C/e: FY C/e QA: RV

Journal of Sports Sciences, 2014
Vol. 00, No. 00, 1–8, http://dx.doi.org/10.1080/02640414.2014.924054

Routledge
Taylor & Francis Group

Correlation between architectural variables and torque in the erector spinae muscle during maximal isometric contraction

AQ1

ANTONIO CUESTA-VARGAS[1,2] & MANUEL GONZÁLEZ-SÁNCHEZ[3]

[1]*Physical Therapy, Paseo de Martiricos SN, University of Malaga, Malaga 29007, Spain,* [2]*School of Clinical Sciences, Faculty of Health, Queensland University of Technology, Brisbane, Australia and* [3]*Psychiatry and physiotherapy, University of Malaga, Malaga, Spain*

(*Accepted 10 May 2014*)

Abstract

This study analysed whether a significant relationship exists between the torque and muscle thickness and pennation angle of the erector spinae muscle during a maximal isometric lumbar extension with the lumbar spine in neutral position. This was a cross-sectional study in which 46 healthy adults performed three repetitions for 5 s of maximal isometric lumbar extension with rests of 90 s. During the lumbar extensions, bilateral ultrasound images of the erector spinae muscle (to measure pennation angle and muscle thickness) and torque were acquired. Reliability test analysis calculating the internal consistency (Cronbach's alpha) of the measure, correlation between pennation angle, muscle thickness and torque extensions were examined. Through a linear regression the contribution of each independent variable (muscle thickness and pennation angle) to the variation of the dependent variable (torque) was calculated. The results of the reliability test were: 0.976–0.979 (pennation angle), 0.980–0.980 (muscle thickness) and 0.994 (torque). The results show that pennation angle and muscle thickness were significantly related to each other with a range between 0.295 and 0.762. In addition, multiple regression analysis showed that the two variables considered in this study explained 68% of the variance in the torque. Pennation angle and muscle thickness have a moderate impact on the variance exerted on the torque during a maximal isometric lumbar extension with the lumbar spine in neutral position.

Keywords: *ultrasonography, pennation angle, muscle thickness, lumbosacral region, reliability, multiple regression analysis*

1. Introduction

The erector spinae is primarily responsible for lumbar extension, and also contributes to the lateral tilt of the trunk and maintaining posture (Bogduk, Macintosh, & Pearcy, 1992; Stokes, Hides, Elliott, Kiesel, & Hodges, 2007). These functions therefore merit further study of this important muscle group in the lower back, to identify normal biomechanical behaviour in comparison with participants suffering from musculoskeletal disorders that could be conditioned by abnormal behaviour of this muscle, such as low back pain sufferers (McGill, Grenier, Kavcic, & Cholewicki, 2003; Stokes et al., 2007).

The forces produced by muscle contractions generate joint movements, which depend on muscle-tendon forces and the length of the lever arm, defined as the perpendicular distance from the rotation centre of the joint to the muscle-tendon action line (Pandy, 1999; Tsaopoulos, Baltzopoulos, & Maganaris, 2006). It is common for researchers to measure changes in functional parameters that depend on strength (force, torque, etc.) (Al-Mulla, Sepulveda, & Colley, 2011; Delp, Suryanarayanan, Murray, Uhlir, & Triolo, 2001; Larivière et al., 2010) in order to understand the factors contributing to joint movements, from anatomical (lever arm or muscle size for example) and/or neuromotor (synergist, antagonist and agonist activation) perspectives (Blazevich, Coleman, Horne, & Cannavan, 2009).

The most common procedure for measuring the muscle force in a laboratory involves the use of Isokinetic dynamometer connected to computers (Clemons et al., 2004). The variable that is most often obtained from their use is the torque, defined as the product of the intensity of the force (modulus) by the distance from the point of application of the force to the axis of rotation (Al-Mulla et al., 2011; Tsaopoulos et al., 2006).

