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Muscle recruitment patterns of the subscapularis, serratus anterior and other shoulder girdle muscles during isokinetic internal and external rotations

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ABSTRACT
The aims of this study were to investigate the differences in peak muscle activity and recruitment patterns during high- and low-velocity, concentric and eccentric, internal and external isokinetic shoulder rotations. Electromyographic activity of the rotator cuff and eight superficial muscles of the shoulder girdle was recorded on 25 healthy adults during isokinetic internal and external shoulder rotation at 60°/s and 240°/s. Peak muscle activity, electromyographic envelopes and peak isokinetic moments were analyzed using three-factor ANOVA and statistical parametric mapping. The subscapularis and serratus anterior showed moderate to high peak activity levels during each conditions, while the middle and posterior deltoids, upper, middle and lower trapezius, infraspinatus and supraspinatus showed higher peak activity levels during external rotations (+36.5% of maximum voluntary activation (MVA)). The pectoralis major and latissimus dorsi were more active during internal rotations (+40% of MVA). Only middle trapezius and pectoralis major electromyographic activity decreased with increasing velocity. Peak muscle activity was similar or lower during eccentric contractions, although the peak isokinetic moment increased by 35% on average. The subscapularis and serratus anterior appear to be important stabilizers of the glenohumeral joint and scapula. Isokinetic eccentric training at high velocities may allow for faster recruitment of the shoulder girdle muscles, which could improve joint stability during shoulder internal and external rotations.

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KEYWORDS
Electromyography; shoulder; subscapularis; rotator cuff; isokinetics

Introduction

Chronic shoulder injuries are the most common injuries among overhead athletes such as baseball pitchers (Makhni, Lee, Nwosu, Steinhaus, & Ahmad, 2015), tennis players (Correia, 2016) and swimmers (Wanivenhaus, Fox, Chaudhury, & Rodeo, 2012). The shoulder complex being the most mobile joint of the human body, it relies on its surrounding muscles to create movement as well as ensure stability about the glenohumeral joint (Boettcher, Cathers, & Ginn, 2010). However, the repetitive nature of overhead sports when combined with faulty biomechanics, muscle imbalances or fatigue can lead to chronic shoulder pathologies such as functional instability and secondary impingement (Cools, Borms, Castelein, Vanderstukken, & Johansson, 2016). In consequence, a growing body of literature exists on injury prevention and rehabilitation of the shoulder. Lately, eccentric training has gained in popularity among clinicians and researchers, as pointed out by Camargo, Alburquerque-Sendin, and Salvini (2014) in their review on eccentric training in the management of rotator cuff tendinopathy. Although improvements in symptoms associated with shoulder pathologies have been observed from eccentric training of the rotator cuff in clinical setting, there is limited evidence on the mechanisms underlying these improvements (Camargo et al., 2014; Cools et al., 2016).

In clinical EMG studies, muscle activity has been measured during rehabilitation exercises performed at low velocities (Alizadehkhaiyat, Hawkes, Kemp, & Frostick, 2015; Reinold et al., 2004) or with submaximal loads (Heuberer, Kranzl, Laky, Anderl, & Wurnig, 2015; Uga, Endo, Nakazawa, & Sakamoto, 2016). Yet, basic skills in overhead sports usually require high rotational velocities and maximal force production about the glenohumeral joint; anywhere from 240°/s for the swimming stroke (Beach, Whitney, & Dickoff-Hoffman, 1992) to 7700°/s during a baseball throw(Seroyer et al., 2010). Given that scapular kinematics significantly differs between slow and fast athletic velocities during shoulder flexion or scapular plane abduction (Prinold, Villette, & Bull, 2013), it is likely that the muscle activity and coordination pattern of rehabilitation exercises are very different to their athletic counterparts (e.g. external/internal rotations and swim stroke or overarm throw). It would therefore be beneficial to investigate muscular activity during clinical exercises performed at high velocity.

The use of an isokinetic dynamometer enables researchers to measure strength at high velocities and in maximal effort conditions. Most studies on the isokinetic shoulder strength of athletes have been performed at low velocities (30 to 180°/s) (Bak & Magnusson, 1997; Batalha, Raimundo, Tomas-Carus, Marques, & Silva, 2014). Nonetheless, Andrade et al.

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The supplemental material for this article can be accessed here.

