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Muscle forces of the shoulder complex with different external loads and movements: a biomechanical simulation analysis

Forças musculares do complexo do ombro em diferentes cargas e movimentos: Uma simulação biomecânica

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ABSTRACT: The analysis of the force produced by each muscle has great clinical relevance, guiding professionals to training or treatments that are more precise, specific, and individualized to structures and muscles of interest. The aim of this study was to estimate the individual muscle force of the shoulder complex during three shoulder movements with three different loads. Fifteen healthy male subjects with right upper limb dominance, without shoulder injury performed five repetitions of shoulder abduction, scapular plane elevation (scaption) and flexion movement in a range of motion of 120° with a speed of 45°/s were kinematics data were captured. The movements were evaluated in three load situations: without external load, with dumbbell, and with elastic resistance with the load defined as 5% of subject weight. OpenSim software was used to estimate the inverse kinematics and individual muscle force with an upper limb biomechanical model from the platform, the upper extremity dinamic model. The muscles peaks and behaviors forces of Deltoid (anterior, middle and posterior), supraspinatus, infraspinatus, teres (major and minor), subscapularis, and long biceps brachii were estimated with static optimization. For statistical analysis, a generalized estimating equation model (GEE) was used with SPSS 20.0 to compare the peak values. Almost all muscles presented statistical differences ($p<0.05$) with varying loads in all tested movements The muscles with no external load factor differences were the posterior deltoid, teres major, and subscapularis muscles. It can be concluded that despite the lack of validation for the present biomechanical model, we could see different individual muscle forces through different external loads identifying which exercise produce more force in certain muscles guiding a more specific rehabilitation/exercise program.

Keywords: Shoulder; Biomechanical Simulation; Rehabilitation.

RESUMO: As análises das forças produzidas por cada um dos músculos têm grande relevância clínica, guiando os profissionais nos seus treinamentos e tratamentos, fazendo com que estes sejam mais precisos, específicos e individualizados as estruturas e músculos de interesse. O objetivo do estudo foi estimar as forças musculares individuais do complexo do ombro durante três movimentos com três diferentes cargas. Quinze sujeitos saudáveis com dominância do membro superior direito, sem histórico de lesão realizaram cinco repetições dos movimentos de abdução de ombro, elevação no plano da escápula e flexão de ombro numa amplitude de movimento de 120º com uma velocidade de 45º/s onde foram obtidos dados cinemáticos do complexo do ombro. Os movimentos foram avaliados em três situações de carga: sem carga , com halter e com faixa elástica. A carga foi definida em 5% do peso corporal do sujeito. O *software OpenSim* foi utilizado para estimar a cinemática inversa e as forças musculares individuais através de um modelo biomecânico de membro superior da plataforma, *Upper Extremity Dynamic Model*. Os valores de picos e o comportamento das forças dos músculos deltóide (anterior, médio e posterior), supraespinal, infraespinal, redondo (menor e maior), subescapular e cabeça longa do biceps braquial foram estimadas através da otimização. Para análise estátistica, equações estimativas generalizadas (GEE) foram realizadas no SPSS 20.0 para comparar os valores de pico. Praticamente todos os músculos apresentaram diferença estatistica ($p<0,05$) nas variações de carga nos movimentos testados. Os músculos que não apresentaram diferença com a variação de carga foram o deltoide posterior, redondo maior e o subescapular. Pode-se concluir que apesar da limitação da validação do modelo biomecânico, podemos observar quais exercicios produzem mais força em determinados músculos auxiliando a guiar os programas de exercício/reabilitação.

Palavras-chave: Ombro; Simulação Biomecânica; Reabilitação

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Introduction

The shoulder complex has the greatest range of motion of any group of joints in the human body because of the arthrokinematics of those joints and the muscle actions involved in shoulder and shoulder girdle movements. In view of these particular characteristics, it becomes difficult to predict individual muscle forces necessary to balance a given external force[1,2]. Therefore, forces imposed to the shoulder complex have usually been estimated as proximal forces, that is, without distinguishing between the muscle and joint forces acting on a specific joint[3–5]. However, analysis of individual forces, especially forces that each muscle provides to generate a certain movement under a given external load, reveals important considerations about movement control and mechanical overload imposed on shoulder structures.

Analysis of the force produced by each muscle has great clinical relevance, guiding professionals in training or treatments that are more precise, specific, and individualized to structures and muscles of interest. It is even more important to evaluate that force with varying external loads, on different planes of movement, and through several ranges of motion. One of the methods used for obtaining this information is biomechanical modeling software.

In OpenSim, it is possible to evaluate repercussions of movements in musculoskeletal geometry, joint kinematics and muscle forces[6,7]. The optimization process of OpenSim is important for identifying the magnitude of force for each muscle during scapular plane elevation exercise, abduction, and shoulder flexion. These exercises have historically been grounds for debate in the rehabilitation field, mainly due to uncertainties about overload and muscle force modification when exercise is performed at different degrees and planes of movement[8]. Thus, the aim of the study was to estimate the individual muscle forces within the shoulder complex during three movements with three different external loads.