In biomechanics, ultrasound is commonly used to assess changes in muscle architectural variables such as muscle thickness (Bojsen-Moller, Hansen, Aagaard, Kjaer, & Magnusson, 2003; Mannion et al., 2008; Masuda, Miyamoto, Oguri, Matsuoka, & Shimizu,

AQ2

Correspondence: Antonio Cuesta-Vargas, Physical Therapy, Paseo de Martiricos SN, University of Malaga, Malaga, 29007 Spain. E-mail: acuesta@uma.es

© 2014 Taylor & Francis

PROOF ONLY

2005; Nogueira et al., 2009; Springer & Gill, 2007; Watanabe, Miyamoto, Masuda, & Shimizu, 2004) and/or pennation angle (Fukunaga, Kawakami, Kuno, Funato, & Fukashiro, 1997; Kawakami, Abe, & Fukunaga, 1993; Mahlfeld, Franke, & Awiszus, 2004). Pennation angle is defined as the angle between a parallel aponeurosis line and the line of the clearest fascicle as the positive angle (Hodges, Pengel, Herbert, & Gandevia, 2003), and muscle thickness was defined as the distance between superficial and deep muscle aponeurosis at a 90° angle from the deep aponeurosis (Bland, Prosser, Bellini, Alter, & Damiano, 2011). Both architectural variables have been used most frequently to assess the dynamic behaviour of muscle using ultrasound (Hebert, Koppenhaver, Parent, & Fritz, 2009; Stokes et al., 2007; Teyhen et al., 2007). Studies have shown that the reliability of ultrasound in detecting changes in paraspinal muscles varies from moderate to excellent, giving intra-class correlation coefficient values of between 0.72 and 0.98 (Stokes et al., 2007).

Different studies have evaluated quantitative architectural variables of paraspinal musculature to analyse the behaviour and the change in muscle morphology, using static and dynamic images, for various types of contraction (Kiesel, Uhl, Underwood, & Nitz, 2008; Kiesel, Uhl, Underwood, Rodd, & Nitz, 2007; Lee et al., 2007; Masuda et al., 2005; Watanabe et al., 2004). However, to our knowledge, there are no tests examining how pennation angle and muscle thickness of the erector spinae interact with the torque to mediate lumbar extension.

The aim of this study was therefore to analyse whether a significant relationship existed between the torque of the erector spinae muscle and the muscle thickness and pennation angle measured by ultrasound during a maximal isometric lumbar extension from a sitting position with the lumbar spine in neutral position. The hypothesis was that there was a significant correlation between the dependent variable (torque) and the independent variables (muscle thickness and pennation angle) of the erector spinae. This finding may facilitate the understanding of how architectural changes occur during erector spinae maximal isometric extension.

2. Methods

The study was of cross-sectional design and examined the correlation between muscle thickness and pennation angle and the torque during a maximal isometric lumbar extension with the lumbar spine in neutral position and an angle of 90° between the hips and the trunk.

The study had the following inclusion criteria: healthy adults between 18 and 40 years of age and of both gender with no history of low back pain in the year preceding the study. Participants were excluded if they suffered flashpoint processes in the lumbar spine as a result of spinal disorders or suffered from pain, nerve root/radicular pain, an infection, osteoporotic fractures or neoplastic, metastatic or arthritic disease. Those suffering from scoliosis or any column asymmetry, cognitive impairment of any aetiology or unable to perform the movements in the trial and/or participants with a body mass index over 35 kg/m^2 were also excluded. Forty-six participants took part and five participants were excluded in the present study.

All participants provided written informed consent. This study was conducted in accordance with the Ethical Principles for Medical Research Involving Human Subjects (Williams, 2008) and approved by the ethics committee of the University of Malaga.

According to the Spanish laws on personal data protection (Organic Law 15/1999 and Royal Decree 1720/2007), the anonymity of each participant is guaranteed at all times as well as a perfect personal data escrow. The data were stored on a computer and encrypted password protected and only the two researchers of this study had access to them.

2.1. Screening questionnaires

To better define the group of participants who took part in this trial, each completed four self-administered questionnaires: SF-12 (Luo et al., 2003; Ware, Kosinski, & Keller, 1998), EuroQol 5D (Badia, Roset, Montserrat, Herdman, & Segura, 1999), the Örebro Musculoskeletal Pain Questionnaire (Linton & Halldén, 1998) and the Roland Morris Questionnaire (Roland & Morris, 1983a, 1983b) before commencing the study, which allowed us to develop a general screening group in terms of general health state, quality of life, pain and disability caused by back pain, respectively. The reliability of these tools is 0.70–0.89 (Luo et al., 2003; Vilagut et al., 2008; Ware et al., 1998), 0.86–0.90 (Badia et al., 1999; Van Agt, Essink-Bot, Krabbe, & Bonsel, 1994), 0.98 (Linton & Halldén, 1998) and 0.87 (Kovacs et al., 2002), respectively.