(2010) tested handball athletes in internal and external rotation at 60 and 300°/s and showed that concentric internal and external rotation moment decreased as the velocity increased and the opposite relationship was reported during eccentric tasks. However, as reported by Mayer et al. (2001), isokinetic testing at velocities higher than 180°/s may not be accurate as the subjects may not be able to produce enough moment to reach the set velocity in time. Indeed, as the target testing velocity increases, the duration of the isokinetic phase (constant angular velocity) is reduced and may even be nonexistent (Baltzopoulos, 2008). Although only the moment during the isokinetic phase should be considered for analysis, most isokinetic dynamometers provide moment output throughout the movement but rarely display the matching angular velocity. The peak moment data extracted may thus, unbeknown to the experimenter, be taken from the acceleration or deceleration phases (Baltzopoulos, 2008). Therefore, the use of a high-power dynamometer would allow longer relative duration of the isokinetic plateau even at higher speed.

A limited number of studies has combined EMG and isokinetic testing of the shoulder, which makes it difficult to infer on the muscle recruitment patterns during these types of movement, especially in relation to the velocity and type of contraction (concentric vs eccentric). As Duchateau and Baudry (2014) pointed out in their review, during eccentric contractions the EMG amplitude is either similar or lower despite an increased force production compared to concentric contractions. However, these findings come from studies on the lower extremities and, to our knowledge, there are no studies confirming this pattern at the shoulder. Cools, Declercq, Cambier, Mahieu, and Witvrouw (2007) have studied muscle activity during isokinetic external rotation of the shoulder, however, they only measured the activity of the trapezius muscles during concentric external rotation at 60°/s. David et al. (2000) on the other hand, studied onset and peak EMG activity of the rotator cuff, biceps, deltoids and pectoralis major during eccentric and concentric internal and external rotations of the shoulder at 60 and 180°/s. However, no statistical analysis was carried out to compare the muscular activation patterns between the different conditions. Thus, an analysis of the differences in muscle activation patterns across velocities and types of contraction during isokinetic rotation of the shoulder would improve our understanding of the roles of the muscles and provide valuable data toward the design of evaluation and rehabilitation protocols.

Therefore, the purpose of our study was to examine the effect of speed and type of contraction on the muscular recruitment patterns of the rotator cuff, scapula stabilizers and other superficial muscles acting at the shoulder complex during isokinetic concentric and eccentric internal and external rotations. More specifically, our objective was to determine if there were differences in the peak EMG activity and in the recruitment pattern between the two types of movement (internal versus external rotation), two velocities (60 vs 240°/s), and the type of contraction (concentric vs eccentric) for the shoulder girdle muscles.

Methods

Participants

Eleven males and fourteen females (all right-handed, mean age, 22.6 years (SD 4.4); height, 174 cm (SD 9); weight, 68.7 kg (SD 10.6)) volunteered to participate in this study. Participants were either physically active adults (n = 17) or competitive swimmers (n = 9). All participants were free from shoulder pain or injury at the time of testing and had no history of shoulder surgery or arthroscopical interventions to either shoulder. The protocol was approved by the local ethics committee and all participants read and signed a written informed consent form.

Electromyographic recording

Intramuscular paired hook fine-wire electrodes (30 mm x 27 ga, Natus Neurology, Middleton, WI, USA) were inserted under sterile conditions into the supraspinatus, infraspinatus and subscapularis based on the recommendations from Kadaba et al. (1992) and Morris, Kemp, Lees, and Frostick (1998). For the subscapularis muscle, only one pair of fine-wire electrodes were used and the needle used for insertion was oriented toward the lower fibers of the muscle. After shaving and cleaning the skin with alcohol, surface EMG sensors (Delsys Trigno Wireless EMG, Natick, MA, USA) were placed according to SENIAM recommendations over the belly of the pectoralis major, latissimus dorsi, upper, middle and lower trapezius, posterior and middle deltoids, and the lower fibers of serratus anterior (Figure 1).

