Torque and Force Production During Shoulder External Rotation: Differences Between Transverse and Sagittal Planes

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In joints with 3 degrees of freedom, such as the shoulder joint, the association of different movements results in changes in the behavior of the moment arm of the muscles. The capacity of torque production for the same movement can be changed when movements take place in a different plane. The objective of this study is to quantify differences between torque production and resultant force estimated during the shoulder external rotation in two movement planes: the transverse and sagittal planes (with 90° of shoulder abduction). Eight individuals were evaluated using an isokinetic dynamometer and an eletrogoniometer for movements in the transverse plane and six individuals for movements in the sagittal plane. The results showed that the execution of the external rotation in the sagittal plane allowed greater torque magnitudes and resultant force compared with those in the transverse plane, probably owing to a prestretching of infraspinatus and teres minor.

Keywords: biomechanics, rehabilitation, upper limb

Joint movement depends on the force that muscles produce and on the distance over which this force is applied in relation to the rotation axis of the joint (moment arm) (Otis et al., 1994; Liu et al., 1997; Wilde et al., 2002).

The knowledge of torque, force, and moment arm behaviors and the influence of force and moment arm on the produced torque can be of great use in the control of the overload applied to the muscle-tendinous tissue. The understanding of how moment arm and factors that interfere in the force production capacity interact on torque production is essential for the understanding of human movement, as well as, for improving the exercise plan in rehabilitation programs (Walmsley & Szibbo, 1987; Magee & Reid, 1996; Andrews et al., 2000). Additionally, it is common to change the execution plane of the exercise with the aim of increasing the difficulty and the resistance of a certain exercise (Hageman et al., 1989; Wilk et al., 2002).

In joints with three degrees of freedom, such as the shoulder joint, the association of different movements results in changes to muscle moment arm behavior and muscle lengths. In this way, the torque production capacity for the same movement can be altered, when movements take place on a different joint plane (Hageman et al., 1989; Kuechle et al., 2000).

The shoulder external rotation (ER) was chosen as the object of this study because it is one of the most important strengthening exercises in shoulder rehabilitation programs and because it is performed in more than one plane of execution depending on the rehabilitation phase (Wilk et al., 2002).
The objective of this study was to quantify differences between torque production and resultant force estimated during the ER in two different movement planes: the transverse and sagittal planes (with 90° of shoulder abduction).

**Methods**

Eight subjects (1 female and 7 male), aged between 19 and 25 years, participated in the data collection of ER torque and angles in the transverse plane. Four of the same eight individuals and an additional two subjects (all males aged between 22 and 25 years) participated in the collection of ER in the sagittal plane. Winpipe software was used to calculate the sample size in each plane, with 80% of test power and a significance level of 0.05. Only half of the subjects performed both tests because it was impossible to contact the other four individuals to go to the laboratory on another day. All the subjects were nonathletes but practiced regular physical activities (two or three times per week), were right-handed, and had mean body weight of 70 kg (±6 kg) and mean height of 170 cm (±10 cm). In each subject, the right shoulder was evaluated and none of the subjects had any history of injury in the evaluated shoulder. All subjects read and signed university-approved informed consent documents for human subjects prior to participation.

Data collection was carried out on a Cybex Norm isokinetic dynamometer (Dataq Instruments, Inc., USA). To register the joint position in relation to the time with greater precision, a Biomectrics Ltd XM 180 eletrogoniometer (Cwmfelinfach, U.K.) was used. The eletrogoniometer was adapted to the isokinetic dynamometer. Both instruments, the isokinetic dynamometer and the eletrogoniometer, were connected to a Pentium III 650-MHz microcomputer using an analog-to-digital converter set to a sampling frequency of 500 Hz. The software SAD32 (System of Data Acquisition, developed by the Mechanical Measurements Laboratory of the Federal University of Rio Grande do Sul) and the software MATLAB (MathWorks Inc, USA) were used for data treatment.

Data collection was carried out on two different days, to avoid muscle fatigue. First, torque and angle data were collected from the transverse plane, and then on another day, the torque and angle data of ER were collected from the sagittal plane.

The data collection procedures consisted of five phases: preparation, positioning, calibration, familiarization with the test, and testing. In the preparation phase, prior to the test, the subjects completed a warm-up and stretched the right upper limb. The subjects were asked to stretch the external and internal rotators unaided for few seconds. For ER, in the transverse plane, the subjects were required to stand with the arm adducted, with 90° of elbow flexion and without any pronation or supination of the forearm (Figure 1, left). In the sagittal plane, a lying position was adopted with the right upper limb at 90° of shoulder abduction, 90° of elbow flexion, and without any pronation or supination of the forearm (Figure 1, right). These standard positions were recommended by the manufacturer. The isokinetic

![Figure 1 — Left: positioning for the transverse plane. Right: positioning for the sagittal plane.](image)
dynamometer has Velcro straps that hold the subject in the correct position for the test, avoiding any possible change to the plane of interest.

For each subject, the range of movement (ROM) was determined in both planes from the maximum internal rotation (IR) position to the maximum external rotation position at which the individual felt capable of producing maximum torque. The zero angle of rotation was established as being that corresponding to the neutral rotation position, considered the position without any shoulder rotation.