2.2. Ultrasound image acquisition

Five-cm-wide ultrasound head (SonoSite ultrasound mod, Titan, with a linear array transducer and frequency range of 6–13 MHz for ultrasound image acquisition) was placed longitudinally at the level of L_3–L_4 and separated by 3 cm from the line drawn from the level of the spinous processes. The ultrasound image acquisition was performed bilaterally. The ultrasound image was 6.5 cm deep. Before the study, an extensive pilot testing with ultrasound

PROOF ONLY

studies was conducted to determine a correct ultrasound image acquisition protocol (Stokes et al., 2007).

Ultrasound gel was applied between the skin and the head to get better acoustic coupling. It made a mark on the skin and the head of the ultrasound was therefore always placed at the same site.

For the analysis of all architectural variables, the clearest image was chosen to ensure the right selection of the reference points of each measured parameter. Muscle thickness and pennation angle were measured following an adapted procedure described by Hodges et al. (2003). Thickness was measured as the distance between the superficial and deep aponeuroses. Pennation angle was measured between a parallel deep aponeurosis line and the line of the clearest fascicle as the positive angle.

Figure 1 shows an example of how muscle thickness and pennation angle were obtained from the ultrasound images.

2.3. *Peak torque measurement*

To record the maximum muscle strength of each participant, a computerised Isokinetic dynamometer (Real Power, Globus Italia) was positioned between two chains. The sequence of objects between the wall and the lumbar extension machine was as follows: chain, computerised isokinetic dynamometer and chain (Figure 2).

Lumbar extension strength was recorded within 5 s of each repetition. The peak recorded after three repetitions was considered the maximum peak force. The torque was calculated multiplying the value of that peak of force (N) by the distance between the computerised Isokinetic dynamometer and the push arm of the machine (0.95 m).

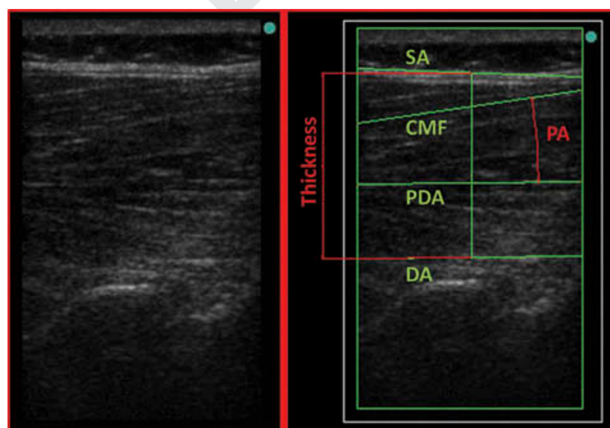

Figure 1. Example of architecture variables measured from ultrasound image.

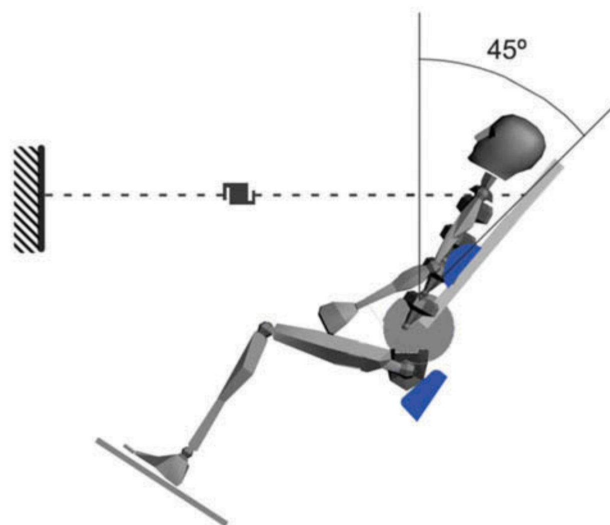

Figure 2. Scheme of the position of the participants and execution of the gesture analysis.

