is important to understand the magnitude for overall understanding of the effects on the shoulder joint. The direction of the reaction forces along with their magnitudes was used to develop a strain index [11]. Tasks' strain indexes were used to categorize their effect on the shoulder. This study was performed to gain a better understanding of how tasks with various force directions can be strenuous on the shoulder. We hypothesized that the forces pushing down on the hand would cause the highest shoulder strain.

2. Background

2.1. AnyBody

AnyBody Modeling System, a musculoskeletal modeling program, was used in order to simulate the various tasks researched. The system uses a body model compromised of the bones, joints, and muscle-tendons. Complex movements can be analyzed easily, taking into account various complications that would be difficult to solve by hand. The system is capable of incorporating the possible degrees of freedom that the body has and realistic movements that can be made. It is also capable of simulating the location and interaction between the two. Finally, the system is capable of using any of the various recruitment strategies including linear, quadratic, polynomial, min/max strict or composite recruitment.

The system uses an object-oriented script language that is capable to be edited to fit the specific needs of the user. Within the script anatomical specifications for the glenohumeral, elbow, and wrist joints, among others, are given. An input file allows the user to specify the dimensions of the external force in terms of the x, y, and z directions. In each trial of the study the input file can be changed to represent the different tasks being studied. The output file provided by AnyBody provides force vectors in three orthogonal directions.

2.2. Recruitment strategies

Muscle recruitment is the method of which muscle set will be used to balance an external force [13]. Within the body the central nervous system systematically decides a set of muscles which optimally balance that force. In terms of modeling, a set of equilibrium equations can be used. AnyBody uses several different recruitment strategies but in this study three specific strategies were analyzed. The three recruitment strategies that were used were quadratic, polynomial and min/max strict recruitment.

The quadratic recruitment strategy uses Eq. (1) to simulate the muscle recruitment.

$$\boldsymbol{G} = \left(\frac{f_i}{N_i}\right)^2 \tag{1}$$

Large numbers in the sum are penalized so it is likely that a large number of muscle groups would be recruited. The use of more muscles would distribute the force more evenly and most likely cause less strain on the muscles. Quadratic recruitment is widely supported by biomechanical scientists because its simulation often lies well with experimental data collected in studies [13]. In terms of the human body the quadratic strategy is advantageous because it agrees with the thoughts of elasticity of the muscles. The fact that muscles is capable of pushing, pulling and storing energy lends to the fact that the force exerted on the muscles is distributed in a quadratic manner.

The second recruitment strategy that was used in the study was polynomial shown in Eq. (2).

$$\boldsymbol{G} = \left(\frac{f_i}{N_i}\right)^p \tag{2}$$

Where p represents the integer that the equation is raised to. Polynomial recruitment is considered a better option than even the quadratic because the higher exponent further penalizes the muscle groups and distributes the loads over more muscle groups. The value of p can be specified by the user but if it is not specified, and for this study, the value defaults to Eq. (3). Experiments show that the higher the p-value the better the distribution across muscles, however when the value gets too high it can overload the muscles causing strain on the muscles [13].

Finally, the min/max strict recruitment strategy was used. Unlike the other two methods discussed min/max strict does not use an equilibrium equation but rather an algorithm. The recruitment strategy did try to take the best of both worlds by minimizing fatigue and maximizing the relative load the muscles can handle. The human body works in a way that the muscles try to endure as much strain as possible before failure. Min/max strict recruitment is often thought of as the most realistic because the muscles work in an efficient manner. However, the major downside in the strategy is that the modeling of the strategy can often lead to abrupt changes in the muscles recruited. These changes are unrealistic and impossible for the body to perform.

3. Methods

3.1. Simulation

In this study, static force exertions in three anatomical planes were studied. The three different planes that were studied were the sagital plane, which splits the body left and right, the frontal plane, which divides the body front and back, and the transverse plane, which divides the body top and bottom. Within each plane, 12 force directions were studied, located at 30° intervals (Fig. 1). A simulation was run in AnyBody modeling with a 40 Newton force applied to the palm of the right hand in each of the 12 directions in each plane, for a total of 36 trials. In the simulation, the model was standing upright with 15° of glenohumeral flexion, 10° of glenohumeral abduction, elbow flexion of 75°, and 0° of glenohumeral external rotation, elbow pronation, and wrist abduction and flexion. Each of these 36 simulations was run with the polynomial, quadratic, and min/max strict recruitment strategies.