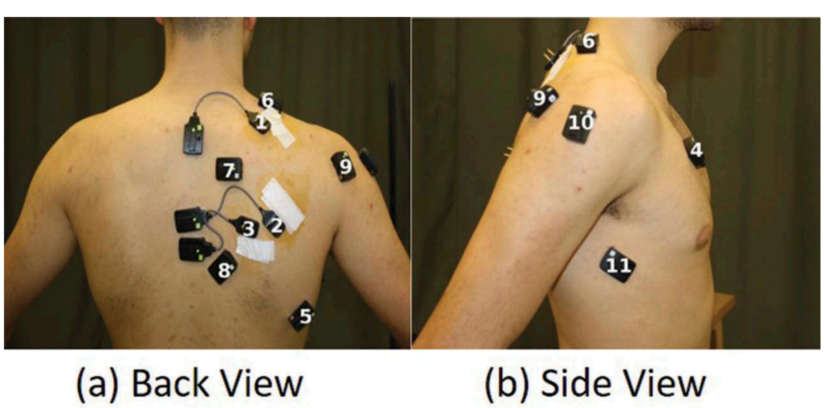


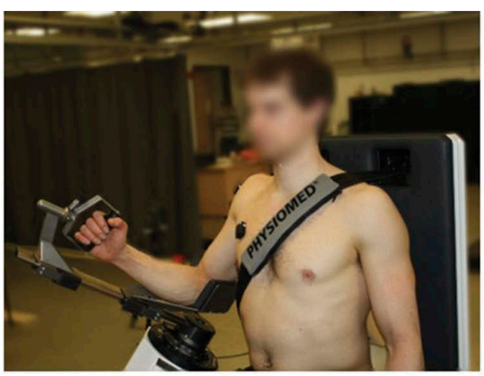
Figure 1. Placement of the surface and intramuscular EMG sensors: 1- Supraspinatus, 2- Infraspinatus, 3- Subscapularis, 4- Pectoralis Major, 5- Latissimus Dorsi, 6- Upper Trapezius, 7- Middle Trapezius, 8- Lower Trapezius, 9- Posterior Deltoid, 10- Middle Deltoid, 11- Serratus Anterior.

Fifteen maximal voluntary isometric contractions (MVICs) were completed to obtain maximum voluntary activation (MVA) of each of the 11 muscles of interest, according to the method proposed by Dal Maso, Marion, and Begon (2016). Participants completed two 5-seconds contractions for each MVIC position with a 1 minute rest between contractions. Ten minutes of rest were added between the end of the MVICs and the start of the isokinetic testing protocol to minimize potential effect of fatigue.

Evaluation protocol

Participants dominant shoulder was evaluated on a CON-TREX®MJ isokinetic dynamometer (Physiomed, Schnaittach, Germany) with modified software to enable faster acceleration and deceleration. Participants were seated with their arm abducted 30° in the scapular plane (about 30° shoulder flexion) and the elbow flexed at 90°. (Figure 2). They were asked to maintain an upright posture throughout the test to minimize the contribution of the torso during the efforts.

The protocol consisted of a series of maximum concentric and eccentric shoulder internal and external rotations at velocities of 60 and 240 /s. Prior to testing, participants completed submaximal trials of each testing condition to warmup and familiarize themselves with the procedures. The testing range of motion (RoM) was individualized for each subject (mean RoM, 98.69° (SD 14.23)). The order in testing velocities was randomized across subjects. For each velocity the sequence of contractions was internal concentric (IR), external concentric (ER), internal eccentric (IX) and external eccentric (EX). Testing of internal and external rotation strength was alternated to ensure adequate recovery of the targeted muscle groups, and concentric contractions were performed before eccentric contractions to reduce possible effect of muscle damage on muscle activity (Beck, Ye, & Wages, 2016). For clarity, the 8 different testing conditions will be referred to IR-60, ER-60, IX-60, EX-60, IR-240, ER-240, IX-240, and EX-240. For each condition, three repetitions were completed, with 30 seconds rest in between. Recording of the moments produced was done by use of the dynamometer's *continuous passive motion* mode to ensure that an isokinetic plateau was attained even at the highest velocity. Signal from the EMG sensors and the isokinetic dynamometer were synchronized and sampled at 900 Hz using Nexus 1.8.5 (Vicon Motion Systems, Oxford, UK).



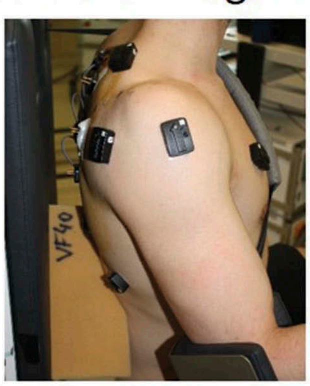


Figure 2. Participants were seated and secured with a security belt on the ContrexMJ (a). Blocks of dense foam were placed between the seat and the participant's back to avoid any contact between the seat and the EMG sensors (b).

Data processing

EMG data was filtered using a 4th order Butterworth bandpass filter (10–450 Hz) and rectified. The EMG linear envelope was obtained by applying a 4th order zero-lag Butterworth 5 Hz lowpass filter. Each repetition was time normalized (−25% to 100%) according to the start (0%) and end (100%) positions of the dynamometer's lever for further analyses of EMG time histories. Peak EMG activation of each muscle was extracted for every repetition, normalized to MVA and averaged across the three repetitions. The MVA value for each muscle was calculated as the maximum activation across the 15 positions (Dal Maso et al., 2016). Levels of muscle activity were defined using an established grading system in which 0% to 10% of MVA is deemed relatively inactive, 10% to 20% minimally active, 21% to 35% moderately active, 36% to 50% moderately strongly active and greater than 50% strongly active (Day, Taylor, & Green, 2012). Due to technical issues during recording (e. g. large baseline noise, loss of signal during a trial, etc), 4.7% observations had to be removed from analysis (Table 1). One participant refused to have intramuscular EMG, therefore 24 (8 conditions x 3 repetitions) of the trials removed for each of the rotator cuff muscles are due to this absence of recording.