2.4. *Experimental protocol*

Participants performed a 5-min warm-up. Then participants were seated in the apparatus where the test was to be performed. It was verbally explained to all participants how to perform the test and during the explanation it was emphasised that the isometric lumbar extension had to be maximum. Then, the training started and each subject performed between three and five maximum executions. The intensity of these maximal isometric lumbar extensions was monitored by a researcher using the Isokinetic dynamometer and a computer to ensure that participants understood the instructions. Each participant was given the same verbal test instructions before the test and all were encouraged in the same way during the execution of the test. After the training period, the participants had 5-min rest break.

Each participant performed three repetitions of the maximal isometric lumbar extension. The rest time between sets was 90 s. The maximum voluntary contraction was defined as the highest torque value measured during the isometric contraction (Häkkinen & Häkkinen, 1991).

Figure 2 shows the type of movement made by each participant. It should be noted that the chains and the Isokinetic dynamometer stopped the movement at a 45° angle from the vertical, which was at 90° from the lower limbs (Figure 2).

During the execution, ultrasound images and torque measures were acquired. The architectural variables (pennation angle and thickness) were obtained bilaterally after analysing the ultrasound images. The start and end of the synchronising of all systems during each test were marked by an activation device or trigger, which indicates the exact torque value for each ultrasound images analysed offline.

COLOUR ONLINE BLACK & WHITE IN PRINT
COLOUR ONLINE BLACK & WHITE IN PRINT
PROOF ONLY

2.5. Statistical analysis

The statistical treatment consisted of a participant group descriptive analysis, a correlation between all the variables studied in this trial using a Pearson correlation test. The correlation coefficients classification used to understand the results was: $r < 0.49$, poor correlation, $0.50 > r < 0.74$, moderate correlation, $r > 0.75$, strong correlation (Portney & Watkins, 2000).

Moreover, through a linear regression an estimate of the contribution of each independent variable (muscle thickness and pennation angle) to the variation of the dependent variable (torque) was calculated.

For each variable (muscle thickness, pennation angle and torque), the reliability of the measure was calculated. Reliability was considered as a test-retest standard deviation of differences either as the 95% limits of agreement (Atkinson & Nevill, 1998; Nevill & Atkinson, 1997). For this, the three measures were acquired during maximal isometric lumbar extensions and they were used to calculate the internal consistency (Cronbach's alpha) of the measure, together with the 95% confidence interval for each variable.

These calculations were performed using the Statistical Package for the Social Sciences (SPSS) (version 17.0 for Windows, Illinois, USA).

3. Results

Table I summarises the descriptive values of the participants. Forty-six adult (21 males and 25 females) participated in this study. The males and females averaged 30.39 years of age with standard deviations of 8.2 and 7.4 years, respectively. The average male height was 178.1 (±6.7) centimetres, with 165.8 (±5.2) centimetres for the females. On average, the men weighed 78.6 (±14.4) kg and the females were 57.9 (±6.7) kg. Body mass index for males and females was 21.61 (±3.44) kg/m^2 and 24.84 (±2.87) kg/m^2, respectively. The rest of the characteristics describing the group are presented in Table I.

The results after the reliability test performed on muscle thickness and pennation angle (architectural variables) showed a very high stability measure, with Cronbach's alpha values for right angle 0.976 (95% CI: 0.940–0.991), for left angle 0.979 (95%CI: 0.965–0.989), for right muscle thickness 0.983 (95%CI: 0.963–0.991) and for left muscle thickness 0.980 (95%CI: 0.966–0.992). Furthermore, the reliability of torque also showed a very high stability measure, with 0.994 (95%CI: 0.992–0.997) in Cronbach's alpha values. Table II shows, in addition, the Standard Error of Measurement (SEM) values for the different variables considered.

Table II. Reliability values of the different results variables.

	SEM (Stand. Error. Measu.)	Cronbach's α	IC (95%)	
			Min.	Max.
Pennation $Angle_{Right}$	**0.200**	**0.976**	0.940	0.991
Pennation $Angle_{Left}$	**0.221**	**0.979**	0.965	0.989
Muscle $Thickness_{Right}$	**0.772**	**0.983**	0.963	0.991
Muscle $Thickness_{Left}$	**0.767**	**0.980**	0.966	0.992
Torque	**1.564**	**0.994**	0.992	0.997

Table I. Descriptive analysis results of the participants.