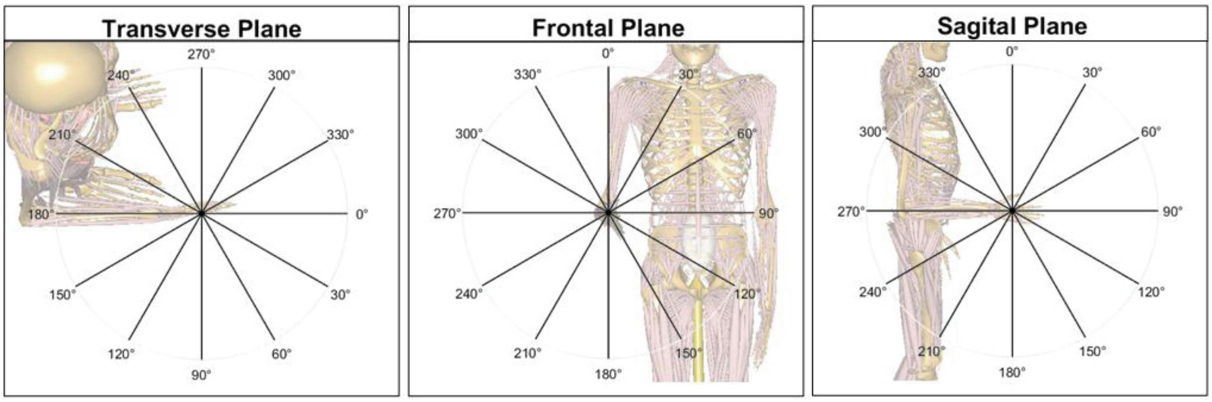

Fig. 1. Graphical representation of the 12 directions, at 30-degree intervals, in the transverse, frontal, and sagittal planes.

3.2. Calculation

The output of the simulations was three force vectors that were used as inputs in the strain index calculations. A compressive force (F_c) in the medial direction, as well as a force in the inferior-superior ($F_{I/S}$) and anterior-posterior ($F_{A/P}$) directions is given in the output file. The interaction between these three forces was used to create the strain index [3]. The magnitudes of the resultant forces were found in Eqs (3) and (4).

$$R_f = \sqrt{F_c^2 + F_{I/S}^2} \tag{3}$$

$$R_t = \sqrt{F_c^2 + F_{A/P}^2} \tag{4}$$

Where R_f was the resultant force in the frontal plane and R_t was the resultant force in the transverse plane. Angular deviation of the two resultant forces were then calculated using Eqs (5) and (6).

$$\beta = \tan^{-1}\left(\frac{F_{I/S}}{F_C}\right) \tag{5}$$

$$\gamma = \tan^{-1}\left(\frac{F_{A/P}}{F_C}\right) \tag{6}$$

Where β was the angular deviation in the frontal plane and γ was the angular deviation in the transverse plane.

The maximum resultant forces in the frontal and transverse planes were used as MVCs for the study. Equations (7) and (8) were then used to standardize the forces.

$$N_f = \left(\frac{R_f}{R_{f-MVC}}\right) \tag{7}$$

$$N_t = \left(\frac{R_t}{R_{t-MVC}}\right) \tag{8}$$

Where N_f was the normalized force in the frontal plane and N_t was the normalized force in the transverse plane. The angles found above were also normalized by the maximum angular deviation of 45° shown in Eqs (9) and (10).

$$A_f = \left(\frac{\beta}{45}\right) \tag{9}$$

Table 1
Strain values for directions in each plan using each recruitment strategy. Strain values are coded as: < 30 (black), > 30 and $<$ 60 (italic), and > 6 (gray)

	Frontal			Transverse			Sagital		
	Quad	Poly	MMS	Quad	Poly	MMS	Quad	Poly	MMS
0°	**0.6**	**0.8**	**7.2**	**16.9**	**9.4**	**28.9**	**0.6**	**0.8**	**7.2**
30°	**18.4**	**18.4**	**19.7**	**3.5**	**8.9**	**23.7**	**7.4**	**8.6**	**10.5**
60°	**21.7**	**18.6**	**17.9**	**26.5**	**8.4**	*47.4*	**13.4**	**14.3**	**15.9**
90°	*40.2*	*32.5*	**12.1**	*46.7*	**5.9**	70.5	**16.9**	**21.2**	**28.9**
120°	*45.4*	*47.8*	**25**	61.5	**11.6**	85.8	**21.6**	**27.8**	*37.2*
150°	*45.5*	*49.1*	*58.8*	67.3	**20.6**	86.7	*32.7*	*41*	*49.7*
180°	*53*	*59.7*	71.3	63.8	**27.2**	67.3	*53*	*59.7*	71.3
210°	*59.4*	67.2	80.2	*47.2*	**25.8**	*38.4*	67.8	73.8	*37.9*
240°	*58.6*	68.3	82.4	**27.6**	**16.6**	**11.6**	74.4	80.2	*44.2*
270°	*46.7*	*55.1*	*70.5*	*40.2*	**16**	**12.1**	63.8	67.8	67.3
300°	*39.2*	*42.4*	*49.2*	*40.3*	**15.8**	*36.3*	*38.6*	*38.8*	*44.2*
330°	**22.3**	**23.8**	**25.4**	*33.6*	**15.9**	*38*	**21.6**	**22.1**	*37.9*