Familiarization with the test involved three repetitions of submaximal concentric ER and IR contractions. During the testing, the subjects completed five repetitions of maximal concentric ER contractions at an angular speed of 60°/s.

Torque and angle data were digitally filtered using a third-order Butterworth filter with cut-off frequencies set at 3 Hz for angle data and 10 Hz for torque data. After the signal was filtered, averages of the five repetitions were calculated. The convention used in this study was negative values for ER angles and positive values for IR.

Once the ER mean torque curve had been obtained, the resultant force performed by the external rotators was estimated by dividing the values of the torque curve by the moment arm values of this musculature. The torque curve represents the net effect of muscle activity. Passive structures such as ligaments and friction effects on the joint also come into play to contain the range; however, at low and moderate movement speeds, the contribution of these situations can be considered negligible (Winter, 2005). Thus, the resultant force calculated using this torque curve will basically represent the net force produced by all the muscles involved, and will be named resultant force. To estimate resultant force, the mean moment arm was calculated. This mean was weighted by the physiological cross-sectional area (PCSA) of each muscle, resulting in the weighted mean moment arm (WMMA), as shown in Equation 1:

\[
WMMA = \frac{\sum_{i=1}^{n} MA_i \times PCSA_i}{\sum_{i=1}^{n} PCSA_i}
\]

where MA is the moment arm, PCSA is the physiological cross-sectional area, \( i \) represents each muscle considered, and \( n \) represents the total number of muscles.

The muscles included in this analysis were the supraspinatus, infraspinatus, teres minor, posterior deltoid, middle deltoid, and anterior deltoid. It is important to notice that these muscles were included because they presented moment arms to shoulder ER. Moment arms and PCSA values were obtained from the literature (Kuechle et al., 2000).

Statistical analysis was carried out using the SPSS software, version 13.0. The mean and standard error were determined for each subject and then for each plane analyzed. Since the sample was relatively small, comparisons of peak torque, peak force, and their corresponding angles were made using the Mann–Whitney test, and comparisons of torque curve and the resultant force curve in the whole ROM were made using a Wilcoxon test, at 10° intervals, from −40 (ER) to 40 (IR). To represent each position, an average around each point was calculated that included all measurements within a 5° radius of each central point. Thus, to represent the torque or force at the angular position of 30°, for example, all values from 25° to 35° were averaged. An alpha level of \( p < 0.05 \) was used to determine statistical significance.

**Results**

The following results refer to the average of five repetitions and their respective standard errors. The standard errors are presented only in one direction to permit better graphical visualization. However, they should be considered in both directions.

Figure 2 presents the ER torque behavior in the sagittal and transverse planes. At the beginning of the movement, in the sagittal plane, there is an increase in the magnitude, and later, the torque tends to remain constant in the middle ROM. While this “plateau” is maintained, a light increase occurs, which represents the peak torque. At the end of the movement, the torque curve presents a descending phase. The ER peak torque in the sagittal plane occurred at the angle of −34°, where the shoulder is rotated externally, with a mean value of 43 N·m. The ER torque in the transverse plane presented a different behavior from that found in the sagittal plane. The ER peak torque in the transverse plane was
reached when the shoulder was internally rotated at 28°. The maximum torque value was 28 N·m.

In the ER WMMA in the sagittal plane, there is a steady increase in the whole ROM with a relative variation of approximately 200%, as displayed in Figure 3. The highest magnitude of the external rotators WMMA occurred at −80°, the moment arm being 0.94 cm. The ER WMMA behavior in the transverse plane is different from that found in the sagittal plane (see also Figure 3). In the beginning of the movement, the moment arm is about 0.74 cm, reaching the maximum value of 1 cm at −3.7°, when the shoulder is externally rotated. At the end of the movement, the moment arm is about 0.81 cm. The relative variation in this plane is much smaller when compared with the sagittal plane (approximately 25% throughout every ROM).

Figure 4 presents the behavior of the ER resultant muscular force in the sagittal and transverse planes. In the sagittal plane, this curve can be divided in two defined phases: an ascending initial phase until peak force is reached and a descending phase until the end of the movement. Unlike the torque behavior, the peak force is reached when the shoulder is internally rotated, before reaching the neutral position and without presenting any “plateau” throughout the ROM. The ER peak force was reached at 35° with a value of 10,227 N. The behavior of the ER resultant muscular force in the transverse plane is very similar to that of the ER torque in the same plane. Moreover, it is also very similar to the behavior of the ER resultant muscular force in the sagittal plane, as can be seen in this Figure 4. It is important to note the differences in

![Figure 2 — External rotators mean torque in the sagittal and transverse planes and standard error.](image)

![Figure 3 — External rotators weighted mean moment arm in the sagittal and transverse planes.](image)
the resultant force magnitudes between the two planes, because the resultant force in the sagittal plane reaches greater values than the resultant force in the transverse plane.