Methods

The sample was composed by 18 male subjects, right-handed, with a mean age of 27.3 (± 5.4) years old, mean height of 176 (± 6) cm, and mean weight of 75.3 (± 8.2) kg. This study was previously approved by the Ethics and Research Committee of the UFRGS under No.2007717. Inclusion criteria were physically active subjects and exclusion criteria were presence of pain or previous shoulder injury[9]. To participate in the study, the individuals signed the free informed consent form, which follows the Declaration of Helsinki.

Participants initially performed warm-up exercises and became familiar with the movements, which was followed by placement of reflexive markers (spinous processes of C7 and T8, suprasternal notch, xiphoid process, acromioclavicular joint, angulus acromialis, processus coracoideus, inferior angle of scapula, trigonum spinae scapulae, medial epicondyle, lateral epicondyle, radial styloid, and ulnar styloid) according to the International Society of Biomechanics[10]. All subjects were positioned in the center of the capture area (in the middle of five digital video cameras) and performed scaption, abduction, and flexion of the shoulder with a range of motion of 120 degrees. Each movement was performed separately with three different external loads: elastic resistance, dumbbell, and no external load. Each movement consisted of five repetitions at a speed monitored by a metronome, adjusted for angular velocity of 45°/sec. The load for the dumbbell and elastic resistance external loads was defined as 5% of the subject weigth, with a mean of 3.8 (0.04) Kg. For the elastic resistance situation the load was reached at the end of the repetition movement[9,11].

Kinematic parameters were acquired using five digital video cameras with a frequency of 50 Hz. In order to process the kinematic data, Dvideow software digitized[12] points of interest for spatial reconstruction. The external applied force collected for the elastic resistance band. A one-dimension load cell (Alpha Instruments, model SV20) with a sampling frequency of 100 Hz was positioned at the lower end of the elastic band. In order to identify the direction of the force, two reflective markers were placed at both ends of the elastic band.

Kinematic and kinetic data were exported for use in OpenSim software. The biomechanical model used in this study was the *Upper Extremity Dynamic* Model[13], which adapted a previously developed model[14] but added inertial parameters and segment mass. This model includes all upper limb bones weighing 4.77 kg based on a 75-kg male (Figure 1) and presents seven degrees of freedom[13].

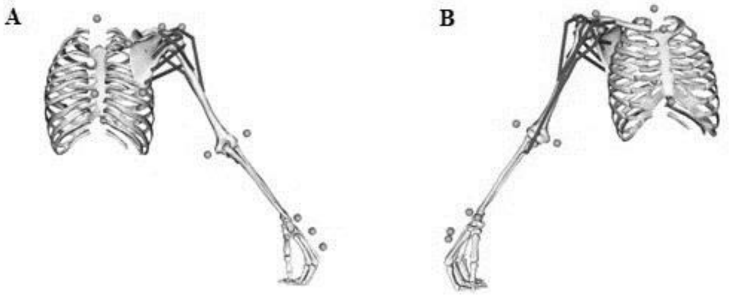

Figure 1. Upper Extremity Dynamic Model with muscles and markers used in the study. Posterior (A) and anterior (B) view.

The data processing in OpenSim went through four main steps. Initially, the virtual markers were added manually on the model to match the placement of reflective markers on the participants. The second step is known as scaling, which allowed researchers to size the model to match the anthropometry of each subject. The dimensions of each body segment in the model were scaled based on the relative distance between pairs of markers obtained from a motion capture system and the corresponding virtual local markers on the model. The mass properties of body segments were proportional so the total mass of the individual was reproduced. The third step, inverse kinematics, determined linear and angular movements in the model's coordinates that best reproduced marker movements from the experimental motion capture. The last step was to estimate the individual muscle force and was performed through the Static Optimization tool that calculates data from each frame, based on inverse kinematics and minimizing the sum of the quadratics of muscle activations[6]. All the data were filtered in OpenSim using a fourth-order Butterworth filter with a low pass of 6Hz. After data processing, the simulation model provided individual muscle force of the five repetitions for the following muscles: deltoid (anterior, middle and posterior), supraspinatus, infraspinatus, subscapularis, teres major, teres minor, and long head biceps brachii.

To better understand the synergic action between muscles, muscle activation was used, which is the individual tested muscle force normalized by the maximum muscle force from literature. The muscle activation was exported to BTS SMART-Analyzer software and, based on the kinematic data of the shoulder elevation angle, all five repetitions were used to obtain the mean individual muscle force for each muscle evaluated. To compare the influence of the external load and the movement over the individual muscle force it was used the peak of muscle force.

Individual muscle activation was used for descriptive analysis through the angle of the movement. Peak muscle force was then analyzed in SPSS 22.0 software for inferential statistics. Normality of the data was not tested, based on the assumption that Generalized Estimating Equations (GEE) can be used for both parametric and non-parametric data[15]. GEE method was used, assuming the main factor "external load" (elastic resistance, dumbbell, and lack of external load), the main factor "movement" (scaption, abduction and flexion), and the interaction between them. The Bonferroni correction was used as a post-hoc test, assuming an alpha of 0.05.