$$A_t = \left(\frac{\gamma}{45}\right) \tag{10}$$

Where A_f was the normalized resultant force direction in the frontal plane and A_t was the normalized resultant force in the transverse plane. The strain index in both planes was found by multiplying the normalized force by the normalized direction and then scaling the values by multiplying the values by 100, as shown in Eqs (11) and (12).

$$I_f = (N_f x A_f)\, x100 \tag{11}$$

$$I_t = (N_t x A_t)\, x100 \tag{12}$$

Where I_f was the strain index in the frontal plane and I_t was the strain index in the transverse plane. Finally, the sum of the absolute values was taken as shown in Eq. (13).

$$I = |I_f| + |I_t| \tag{13}$$

The final strain index value, I, represents the amount of exertion a subject would have to use to counter the force.

4. Results

The strain index values varied from a minimum of 0.6 to a maximum of 86.7 (Table 1). Based on our results, the values have been separated into three-risk categories: low (black; 0–30), medium (italic; 30–60), and high (60–100). A minimum strain index of 0.6 was produced from a force located at 0° in the sagital and frontal planes. The maximum strain index value achieved was from a force located 150° from the origin in the transverse plane. In terms of recruitment strategies, the quadratic recruitment strategy produced the overall study minimum index of 0.6, and a maximum value of 74.4 located 240° from the origin in the sagital plane. The polynomial recruitment strategy showed a minimum strain index value of 0.8, produced form a force located at 0° in the sagital and frontal planes, and a maximum value of 80.3 located 240° from the origin in the sagital plane. Finally, the min/max recruitment strategy produced a minimum value of 7.2 located at 0° in the sagital and frontal planes, and the maximum value was that of the overall study. In both the sagital and frontal planes the minimal value is less than one while the maximum is around 70. However, in the transverse plane the minimum is almost 3.5 and the maximum is over 85.