	MEAN (CI 95%)	Women (CI 95%)	Men (CI 95%)
EQ 5D (0–1)	0.92 (0.61/1.00)	0.92 (0.75/1.00)	0.92 (0.61/1.00)
EQ VAS (0–100)	79.76 (49/100)	79.05 (56/95)	80.26 (49/100)
PHS (0–100)	51.77 (22.81/65.96)	50.23 (22.81/61.01)	52.85 (40.80/65.96)
MHS (0–100)	49.14 (18.92/62.24)	50.26 (41.10/62.24)	48.35 (18.92/59.73)
ÖMPQ (210–0)	47.22 (2/116)	53.53 (2/116)	42.78 (5/98)
RMQ (24–0)	1.43 (0/9)	1.47 (0/9)	1.41 (0/9)
Torque (N·m)	62.26 (40.54/109.20)	50.23 (40.54/65.52)	72.28 (40.95/109.20)
Angle Right (°)	12.94 (10/17)	12.63 (10/16)	13.42 (11/17)
Angle Left (°)	12.65 (10/16)	12.58 (10/16)	12.89 (10/15)
Thickness Right (mm)	30.6 (0.23/0.38)	29.43 (0.23/0.34)	31.48 (0.25/0.38)
Thickness Left (mm)	31.2 (0.24/0.37)	30.01 (0.24/0.35)	31.91 (0.25/0.37)
N	46	26	21

Notes: EQ 5D: EuroQoL 5 dimensions.
EQ VAS: EuroQoL VAS.
PHS: Physical Health State.
MHS: Mental Health State.
ÖMPQ: Örebro Musculoskeletal Pain Questionnaire.
RMQ: Roland Morris Questionnaire.

PROOF ONLY

Table III. Correlations between torque, pennation angle (right and left sides) and muscle thickness (right and left sides).

	Torque	Angle Right	Angle Left	Thickness Right	Thickness Left
Torque	1				
Angle Right	−0.218	1			
Angle Left	−0.016	**0.614 (p < 0.001)**	1		
Thickness Right	0.157	**0.490 (p < 0.001)**	**0.295 (p = 0.019)**	1	
Thickness Left	0.201	**0.392 (p = 0.007)**	**0.574 (p < 0.001)**	**0.762 (p < 0.001)**	1

Note: Table II: Correlations between each variable considered in this study.

Table IV. Analysis of the degree of contribution of each independent variable to the dependent variable using a multiple regression.

DEPENDENT VARIABLE	Independent variables predictor	Standardised Beta	Sig	R^2
Torque B coef. No Stand. 4.827				0.680
	Right Angle	−0.537	0.142	
	Left Angle	0.443	0.025	
	Right Thickness	0.402	0.090	
	Left Thickness	−0.807	0.020	

Note: Table III: Results of the Multiple regression analysis

Table III summarises the results obtained after conducting a bivariate correlation analysis between the variables. It is interesting to note how both muscle thickness and pennation angle were mild and significant in relationship.

Table IV summarises the results of the multiple linear regression analysis, where the dependent variable was the torque and the independent variables were those of muscle architecture, and are given in Table III.

The critical significance level (F) reached a value of 0.001, indicating a highly significant relationship between the dependent variable (torque) and the independent variables (thickness and pennation angle). Therefore, the regression line provides a good fit to the point cloud.

4. Discussion

The aim of this study was to examine the relationship between the variables of muscle architecture (pennation angle and muscle thickness) and the torque during a maximal isometric lumbar extension with the lumbar spine in neutral position and an angle of 90º between the hips and the trunk. To our knowledge, this is the first time a study has shown a relationship between architectural variables and erector spinae muscle torque during a maximal isometric lumbar extension.

The architectural variables were observed to significantly correlate with each other during the maximal isometric lumbar extension. In addition, multiple regression analysis showed that the four variables (right and left thickness and angle) considered in this study explained 68% of the variance, thus confirming our hypothesis.