Table 1 presents the statistical analysis of peak torque, peak force, and their corresponding angles. The only variable in which there is no apparent significant statistical difference between the two planes is the peak force angle, with \( p = 0.573 \). The other variables are \( p < 0.05 \).

Figure 5 presents the statistical analysis of torque differences between the two planes throughout the whole ROM. In the IR, the angles at which there was no apparent statistical difference were 30° and 40°, with \( p = 0.107 \) and 0.487, respectively.

Figure 6 presents the statistical analysis of the resultant force differences between the two planes and shows a significant statistical difference throughout the ROM.

**Discussion**

External rotation torque values in the sagittal and transverse planes are different in magnitude and in curve behavior throughout the ROM. This shows the effects of changing the plane where the movement is carried out. For a same joint movement, changing the plane causes alterations to the moment arm behavior and magnitude (owing to geometric alterations) and to force production capacity owing to alterations in the force–length relationship.

In this study, the differences found in joint-plane-related torque behavior show variations in values in accordance with the findings in other movements reported by Hageman et al. (1989). These authors reported greater ER and IR peak torques reached at 45° of shoulder abduction when compared with ER and IR torques reached at 45° of shoulder flexion.
Another study, carried out by Walmsley & Szibbo (1987), also found differences in ER and IR torque in three positions: neutral position, 90° of shoulder abduction, and 90° of shoulder flexion. These authors found significant differences in the ER peak torque between the 90° of flexion and the neutral position as well as between 90° of flexion and 90° of abduction, but they failed to compare the neutral and abduction positions. Our results also show differences, but they are related to the neutral position and 90° of abduction only. These differences related to the movement plane may be explained by changes in the force–length relationship of the involved musculature and by gravitational forces that affect the shoulder complex (Walmsley & Szibbo, 1987; Hageman et al., 1989).

The behavior of the resultant force in both planes is similar, though there are statistically significant differences in their magnitude. The simple execution of this movement in the sagittal plane seems to have provided an increase in force production capacity. Force production capacity depends on the following factors: force–speed relationship, force–length relationship, and temporal and spatial summation of motorneurons (Enoka, 1988; Soderberg, 1997). The variations regarding the factors related to contraction velocity and stimulus summation were minimized, because, in the current study, the angular speed was fixed at 60°/s and the subjects were requested to produce maximum force (Soderberg, 1997). As a consequence, the only factor capable of influencing force production capacity, which was not controlled in this study, is the force–length relationship. In a certain way, the results of ER resultant force indirectly show the influence of the force–length relationship on the force production capacity. Therefore, even with a small number of subjects, it is possible to infer the influence of the movement plane on force production capacity. Increased force production capacity in the sagittal plane may be due to a prestretching of two external rotator muscles that are considered primary motors of this movement: the inferior portion of the infraspinatus and the teres minor. These muscles are shoulder adductors and present the highest ER moment arm magnitudes (Otis et al., 1994; Hughes et al., 1998; Kuechle et al., 2000; Kapandji, 2000). Hence, the execution of the ER starting from 90° of abduction might have caused prestretching of these muscles, altering their force–length relationship. It is known that force enhancement occurs following stretching, but not all the mechanisms related have yet been explained. Some studies suggest that the explanation for this force enhancement might be the nonuniform length of the sarcomere together with passive force enhancement (Lee & Herzog, 2002; Rassier et al., 2003).

The variation in the behavior of the WMMA was different in the two movement execution planes. With regard mechanical aspects, the 90° of shoulder abduction caused a WMMA peak displacement to the end of the ER ROM. In the transverse plane, the magnitude of the variation in the WMMA behavior was smaller and there were increases and decreases throughout the ROM.

The results of this study suggest that changing the joint movement plane of execution has a significant influence on the torque and force production capacity. Identical external resistance during muscular reinforcement exercises will result in different overloads in the tendinous-muscle unit. Shoulder joint rehabilitation involves exercise progression in accordance with the pertinent characteristics of the patient, the injury, and any surgical procedure, if performed (Kibler et al., 2001; Rubin & Kibbler, 2002; Hayes et al., 2004). It is plausible to admit that these characteristics influence the rehabilitation progression, but alternative criteria may be used based on shoulder mechanics during exercise progression (Hayes et al., 2004). Regarding these criteria, we believe that the analysis of moment arm behavior and force production capacity can be useful as a rehabilitation progression criteria. Therefore, a weak muscle can be recruited in a movement where it acts as an accessory muscle (in other words, when it presents a small moment arm).

Considering primary motor muscles, the imposed load can be controlled starting from the relationship between resistance torque, torque production capacity, moment arm behavior, and force behavior. With these aspects in mind, the professional can choose to generate greater resistance in a ROM where there is a mechanical advantage (moment arm) and/or a force–length relationship advantage, if the objective is to cause smaller overload on the tendinous-muscle structure. If the objective is to provoke greater overload on this structure, the peak resistance should be, preferentially, in a ROM where both moment arm and force–length relationship are disfavored.

Our final considerations are that the execution of the ER movement in the sagittal plane allowed larger
torque magnitudes and resultant force compared with those in the transverse plane, probably due to a prestretching of infraspinatus and teres minor.

References