Results

Muscle activation is given through the angle of each movement: shoulder abduction (Figure 2), shoulder scaption (Figure 3), and shoulder flexion (Figure 4). The statistical analyses for peak muscle force in each external load situation are shown for muscles that cross the glenohumeral joint (Table 1) and for rotator cuff muscles (Table 2).

Peak Muscle Force: Regardless of the movement performed, highest peak muscle force occurred in movements performed with a dumbbell, followed by those with an elastic band, and the lowest was with no load in most of the evaluated muscles. The muscles with no external load factor differences were the posterior deltoid, teres major, and subscapularis muscles (Tables 1 and 2).

Table 1: Peak Muscle Force with varying loads from muscles of the glenohumeral joint.

	***MOV**	**EXTERNAL LOAD (N)**			**Load**	***Mov**	***Mov Load**
		Without Load	**Dumbbell**	**Elastic Resistance**			
Biceps Brachii	Abduction	48 (4.9) a, b, A, B	246.4 (21.6) a, b, A, C	142.9 (22.7) B, C	<0.001	0.285	<0.001
	Scaption	75.4 (3.7) a, A, B	309.9 (15.5) a, A, C	98.5 (6.3) B, C			
	Flexion	69.5 (6.1) b, A, B	301.0 (10.9) b, A, C	99.9 (10) B, C			
Ant Deltoid	Abduction	63.7 (23.6) a	128.1 (52.7) a	147.6 (56.4)	<0.001	<0.001	<0.001
	Scaption	92.5 (13.9) b, A	171.5 (24) b, A, B	71.1 (12.7) a, B			
	Flexion	183.6 (21.6) a, b, A	425.6 (17.5) a, b, A, B	254.1 (46.4) a, B			
Middle Deltoid	Abduction	441.7 (13.7) a, b, A, B	1071.9 (14.8) a, b, A, C	942 (42.2) a, b, B, C	<0.001	<0.001	<0.001
	Scaption	289.9 (11.2) a, c, A, B	821.6 (28.5) a, c, A, C	451.3 (44.1) a, c, B, C			
	Flexion	231.9 (17.4) b, c, A	474.9 (18.8) b, c, A, B	276 (22.4) b, c, B			
Post Deltoid	Abduction	142.5 (8.4) A, B	197.0 (4.5) a, b, A	192.5 (4.8) a, b, B	0.104	<0.001	<0.001
	Scaption	109.6 (9.6)	122.0 (6.3) a	118.0 (9.1) a			
	Flexion	130.7 (12.4) A	101.5 (10.4) b, A	111 (11.3) b			
Teres Major	Abduction	11.0 (1.2) a, b, A, B	26.9 (5.6) a, c	46.2 (10.3) b, c, A	0.577	0.001	<0.001
	Scaption	63 (6.1) a, b, A, C	16.7 (1.6) a	21.2 (5.4) b, A			
	Flexion	27.6 (4.3) B, C	27 (4.8)	36.8 (7.3)			

Note: Equal lowercase letters indicate significant difference between movements with the same load; Equal capital letters indicate significant difference between loads in the same movement ($p < 0.05$). Values in mean (standard error)
*Mov=Movement.

Table 2: Peak Muscle Force with varying loads from muscles of the rotator cuff.

	*MOV	EXTERNAL LOAD (N)			Load	*Mov	*Mov Load
		Without load	Dumbbell	Elastic Resistance			
Infra-spinatus	Abduction	90.9 (6.9)	294.5 (24.8)	154.9 (36)	<0.001	<0.001	0.342
	Scaption	328.7 (40.4)	453.9 (21.0)	323.2 (31)			
	Flexion	623.3 (64.4)	735.0 (32.3)	561.9 (51.6)			
Teres Minor	Abduction	45.8 (5.1) $^{A, B}$	174.2 (22.2) $^{a, b, A}$	145.9 (20.1) $^{a, B}$	<0.001	<0.001	<0.001
	Scaption	36.2 (8.1) ^{a}	30.9 (7.9) $^{a, c}$	42.9 (9) $^{a, b}$			
	Flexion	88.5 (16.9) ^{a}	100.4 (13.8) $^{b, c}$	86.2 (15.6) ^{b}			
Sub-scapularis	Abduction	88.4 (7.9) $^{a, b, A}$	199.8 (24.9) $^{a, b, A, B}$	101 (17) $^{a, b, B}$	0.183	<0.001	<0.001
	Scaption	333.6 (46.1) $^{a, c}$	308.2 (30.4) $^{a, c}$	277.9 (37.5) $^{a, c}$			
	Flexion	801.3 (79.7) $^{b, c, A}$	567.4 (66.5) $^{b, c, A}$	703.3 (69.2) $^{b, c}$			
Supra-spinatus	Abduction	69.7 (8.8) $^{a, A}$	359.6 (33.3) $^{a, b, A, B}$	116.7 (25.4) ^{B}	<0.001	<0.001	<0.001
	Scaption	117.9 (19.4) $^{a, A}$	189.4 (12.6) $^{a, c, A}$	159.5 (19.9)			
	Flexion	95.7 (33.0)	80.6 (17.1) $^{b, c}$	106.9 (20.3)			