The determination coefficients of regression analysis to estimate what proportion of the torque could be explained by architectural variables were studied. There are no published reports that correlate the angle of pennation and muscle thickness to the torque in mediating erector spinae muscle contraction during lumbar extension. The size of the ultrasound head was insufficient to measure the cross-sectional area (Stokes et al., 2007) of the erector spinae muscle. However, a previous study had linked the dependent variable in this study (torque) with the cross-sectional area, which is influenced by the two architectural variables measured in this study (Blazevich et al., 2009). Blazevich and Coleman (Blazevich et al., 2009) demonstrated a relationship between the torque and muscle volume, where the value of R^2 was 0.603, showing a slightly lower value than that obtained by the regression analysis performed between the dependent and independent variables in the present study (R^2 = 0.680).

The difference between the two studies (the current study and that of Blazevich and Coleman (Blazevich et al., 2009)), as well as the unexplained variance (32% in our study) could be due to the activation of agonist and antagonist muscles, the muscles that support postural stability and muscle fibre type (Blazevich et al., 2009). Moreover, it is important to note that the measurements were taken on participants who were not specifically trained in the contraction of the muscle. Therefore, anatomical and neuronal mechanisms could also explain the rest of the variance not elicited by the variables studied here, which could be studied further in the future.

On the other hand, other studies have analysed differently the correlation between architectural variables and functional capabilities measures. McMeeken et al. presented a correlation between muscle thickness and muscle activation (EMG) of 0.87 in the transversus abdominis muscle during

PROOF ONLY

maximum voluntary contraction (McMeeken, Beith, Newham, Milligan, & Critchley, 2004). Likewise, another study analysed the correlation between the other architectural variables used in the present study (pennation angle) and muscle activation of different leg muscles during maximal isometric contractions placing every muscle in their optimal fibre length setting. The values of the regression of each muscle were 0.76, 0.82, 0.82 and 0.87 for the tibialis anterior, lateral gastrocnemius, medial gastrocnemius and soleus, respectively (Manal, Roberts, & Buchanan, 2008). These results are not consistent with those observed in the present study, where none of the architectural variables showed a significant correlation with the functional variable used in this study (torque).

To our knowledge, there are no published studies assessing the reliability of the pennation angle and muscle thickness of the erector spinae together. The results of the architectural variables' reliability values in this study ranged from 0.976 (pennation angle right side) to 0.983 (right muscle thickness). These reliability results are consistent with previous published ultrasound reliability levels on the paraspinal muscles of 0.72–0.98 (Stokes et al., 2007), which ensures minimal negative effect of the operator dependence on ultrasound use.

On the other hand, no studies measuring the erector spinae pennation angle were found. Some studies have measured the thickness of this muscle using the same method as that employed here (placing the head longitudinally to the muscle) (Masuda et al., 2005; Watanabe et al., 2004). Despite placing the head in the same way and taking measurements at the same point on the lumbar spine (L_3), the average values obtained in the two studies differed from those observed by us.

The erector spinae average thickness values on the right and left, 30.6 mm (±6.1) and 31.2 mm (±5.9), respectively, were different from the corresponding values observed in the study by Watanabe et al. (Watanabe et al., 2004), where the value was 33.9 mm (±8.4), and Masuda et al. (Masuda et al., 2005), where the mean was 39.4 (±4.2 mm). One explanation for the difference could be found at the position of the participants when the ultrasound image was recorded. Participants in the studies of Watanabe et al. (Watanabe et al., 2004) and Masuda et al. (2005) were in full lumbar extension, whereas in our trial, they stopped 45° from the vertical. The authors of the other two studies obtained the same trend, starting from a position of maximum flexion, of muscle thickness increasing progressively as it approached its maximum extension position, where the highest muscle thickness was recorded. This difference is consistent with that observed by Li et al. (Le Li, Tong, Hu, Hung, & Koo, 2009; Le Li, Tong, Song, & Koo, 2007), who observed that decreasing the distance between the origin and insertion of a muscle increased thickness in the arm flexors.

Another explanation could be found in the level of muscle activation during ultrasound. The erector spinae of our participants was performing a maximal isometric lumbar extension at the time the image was taken. However, participants who took part in the trials of Watanabe et al. (2004) and Masuda et al. (2005) had their muscle in a relaxed state during image acquisition. In different muscles of the trunk (Brown & McGill, 2010; Dickx et al., 2010; Koppenhaver, Hebert, Parent, & Fritz, 2009), architectural parameters (including thickness) have been observed to increase progressively with increasing intensity of contraction.