Peak moment was extracted for each isokinetic contraction, normalized to the participant's body weight and averaged across the three repetitions. Only the isokinetic portion of each repetition was retained for this analysis. Two repetitions of the EX-240 condition for one subject and all repetitions of

Table 1. Approximately 5% of the EMG signals were removed from analysis due to technical errors.

Muscles	Sum of trials removed	Percentage (%)
Pectoralis	8	1.4
Latissimus Dorsi	27	4.6
Middle Deltoid	5	0.8
Posterior Deltoid	3	0.5
Upper Trapezius	3	0.5
Middle Trapezius	4	0.7
Lower Trapezius	3	0.5
Serratus Anterior	2	0.3
Supraspinatus	28	4.7
Infraspinatus	46	7.8
Subscapularis	174	29.4
Total	303	4.7

the IX-240 and EX-240 conditions for another subject were removed from analysis as no eccentric moment had been produced (8 out of 600 observations).

Statistical analysis

An a priori statistical analysis showed there were no significant differences in muscle activation levels and normalized moments between the swimmers and the physically active adults, therefore all participants were pooled together to increase statistical power. The distribution of the peak EMG and of the normalized peak moment data were examined by use of Q-Q plots, Shapiro-Wilk and Levene tests. A three-factor (2 x 2 x 2) ANOVA model was used to compare the differences in muscle activation and moment production between the different velocities (60–240°/s), direction (internal-external) and type of contraction (concentric-eccentric), for each of the 11 muscles separately. Post hoc analysis was performed to identify where the significant differences occurred using Tukey's HSD tests.

Differences in time histories of EMG activations were assessed according to a three-factor (2 x 2 x 2) ANOVA model through a 1-dimensional (1D) statistical parametric mapping (SPM) method (Robinson, Vanrenterghem, & Pataky, 2015) on the position-normalized EMG envelope, for each of the 11 muscles.. SPM method allows for statistical analysis of an *n*-dimensional dataset across its continuum and its applications in biomechanics are described in great details in Pataky, Robinson, and Vanrenterghem (2016). Except for the SPM analysis which was performed with the open-source toolbox SPM-1D (©Todd Pataky 2014, version M0.1), all statistics were carried out using R 3.3.0 (R Core Team, 2016). The alpha value was set at 0.05.

Results

Muscular activity

The analysis of peak EMG activity showed that velocity only had an effect on pectoralis ($P < 0.05$) and middle trapezius ($P < 0.05$) muscles while the direction of contraction had an effect on all muscles ($P < 0.001$) except serratus anterior. Type of contraction had an effect on latissimus dorsi, posterior deltoid, subscapularis and lower trapezius ($P < 0.01$). Interactions between speed and direction were only found for pectoralis ($P < 0.05$) while interactions between direction and type of contraction were found for subscapularis ($P < 0.01$).

As illustrated in Figure 3, the subscapularis and serratus anterior were the only two muscles that were at least moderately activated for all conditions (26–64%MVA), although the subscapularis had significantly higher activity during concentric internal rotation (64%MVA for IR) compared to the other three types of contraction (34–43%MVA for ER, IX and EX), at both velocities. Middle and posterior deltoids, upper, middle and lower trapezius, supraspinatus and infraspinatus muscles were significantly more active during external (41–71%MVA) than internal (12–28%MVA) rotations. Conversely, pectoralis major and latissimus dorsi muscles had higher activation during internal (45–85%MVA) than external (12–38%MVA) rotation.

Among the external rotator muscles, only the middle trapezius activity was affected by the velocity of the contraction however post hoc analysis revealed no significant differences between conditions with the same direction when velocity increased. For internal rotation, pectoralis major activity during IX-240 (72%MVA) was significantly lower compared to IX-60 (85%MVA).

Latissimus dorsi was the only muscle for which the peak activity differed between concentric and eccentric contractions of the same movement; peak EMG activity was significantly higher during ER-60 (38%MVA) compared to EX-240 (18%MVA), during IR-60 (69%MVA) compared to IX-60 and IX-240 (45–50%MVA) and during IR-240 (67%MVA) compared to IX-60 (45%MVA) .