Note: Equal lowercase letters indicate significant difference between movements with the same load; Equal capital letters indicate significant difference between the loads in the same movement ($p < 0.05$).
Values in mean (standard error)
*Mov=Movement

Muscle Activation: During the first degrees of amplitude (20–60º) of shoulder abduction movement (Figure 2), it is observed contributions of the middle deltoid, posterior deltoid, supraspinatus, teres major, and long head biceps brachii muscles, primarily when the load was the dumbbell. In the abduction movement between 60° and 90° degrees, we also observed a high magnitude of deltoid and posterior deltoid muscles presenting peak force. In the final degrees of movement, about 90–120°, we observed larger magnitudes in posterior, middle deltoid, and teres minor muscles. The contributions of other muscles during movement in this range of motion were in smaller magnitudes. The muscle that reached its peak value in this range was the teres minor muscle. As for peak values, the middle deltoid, supraspinatus, infraspinatus, and teres minor muscles presented the highest magnitudes of muscle force in abduction movements with a halter.

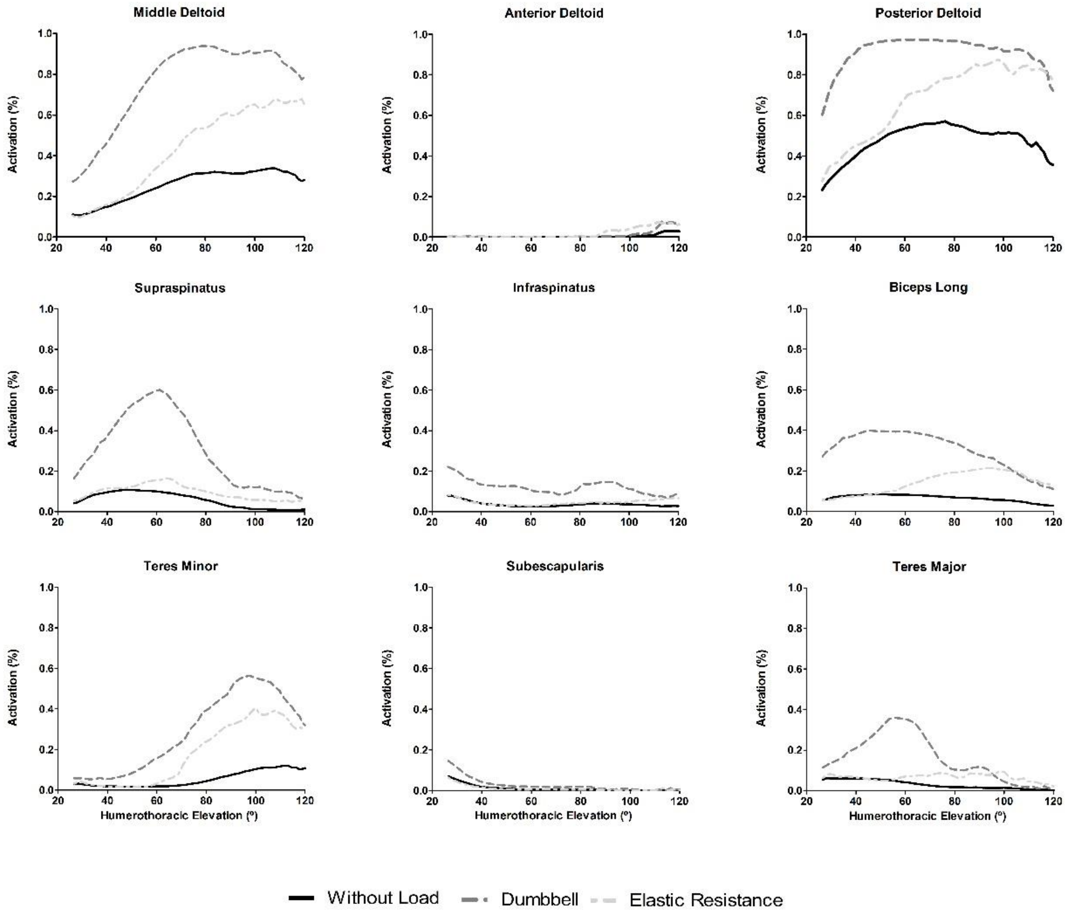

Figure 2. Estimate of muscle activation during shoulder abduction.

During scaption (Figure 3), the middle deltoid behaved in a similar manner as during abduction (Figure 2) along the range of motion but with a lower magnitude, and scaption was associated with other muscles such as subscapular and biceps brachii, as well. The supraspinatus presented a different behavior during scaption than during abduction (Figure 2). While the abduction movement with a dumbbell obtained a large peak at the first degrees of motion, scaption did not achieve such an evident peak.

In flexion (Figure 4), we observed the highest muscle activation for the anterior deltoid, biceps brachii, infraspinatus, teres minor, and subscapularis muscles. The rotator cuff muscles exhibited high magnitudes at the onset of movement, while the anterior deltoid and biceps brachii muscles exhibited high magnitudes throughout the movement.