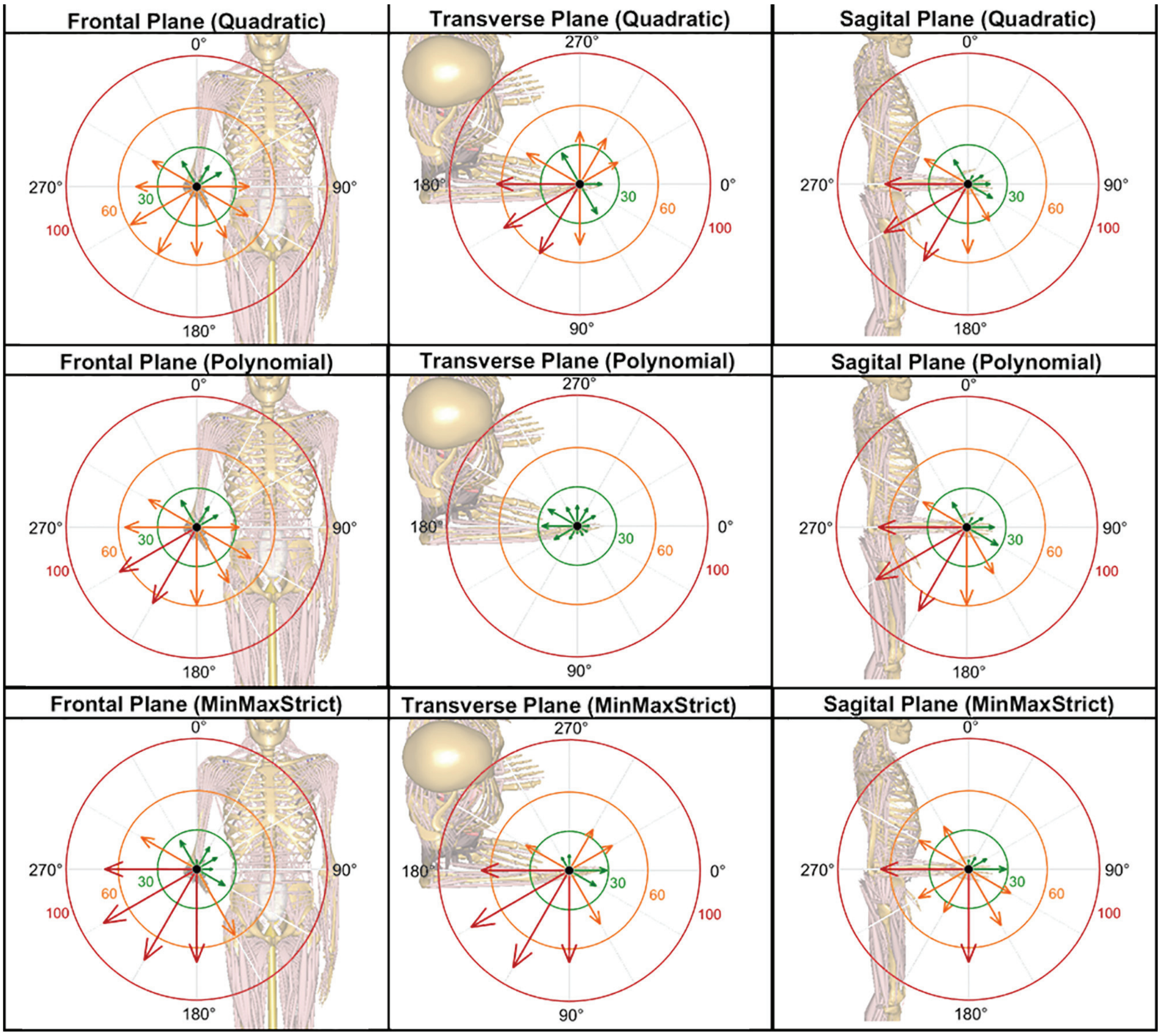

Fig. 2. Graphical representation of strain value results for each direction and each recruitment strategy. Plot lines are color-coded with green as low risk, orange as medium risk, and red as high risk.

5. Discussion

Generally, forces in the downward, leftward, and backward direction resulted in the highest strain values, regardless of recruitment pattern, meaning force exertions in the upward, rightward, and forward direction were the most strenuous. Forces in the opposing direction were generally the lowest strain values, meaning force exertion in the downward, leftward, and backward direction were the least strenuous. In all planes and for all recruitment strategies, the minimal strain occurred at the 0° direction. For the sagittal and frontal planes, this represented the upward direction, meaning that exerting force pushing downward generates the least strain on the shoulder. For the transverse plane, this was a force in the forward direction, meaning that an exertion pulling directly backward generates the least strain. The change in strain as you continue around the 12 directions is generally gradual with no low risk directions adjacent to high-risk directions. Based on these results, when designing workplace tasks, activities that involve pulling backward and pushing downward should be given preference to tasks that involve pushing forward and lifting, when appropriate.

The recruitment strategies showed similar trends. The polynomial recruitment pattern in the transverse plane was an anomaly, with no values rising above low risk level. This suggests that, for the exertions opposing these forces, the direction of the resultant force of the glenohumeral joint was directed in a more medial direction, resulting in higher stability of the shoulder. However, it seems unlikely that forces along those directions would all be low risk when no other combination of plane and recruitment strategy produced a similar result. This causes some doubt in the accuracy of the polynomial recruitment strategy.

All three of the planes follow a similar pattern in terms of minimum and maximum value with the exception of the transverse plane. The transverse plane had a much higher minimum and maximum value. Therefore, tasks that require the worker to work in the transverse plane are more likely to strain the shoulder.

6. Conclusions

The concavity compression mechanism is comprised of the interaction between the head of the humerus and glenoid cavity. An external force on the shoulder can result in compressive and translational forces. Different forces can result in a different amount of strain. AnyBody Modeling System was used to run different trials representing 36 different tasks. An input file was modified for each trial with a single simulation and a total of 36 simulations ran. Recruitment of the muscles is vital to understanding how the load is distributed across the muscles. In this research the recruitment strategies that were studied were quadratic, polynomial and min/max strict. A different objective function was used in each case with varying results. The 36 simulations were in the sagital, frontal and transverse plane with 12 points in each plane located 30° apart. An output file of the three force vectors were used to calculate the strain index value. The minimum strain value was 0.6 and the maximum value was 86.7. The transverse plane was the most dangerous plane and min/max strict was the most dangerous recruitment strategy. Overall, tasks that resulted in pushing caused the highest strain index values; therefore supporting our hypothesis.

Conflict of interest

The authors have no conflict of interest to report.

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