The three-way ANOVA SPM analysis revealed significant effects for the velocity and type of contraction as well as interactions on the EMG envelopes for all 11 muscles. Comparing concentric and eccentric efforts, post hoc tests identified significant temporal differences in the EMG activity of pectoralis major, latissimus dorsi and subscapularis muscles during internal rotation (Figure 4) and for all but pectoralis major muscles during external rotation (Supplementary Fig. S1). Significant differences were seen in the pre-activation region (–25 to 15% of normalized cycle), with a notable faster rise of activity seen during eccentric contraction, the effect being even higher at 240°/s. The opposite observation was made in the last 15–30% of the normalized cycle, with EMG activity during concentric contractions being significantly higher for most muscles.

Isokinetic moments

Velocity ($P < 0.01$) and type of contraction ($P < 0.001$) had an effect on the isokinetic moment produced by participants. No interaction between speed and contraction was found. The participants produced greater peak moment in internal versus external rotation as well as in eccentric versus concentric efforts (Table 2). When going from 60 to 240°/s, moment in ER was significantly reduced by 0.068 N.m.kg-1 (19.67%) while no diminution was seen for IR, IX and EX.

Discussion

This study aimed to examine the differences in muscle recruitment pattern of the shoulder girdle muscles according to the direction (internal vs external), velocity (60 vs 240°/s) and type of contraction (concentric vs eccentric) during isokinetic shoulder rotations. Our findings indicate that subscapularis and serratus anterior muscles may have an important role in stabilization as evidenced by their moderate activity levels in both directions. Moreover, it appears that increased velocity and eccentric contractions may allow for faster recruitment of rotator cuff and scapula stabilizer muscles which could help improve glenohumeral stability.

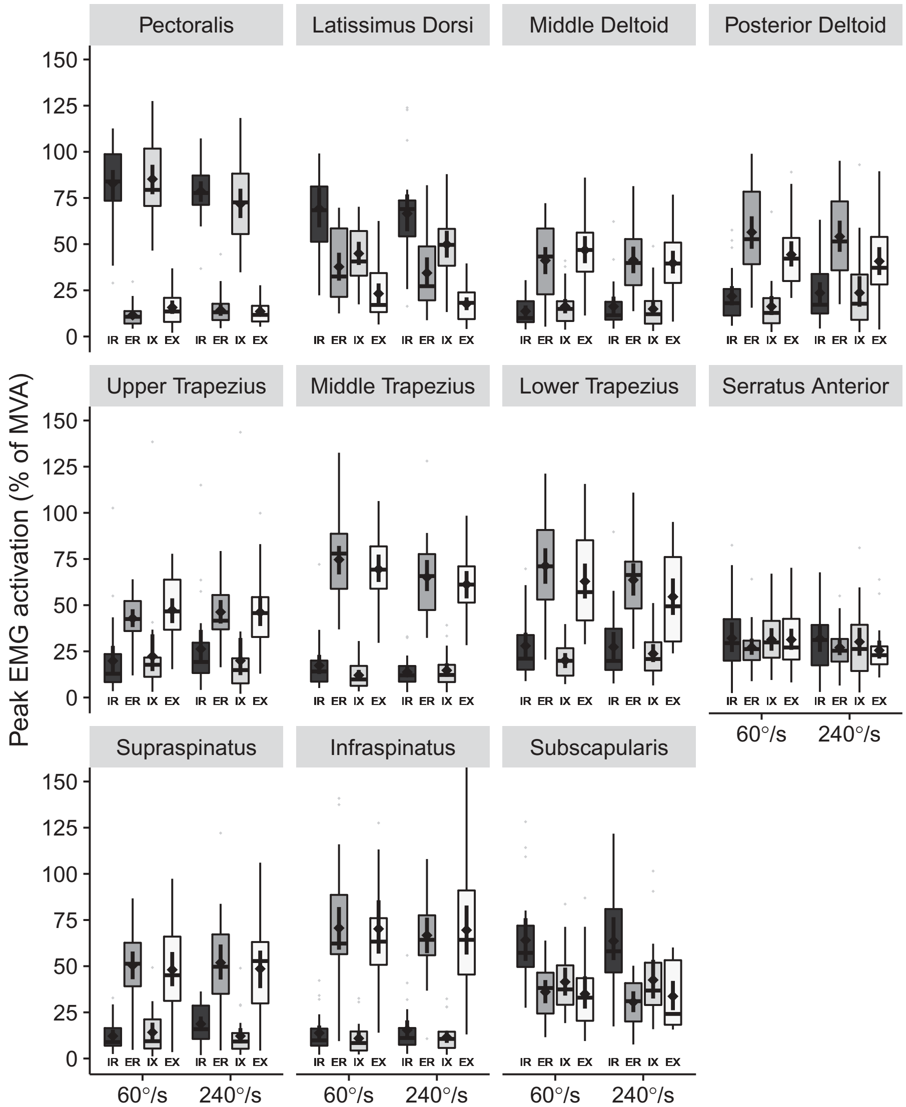


Figure 3. Boxplots of the peak EMG activation of the shoulder girdle muscles during the various conditions. The pectoralis major and latissimus dorsi were more active during IR and IX than ER and EX while on the contrary, middle and posterior deltoids, upper, middle and lower trapezius, supraspinatus and infraspinatus were more active in the external rotation conditions, at both velocities. The subscapularis and serratus anterior were the only muscles recruited to at least moderate activity in all conditions, at both speeds. Dots represent outlier values (> median + 1.58 interquartile range) while the black diamond and line range represent mean and 95 % Confidence Interval.