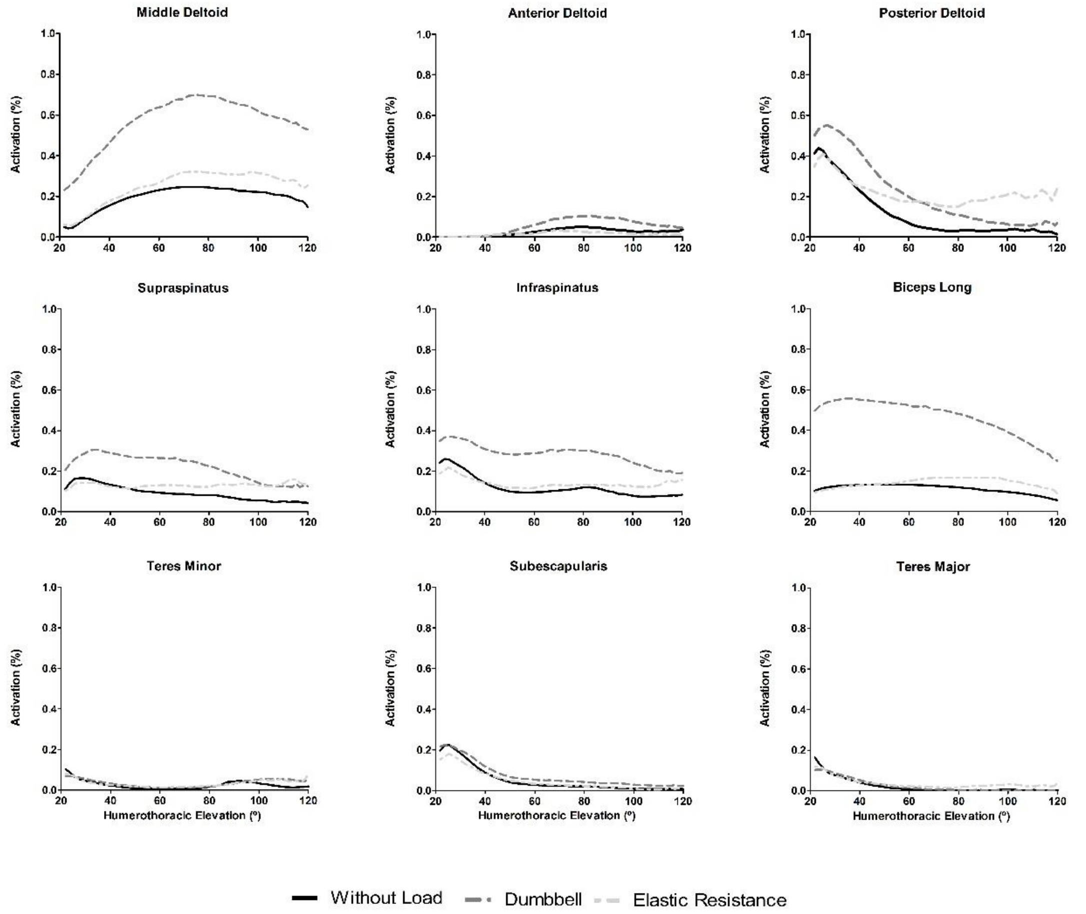

Figure 3. Estimate of muscle activation during shoulder scaption.