A weakness of this study is the differentiation of the groups in terms of gender to improve the accuracy of the analysis when correlating the torque generated during a maximal isometric lumbar extension and the behaviour of the variables considered in this study architecture (pennation angle and muscle thickness). Future studies should increase the sample and analyse gender variance or invariance of participants. In addition, another weakness of this study would be the fixed position of the participant, as this limits the correlation between torque and architecture variables to the lumbar spine neutral position. Increasing the number of positions in which the participants perform the maximum isometric lumbar extension could improve the analysis of the correlation between torque and architectural variables. The procedure described in this study perhaps could be used to analyse difference between healthy and low back pain sufferers.

5. Conclusion

Pennation angle and muscle thickness have a moderate to high impact on the variance exerted on the torque during a maximal isometric lumbar extension with the lumbar spine in neutral position and an angle of 90° between the hips and the trunk.

References

Al-Mulla, M. R., Sepulveda, F., & Colley, M. (2011). A review of non-invasive techniques to detect and predict localised muscle fatigue. *Sensors (Basel, Switzerland), 11*(12), 3545–3594.

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*, Oct *26*(4), 217–238.

Badia, X., Roset, M., Montserrat, S., Herdman, M., & Segura, A. (1999). The spanish version of Euroqol: a description and its applications. European quality of life scale. *Medicina Clínica, 112*(*Suppl 1*), 79–85.

Bland, D. C., Prosser, L. A., Bellini, L. A., Alter, K. E., & Damiano, D. L. (2011). Tibialis anterior architecture, strength,

PROOF ONLY

and gait in individuals with cerebral palsy. *Muscle & Nerve, 44* (4), 509–517.

Blazevich, A. J., Coleman, D. R., Horne, S., & Cannavan, D. (2009). Anatomical predictors of maximum isometric and concentric knee extensor moment. *European Journal of Applied Physiology, 105*(6), 869–878.

Bogduk, N., Macintosh, J. E., & Pearcy, M. J. (1992). A universal model of the lumbar back muscles in the upright position. *Spine, 17*(8), 897–913.

AQ3 Bojsen-Moller, J., Hansen, P., Aagaard, P., Kjaer, M., & Magnusson, S. P. (2003). Measuring mechanical properties of the vastus lateralis tendon-aponeurosis complex in vivo by ultrasound imaging. *Scandinavian Journal of Medicine & Science in Sports, 13*(4), 259–265.

Brown, S. H. M., & McGill, S. M. (2010). A comparison of ultrasound and electromyography measures of force and activation to examine the mechanics of abdominal wall contraction. *Clinical Biomechanics (Bristol, Avon), 25*(2), 115–123.

Clemons, J. M., Duncan, C. A., Blanchard, O. E., Gatch, W. H., Hollander, D. B., & Doucet, J. L. (2004). Relationships between the flexed-arm hang and select measures of muscular fitness. *Journal of Strength and Conditioning Research/National Strength & Conditioning Association, 18*(3), 630–636.

Delp, S. L., Suryanarayanan, S., Murray, W. M., Uhlir, J., & Triolo, R. J. (2001). Architecture of the rectus abdominis, quadratus lumborum, and erector spinae. *Journal of Biomechanics, 34*(3), 371–375.

Dickx, N., D'hooge, R., Cagnie, B., Deschepper, E., Verstraete, K., & Danneels, L. (2010). Magnetic resonance imaging and electromyography to measure lumbar back muscle activity. *Spine, 35*(17), E836–842. AQ4

Fukunaga, T., Kawakami, Y., Kuno, S., Funato, K., & Fukashiro, S. (1997). Muscle architecture and function in humans. *Journal of Biomechanics, 30*(5), 457–463.

Hebert, J. J., Koppenhaver, S. L., Parent, E. C., & Fritz, J. M. (2009). A systematic review of the reliability of rehabilitative ultrasound imaging for the quantitative assessment of the abdominal and lumbar trunk muscles. *Spine, 34*(23), E848–856.