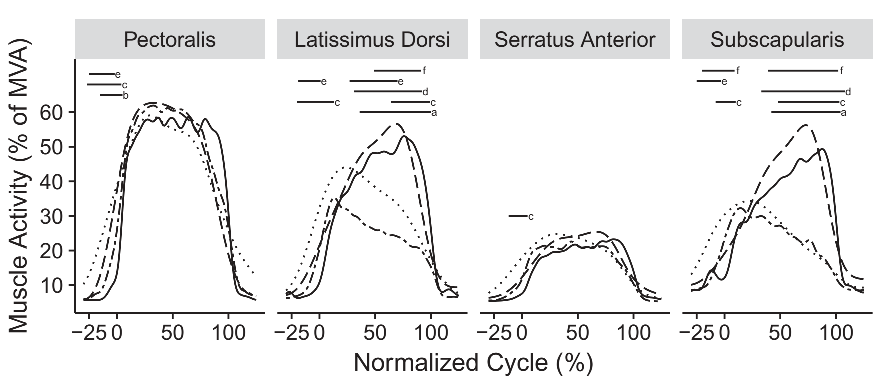


Figure 4. EMG envelopes for each muscle during the various internal rotation conditions. Line type indicates type of contraction; IR-60 (solid), IX-60 (dash-dotted), IR-240 (dashed), IX-240 (dotted). Significant differences in time histories of EMG envelopes from posthoc SPM analysis are denoted by the black lines: IR-60 vs IX-60 (a); IR-60 vs IR-240 (b); IR-60 vs IX-240 (c); IX-60 vs IR-240 (d); IX-60 vs IX-240 (e); IR-240 vs IX-240 (f). Only muscles with significant differences are represented.

Table 2. Mean normalized moment (N.m.kg-1) and standard deviation (SD) produced by participants, grouped by speed and type of contraction.

Speed	Contraction	Mean	SD	Significance
60	IR	0.516	0.157	b c f g
	ER	0.345	0.098	a c e g
	IX	0.642	0.174	a b d e f h
	EX	0.432	0.125	c f g
240	IR	0.474	0.142	b c f g
	ER	0.277	0.080	a c d e g h
	IX	0.634	0.152	a b d e f h
	EX	0.421	0.105	c f g

Letters indicate significant difference with:
a = IR-60; b = ER-60; c = IX-60; e = IR-240; f = ER-240; g = IX-240

Direction of movement

Despite the general consensus that rotator cuff muscles are mainly stabilizers of the glenohumeral joint (Sangwan, Green, & Taylor, 2015), our findings suggest that the supraspinatus and infraspinatus muscles behave more as prime movers than stabilizers. Indeed, those two muscles were highly active during external rotations but showed low activity during internal rotations of the shoulder, which concords with findings of previous studies (Boettcher et al., 2010; Decker, Tokish, Ellis, Torry, & Hawkins, 2003). Shoulder stability may also be ensured by surface muscles in certain situations as shown by Blache, Dal Maso, Desmoulins, Plamondon, and Begon (2015) who observed a high co-contraction of the anterior, middle and posterior deltoids, latissimus dorsi and pectoralis major during manual handling, suggesting an attempt to increase glenohumeral joint stiffness. Still, our results showed direction-specific activity levels for the pectoralis, middle and posterior deltoids and upper, middle and lower trapezius muscles. Some of those muscles may still have a stabilizing role (e.g. middle and lower trapezius stabilizing the scapula during external rotations (Boettcher et al., 2010)), yet they also likely contribute directly to the generation of moment force; pectoralis major and latissimus dorsi in IR/IX; middle and posterior deltoids, supraspinatus and infraspinatus in ER/EX.