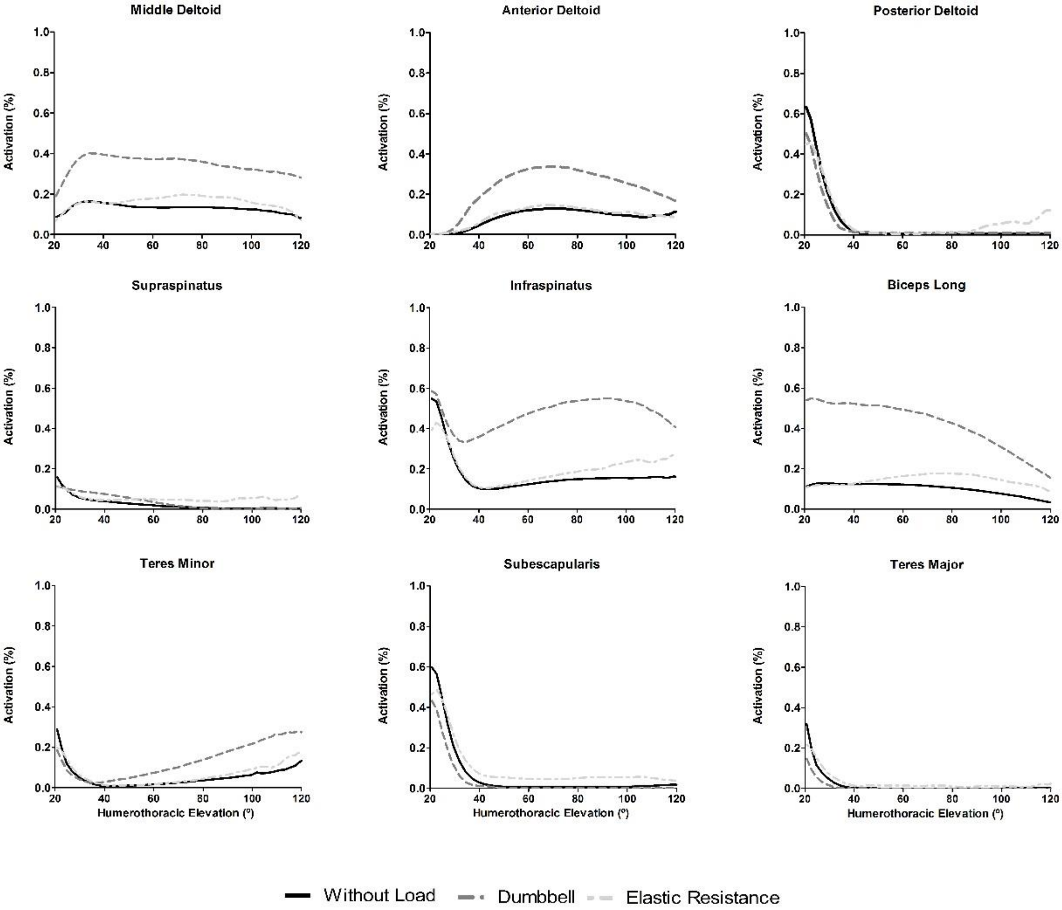

Figure 4. Estimate of muscle activation during shoulder flexion.

Discussion

The aim of this study was to estimate the individual force of shoulder complex muscles involved in abduction, scaption, and shoulder flexion with three different load types—elastic resistance, dumbbell, and no external load. We observed that the magnitudes of muscular strength for each situation followed a pattern, and exercises without load had lower values compared to dumbbell and elastic resistance.

It is necessary to take into account the different actions required for each of the external loads. The line of action with elastic resistance requires force to be applied by the hand; however, the direction of the force is modified according to the execution of the exercise. With a dumbbell, the direction of the force is predominantly vertical. In addition, despite the same weight force as the elastic resistance, a dumbbell may present variations in force necessary to move, as the upper limb accelerates even when controlling the motion with a metronome. Elastic bands result in gradual resistance throughout the exercise, and reach peak at the end of the movement when the band is at its greatest length, independent of speed variations[16].

During abduction (Figure 2), the supraspinatus and the middle deltoid muscles suffered the greatest effect from the external load and presented the highest magnitudes of recruitment in comparison with other evaluated muscles, confirming literature that has presented these muscles as agonists during the first 50° of abduction[17,18]. However, between 60° and 90° of abduction, the middle and posterior deltoids presented the greatest contributions, which agrees with existing literature[19]. The anterior deltoid presented its muscle peak during shoulder flexion (Table 1) and, associated with these muscles, the long head of the biceps brachii is recruited. This multiarticular muscle acts through a large range of motion in both the shoulder and the elbow and contributes effectively throughout the entire cycle of movement[20].

Comparing the results obtained by this study during abduction (Tables 1 and 2) with the one from van der Helm[19], which evaluated individual muscle forces, we observed higher values in the present study. This is possibly due to the active presence of the shoulder girdle muscles, as the upper, middle, and lower fibers of the trapezius and the serratus anterior muscles from the van der Helm model[19] caused by a difference distributions than the present study. That result can be explained by a study by Hapee and Helm[21], since muscles of the scapulothoracic joint can assist with scapula stabilization during movement.

The scaption movement of the present study obtained similar magnitudes for the middle deltoid and rotator cuff muscles without load (Figure 3) when compared to another study[22], which evaluated the individual muscle forces and their contributions to the compressive forces of the shoulder using another musculoskeletal model. In comparison to the same study[22], the middle deltoid showed its peak of muscle activation with similar values over the same range of motion (60°— 90°).

It was observed in the present study that the middle deltoid presented the greatest magnitude of peak values in relation to other muscles, confirming its importance as a principal agonist in this movement. However, during scaption, subscapularis and infraspinatus muscles have higher peak values when compared to abduction (Table 2), probably because they act as movement synergists. In this way, a professional of the movement that has interest to direct the recruitment of subscapularis and infraspinatus associated with the strengthening of the middle deltoid, can use movements in the plane of the scapula. Karlsson and Peterson[23] obtained lower magnitudes of muscular force than the present study, and this may perhaps be explained by the distribution method used. It is worth mentioning that our study does not include shoulder girdle muscles, while the other model does include those muscles[21].