The subscapularis was the only rotator cuff muscle recruited at moderate to high intensities for all testing conditions. This is somewhat at odds with previous research which reported minimal activity for this muscle during external rotation tasks (Dark, Ginn, & Halaki, 2007; Wickham, Pizzari, Balster, Ganderton, & Watson, 2014), but it shows some similarity with the work of Heuberer et al. (2015). Its markedly high peak activity during IR at both velocity may indicate its role as a prime mover in internal rotation. Moderate activity of the subscapularis during external rotation may be explained by its important role in centering the humeral head, resisting antero-posterior and superior translation (Broström, Kronberg, & Nemeth, 1989; Rathi, Taylor, & Green, 2016; Sangwan et al., 2015; Wattanaprakornkul, Cathers, Halaki, & Ginn, 2011; Wickham et al., 2014). Field EMG studies have shown that the subscapularis was highly activated in all phases of throwing and swimming stroke and that deficiencies in its activation pattern were associated with shoulder pathologies in baseball players and swimmers (Glousman et al., 1988; Hess & Richardson, 2005; Scovazzo, Browne, Pink, Jobe, & Kerrigan, 1991). Yet, clinical recommendations in rehabilitation emphasize strengthening of the external rotators of the rotator cuff (Reinold, Gill, Wilk, & Andrews, 2010), probably related to previous findings showing decreased external to internal rotation strength ratio in athletes (Andrade et al., 2010). However, in a recent study, Terrier, Larrea, Malfroy Camine, Pioletti, and Farron (2013) used a musculoskeletal model to show that deficiency of the subscapularis induced a decrease in force of the infraspinatus muscle and resulted in increased upward translation of the humeral head. Based on this and our present findings, we would suggest that more attention be placed on good functioning and proper strengthening of the subscapularis muscle.

Although we followed an established technique (Kadaba et al., 1992), we could not confirm the exact placement of the fine-wires at the end of the experiment. In some participants, visual inspection revealed high similarity between subscapularis and lower trapezius EMG envelopes, which explains why 30% of subscapularis data were excluded from analysis (Table 1). We hypothesize that the wires were sliding out of the subscapularis and into the lower trapezius because of the adhesive tape applied over the wires to avoid entanglement with the surroundings. We thus recommend that the participant performs slow shoulder flexion and abduction movements, throughout the full range of motion following fine-wire insertion prior to taping. This should allow drawing-in of the wires by 3–4 cm, which is analogous to the method proposed by Németh, Kronberg, and Broström (1990) for lateral insertion of fine-wires in the subscapularis. Indeed, subsequent testing using this technique allowed measurement of the subscapularis EMG activity with a similar error rate (artifacts) as for the other muscles.

Similar to the subscapularis, the serratus anterior was moderately activated during both internal and external rotations. This finding is in accordance with previous studies that have identified its important role in stabilization and positioning of the scapula during various shoulder tasks (Struyf et al., 2014). Indeed, the serratus anterior has been shown to contribute to protraction, upward rotation, posterior tilt and external rotation of the scapula (Escamilla, Yamashiro, Paulos, & Andrews, 2009). During our internal rotation conditions, the ability of the serratus anterior to stabilize the medial border and inferior angle of the scapula could prevent scapular winging (Escamilla et al., 2009), therefore providing a solid base for the subscapularis to assist in moment production. Conversely, during our external rotation conditions, the serratus anterior acts in synergy with the middle and lower trapezius muscles to keep the scapula retracted and close to the rib cage, so that the prime movers with attachment to the scapula, such as the infraspinatus, can develop external moment (Boettcher et al., 2010). Uga et al. (2016) reported a higher activity of the serratus anterior and a lower activity of the infraspinatus during isometric external rotation as shoulder abduction angle increased, which allowed subjects to maintain the force generated. Our findings support the role of the serratus anterior as a scapula stabilizer and bolster the importance of monitoring its activity during clinical evaluation of the shoulder complex.

Velocity

Our findings partially support our hypothesis that muscle recruitment is dependent on movement velocity. During external rotations, only middle trapezius peak EMG activity decreased when going from 60 to 240°/s. A similar trend was present for the lower trapezius as well, although not significant. Interestingly, the isokinetic moment produced during ER was the only one reduced at 240°/s velocity. As discussed earlier, middle and lower trapezius work as dynamic stabilizers of the scapula. Boettcher et al. (2010) also suggested that they may assist in generating external rotation force through scapula retraction. Our results are in accordance with this observation and suggest that a decrease in external rotation strength may be indirectly related to a weakness of the scapula stabilizers rather than the external rotators of the shoulder. As for internal rotation, the pectoralis major was the only muscle for which velocity had an effect on peak EMG activity. This decrease was only seen during IX-240 and was not associated with a decrease in IX moment production, which is in agreement with reports of EMG activity during eccentric efforts at the knee joint (Duchateau & Baudry, 2014) (discussed in the next section). Based on the work of Prinold et al. (2013), who showed significant differences in scapular kinematics for movements at fast athletic speeds, we were expecting to observe more differences in muscle activity between the two velocities. The fact that the movements performed in our study were guided by the path of the dynamometer's lever and that the arm was supported may explain why EMG activity of only two out of 11 muscles were affected by an increase in velocity.

Although statistical analysis of peak EMG activities did not show an effect of velocity for most of the muscles studied, SPM analysis of the EMG envelopes revealed a faster rise in muscle activity at the 240°/s, especially during eccentric contractions for the rotator cuff and scapula stabilizers muscles. Those results need to be interpreted carefully, especially with regard to pre-activation (before start of the repetition). Since the duration of the repetition cycle was normalized according to the start and end position of the arm, muscle pre-activation at an earlier phase of the cycle does not necessarily mean that muscle onset is earlier in time, only that it occurs at a different arm position. However, since EMG envelopes for all muscles were similar at both velocities for the remainder of the repetition cycle, our results suggest that velocity may indeed alter the pre-activation muscle recruitment pattern. Therefore, we suggest that performing isokinetic exercises at higher velocities may be an important aspect in strengthening of the athlete's shoulder.

Contraction mode

Eccentric contractions are well known to provide a greater intrinsic force capacity due to lengthening of the muscle fibers during contractions (Duchateau & Baudry, 2014). Indeed, in the present study, a 25 to 55% increase in moment force during eccentric conditions compared to concentric conditions was seen while all ll muscles showed similar or lower peak EMG activity. The subscapularis and latissimus dorsi were the only two muscles with reduced peak EMG activity during eccentric contractions for a given speed. Higher activity in the subscapularis during IR conditions may be seen as an indication of its role as a prime mover during an internal rotation task (Boettcher et al., 2010; Decker et al., 2003; Wickham et al., 2014). On the other hand, the serratus anterior showed similar activation throughout conditions and therefore seems to contribute solely as a stabilizer of the scapula. SPM analysis provided interesting insights on the recruitment pattern differences between concentric and eccentric conditions. Although peak EMG levels were similar between conditions, the EMG envelopes revealed that peak activity was reached earlier during eccentric rotations; before the start of the repetition versus in the last 30% during concentric conditions. To our knowledge, this is the first study to describe this kind of observation. As Cools et al. (2016) reported in their review, limited evidence exists as to why eccentric training of the rotator cuff shows positive outcomes in clinical settings. It is important to consider that comparing eccentric and concentric EMG envelopes through SPM is biased as the movements are performed in opposite direction, thus observed differences may be due to the muscle's initial configuration and related to the length-tension relationship. Nonetheless, our findings indicate that the inclusion of isokinetic eccentric training at progressively higher velocities in a rehabilitation setting may teach faster recruitment of the shoulder girdle muscles which in turn could increase stability of the glenohumeral joint.

Limitations

Our study presents some limitations. Only a single pair of finewire electrodes was used to measure activity of the subscapularis muscle and was inserted toward the lower fibers. Previous work showed that the upper and lower fibers of the subscapularis muscle are recruited at different intensities depending on the arm abduction angle (Decker et al., 2003; Kadaba et al., 1992; Wickham et al., 2014). Recent research also challenges the use of surface EMG to record the activity of the serratus anterior and the latissimus dorsi (Ginn & Halaki, 2015; Hackett, Reed, Halaki, & Ginn, 2014). Hackett et al. (2014) reported that skin movement under the electrodes consistently underestimate serratus anterior activity compared to indwelling electrodes during various isometric and dynamic exercises. Therefore, serratus anterior activity during the present study may not be fully representative of this muscle's true activity. On the other hand, surface EMG on the latissimus tends to overestimate activity during shoulder flexion due to cross-talk of the erector spinae muscle (Ginn & Halaki, 2015). It is however unclear how crosstalk influences the recorded EMG activity during shoulder axial rotations. Finally, the present study only recorded muscle activity at two different velocities (60 and 240°/s). Further work is recommended to determine if the present results can be extrapolated to intermediate (e.g. 180°/s) and higher velocities (e.g. 300°/s).

Conclusions

The muscle activation patterns observed during the various testing conditions of the present study provide us with a better understanding of each muscle's role during shoulder rotations and can help improve evaluation and rehabilitation methods for management of shoulder injuries in overhead athletes. It appears that the subscapularis and serratus anterior play an important role in the stability of the shoulder joint in both internal and external rotations. Thus, dedicated training of those muscles may help reduce the incidence of shoulder injuries through greater stabilization of the glenohumeral joint and optimal positioning of the scapula. As our results suggest, rapid eccentric contractions may teach the athletes faster recruitment of the shoulder girdle muscles while developing higher moment force, which may transfer well to athletic skills in overhead sports. Inclusion of high velocity eccentric training of the shoulder in rehabilitation and strengthening programs may thus be recommended, although future longitudinal intervention studies are needed to confirm our rationale.

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