Despite the results, some limitations existed within this study. One of the main limitations is that the model has a fixed shoulder girdle. Just like in other biomechanical models[22,24], movements of the shoulder girdle are dependent on glenohumeral movement, and scapular degrees of freedom may not be totally representative of reality. From 60° of shoulder abduction, the behavior of the shoulder girdle is fundamental for the range of motion, as well as the recruitment of the rotator cuff muscles are essential for the translation of the humeral head avoiding the subacromial impact[17]. Therefore, this model is limited to individuals without lesions or changes in scapula movement. It is important to emphasize that individuals with scapular dyskinesia may experience different results, and our study did not evaluate the presence of this alteration in our participants. In case of individuals with rotator cuff lesions which have significant changes in scapula movements such as decreased upper rotation, posterior tilt and external rotation[25,26], this information will not be estimated by this model, since it does not present those degrees of freedom. A second limitation of the present model is the absence of shoulder girdle muscles such as trapezius and anterior serratus, all linked to stabilization of the scapula[17,21]. There is another biomechanical model on the same platform of the OpenSim aimed at scapular kinematics during upper limb movements[27]. However, that model[27] does not distribute the proximal force needed to estimate individual muscle force, which was our objective in this study. Hence, it is recommended to use that model to evaluate scapular kinematics, instead of the present study model. Recently, a new upper extremity dynamic model was launched presented scapular kinematics and muscle contributions of the shoulder[29]. So, the results and the applicability of the present model are limited to present the forces on the glenohumeral joint and the behavior of the external loads over different muscles. Another limitation is that only a few specific test conditions were simulated, and the conditions for rehabilitation may vary considerably.

This study reveals important biomechanical considerations for rehabilitation of lesions in the shoulder complex. When magnitudes of muscle force between dumbbell and elastic resistance are compared, it leads clinicians to consider the most appropriate exercise choices for different levels of injury rehabilitation. For patients with acute injury or at the beginning of treatment, exercises using elastic resistance are more compelling because the external load is gradually exerted, which is mainly important for the painful arch of some shoulder injuries[28]. The dumbbell can be challenging for this type of patient, causing pain, incapacity to perform, and even frustration. Exercises with dumbbells can be better tolerated by patients who have already evolved in their treatments, mainly due to the external load during the entire range of motion. Thus, the determination of exercises and loads used for each phase of recovery must take into account individual muscle requirements of the shoulder complex.

Conclusions

It can be concluded that despite the lack of validation for the present biomechanical model, we could see different individual muscle forces through different external loads. With this study, our research hypothesis was confirmed, showing that different exercises and external loads produce statistically significant differences in magnitudes of muscle force for almost all muscles and situations. Our study was able to demonstrate the differences between the loads (dumbbell, elastic resistance and without load) and movement (abduction, scaption and flexion) over the glenohumeral muscles. In special, over the middle deltoid, supraspinatus, posterior deltoid and teres minor during abduction. Middle deltoid during scaption and anterior deltoid and infraspinatus during flexion. There was no differents on movement condition to the biceps long. There was no differents on load conditions to posterior deltoid, subscapularis and teres major. This two points need to be more investigate on future studies considering another exercises like external, internal rotation, extension and horizontal abduction/adduction which are the main function of this muscles.

References

1. Laursen B, Jensen BR, Németh G, Sjøgaard G. A model predicting individual shoulder muscle forces based on relationship between electromyographic and 3D external forces in static position. J Biomech. 1998;31(8):731–9.
2. Favre P, Sheikh R, Fucentese SF, Jacob HAC. An algorithm for estimation of shoulder muscle forces for clinical use. Clin Biomech. 2005;20(8):822–33.
3. Finley MA, Rasch EK, Keyser RE, Rodgers MM. The biomechanics of wheelchair propulsion in individuals with and without upper-limb impairment. J Rehabil Res Dev. 2004;41(3B):385–94.
4. Kulig K, Rao SS, Mulroy SJ, Newsam CJ, Gronley JAK, Bontrager EL, et al. Shoulder joint kinetics during the push phase of wheelchair propulsion. Clin Orthop Relat Res. 1998;354:132–43.
5. Murray IA, Johnson GR. A study of the external forces and moments at the shoulder and elbow while performing every day tasks. Clin Biomech (Bristol, Avon). 2004 Jul;19(6):586–94.
6. Delp SL, Anderson FC, Arnold AS, Loan P, Habib A, John CT, et al. OpenSim: Open-source software to create and analyze dynamic simulations of movement. IEEE Trans Biomed Eng [Internet]. 2007;54(11):1940–50. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-35548933265&partnerID=40&md5=33ed529447b83feca58df933b278c1fc
7. Delp SL, Loan JP. A graphics-based software system to develop and analyze models of musculoskeletal structures. Comput Biol Med. 1995;25(1):21–34.
8. Ishigaki T, Ishida T, Samukawa M, Saito H, Hirokawa M, Ezawa Y, et al. Comparing trapezius muscle activity in the different planes of shoulder elevation. J Phys Ther Sci [Internet]. 2015;27(5):1495–7. Available from: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=4483426&tool=pmcentrez&rendertype=abstract
9. de Toledo JM, Ribeiro DC, de Castro MP, Forte FC, Körbes TS, Rusch MW, et al. Comparison of shoulder resultant net moment between three different exercises and load conditions. Physiother Theory Pract [Internet]. 2013;29(2):124–32. Available from: http://www.ncbi.nlm.nih.gov/pubmed/22765018
10. Wu G, Van Der Helm FCT, Veeger HEJ, Makhsous M, Van Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion - Part II: Shoulder, elbow, wrist and hand. J Biomech [Internet]. 2005;38(5):981–92. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-20144387878&partnerID=40&md5=0061c16426841273a89a29ca540b2283
11. Toledo JM. Determinação do momento proximal resultante e da força proximal resultante no ombro em exercícios de reabilitação com três diferentes situações de carga. Programa Pós-graduação em Ciências do Mov Hum. 2008;
12. Figueroa PJ, Leite NJ, Barros RML. A flexible software for tracking of markers used in human motion analysis. Comput Methods Programs Biomed [Internet]. 2003 Oct;72(2):155–65. Available from: http://www.ncbi.nlm.nih.gov/pubmed/12941519
13. Saul KR, Hu X, Goehler CM, Vidt ME, Daly M, Velisar A, et al. Benchmarking of dynamic simulation predictions in two software platforms using an upper limb musculoskeletal model. Comput Methods Biomech Biomed Engin [Internet]. 2015;18(13):1445–58. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84920750058&partnerID=40&md5=0c5bfd4ffce52676a0dd653f52ce1dc0
14. Holzbaur KRS, Murray WM, Delp SL. A model of the upper extremity for simulating musculoskeletal surgery and analyzing neuromuscular control. Ann Biomed Eng [Internet]. 2005;33(6):829–40. Available from:

https://www.scopus.com/inward/record.uri?eid=2-s2.0-21144437403&partnerID=40&md5=c83c60deeaa6b397a22a724b0c3c5acc

15. Hanley JA, Negassa A, Edwardes MD deB, Forrester JE. Statistical analysis of correlated data using generalized estimating equations: An orientation. Am J Epidemiol. 2003;157(4):364–75.

16. Loss JF, Koetz AP, Soares DP, Scarrone FF, Hennemann V, Sacharuk VZ. Quantificação da resistência oferecida por bandas elásticas. Rev Bras Ciências do Esporte. 2002;24(1):61–72.

17. Phadke V, Camargo PR, Ludewig PM. Scapular and rotator cuff muscle activity during arm elevation: A review of normal function and alterations with shoulder impingement. Rev Bras Fisioter [Internet]. 2009;13(1):1–9. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-67349250642&partnerID=40&md5=a17184dad5d8155f3ff5e09fd5f7508f

18. Ambrósio J, Quental C, Pilarczyk B, Folgado J, Monteiro J. Multibody biomechanical models of the upper limb. Procedia IUTAM. 2011;2:4–17.

19. van der Helm FCT. Analysis of the kinematic and dynamic behavior of the shoulder mechanism. J Biomech. 1994;27(5):527–50.

20. Landin D, Myers J, Thompson M, Castle R, Porter J. The role of the biceps brachii in shoulder elevation. J Electromyogr Kinesiol [Internet]. 2008 Apr 1 [cited 2017 Oct 3];18(2):270–5. Available from: http://www.sciencedirect.com/science/article/pii/S1050641106001295?via%3Dihub

21. Happee R, Van der Helm FCT. The control of shoulder muscles during goal directed movements, an inverse dynamic analysis. J Biomech. 1995;28(10):1179–91.

22. Yanagawa T, Goodwin CJ, Shelburne KB, Giphart JE, Torry MR, Pandy MG. Contributions of the individual muscles of the shoulder to glenohumeral joint stability during abduction. J Biomech Eng [Internet]. 2008;130(2). Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-47149110652&partnerID=40&md5=d98b7abd8e2526ec280a1d505f2dca05

23. Karlsson D, Peterson B. Towards a model for force predictions in the human shoulder. J Biomech. 1992;25(2):189–99.

24. Chadwick EK, Blana D, Van Den Bogert AJ, Kirsch RF. A real-time, 3-D musculoskeletal model for dynamic simulation of arm movements. IEEE Trans Biomed Eng [Internet]. 2009;56(4):941–8. Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-67149094917&partnerID=40&md5=29416a0e7af9d9b4be839f48589855e0

25. Ludewig PM, Reynolds JF. The association of scapular kinematics and glenohumeral joint pathologies. J Orthop Sport Phys Ther. 2009;39(2):90–104.

26. Ludewig PM, Braman JP. Shoulder impingement: biomechanical considerations in rehabilitation. Man Ther. 2011;16(1):33–9.

27. Seth A, Matias R, Veloso AP, Delp SL. A biomechanical model of the scapulothoracic joint to accurately capture scapular kinematics during shoulder movements. PLoS One [Internet]. 2016;11(1). Available from: https://www.scopus.com/inward/record.uri?eid=2-s2.0-84954179738&partnerID=40&md5=3aa6acf9546cea7be4a4d8c4ac6c8000

28. Frost A, Michael Robinson C. The painful shoulder. Surg [Internet]. 2006 Nov [cited 2017 Mar 23];24(11):363–7. Available from: http://linkinghub.elsevier.com/retrieve/pii/S026393190600055X

29. Seth A, Dong M, Matias R, Delp SL. Muscle contributions to upper-extremity movement and work from a musculoskeletal model of the human shoulder. Frontiers in neurorobotics. 2019;13:90.