Häkkinen, K., & Häkkinen, A. (1991). Muscle cross-sectional area, force production and relaxation characteristics in women at different ages. *European Journal of Applied Physiology and Occupational Physiology, 62*(6), 410–414.

Hodges, P. W., Pengel, L. H. M., Herbert, R. D., & Gandevia, S. C. (2003). Measurement of muscle contraction with ultrasound imaging. *Muscle & Nerve, 27*(6), 682–692.

Kawakami, Y., Abe, T., & Fukunaga, T. (1993). Muscle-fiber pennation angles are greater in hypertrophied than in normal muscles. *Journal of Applied Physiology (Bethesda, Md.: 1985), 74* (6), 2740–2744.

Kiesel, K. B., Uhl, T., Underwood, F. B., & Nitz, A. J. (2008). Rehabilitative ultrasound measurement of select trunk muscle activation during induced pain. *Manual Therapy, 13*(2), 132–138.

Kiesel, K. B., Uhl, T. L., Underwood, F. B., Rodd, D. W., & Nitz, A. J. (2007). Measurement of lumbar multifidus muscle contraction with rehabilitative ultrasound imaging. *Manual Therapy, 12*(2), 161–166.

Koppenhaver, S. L., Hebert, J. J., Parent, E. C., & Fritz, J. M. (2009). Rehabilitative ultrasound imaging is a valid measure of trunk muscle size and activation during most isometric submaximal contractions: a systematic review. *The Australian Journal of Physiotherapy, 55*(3), 153–169.

Kovacs, F. M., Llobera, J., Gil Del Real, M. T., Abraira, V., Gestoso, M., Fernández, C., & Primaria Group, K.-A. (2002). Validation of the Spanish version of the roland-morris questionnaire. *Spine, 27*(5), 538–542.

Larivière, C., DA Silva, R. A., Arsenault, A. B., Nadeau, S., Plamondon, A., & Vadeboncoeur, R. (2010). Specificity of a back muscle exercise machine in healthy and low back pain subjects. *Medicine & Science in Sports & Exercise*, Mar *42*(3), 592–599.

Lee, J.-P., Tseng, W.-Y. I., Shau, Y.-W., Wang, C.-L., Wang, H.-K., & Wang, S.-F. (2007). Measurement of segmental cervical multifidus contraction by ultrasonography in asymptomatic adults. *Manual Therapy, 12*(3), 286–294.

Li, L., Tong, K. Y., Hu, X. L., Hung, L. K., & Koo, T. K. K. (2009). Incorporating ultrasound-measured musculotendon parameters to subject-specific emg-driven model to simulate voluntary elbow flexion for persons after stroke. *Clinical Biomechanics (Bristol, Avon), 24*(1), 101–109.

AQ5 Li, L., Tong, K., Song, R., & Koo, T. K. K. (2007). Is maximum isometric muscle stress the same among prime elbow flexors? *Clinical Biomechanics (Bristol, Avon), 22*(8), 874–883.

Linton, S. J., & Halldén, K. (1998). Can we screen for problematic back pain? A screening questionnaire for predicting outcome in acute and subacute back pain. *The Clinical Journal of Pain, 14*(3), 209–215.

Luo, X., George, M. L., Kakouras, I., Edwards, C. L., Pietrobon, R., Richardson, W., & Hey, L. (2003). Reliability, validity, and responsiveness of the short form 12-item survey (SF-12) in patients with back pain. *Spine, 28*(15), 1739–1745.

Mahlfeld, K., Franke, J., & Awiszus, F. (2004). Postcontraction changes of muscle architecture in human quadriceps muscle. *Muscle & Nerve, 29*(4), 597–600.

Manal, K., Roberts, D. P., & Buchanan, T. S. (2008). Can pennation angles be predicted from EMGs for the primary ankle plantar and dorsiflexors during isometric contractions? *Journal of Biomechanics, 41*(11), 2492–2497.

AQ6 Mannion, A. F., Pulkovski, N., Gubler, D., Gorelick, M., O'Riordan, D., Loupas, T., … Sprott, H. (2008). Muscle thickness changes during abdominal hollowing: An assessment of between-day measurement error in controls and patients with chronic low back pain. *European Spine Journal, 17*(4), 494–501.

Masuda, T., Miyamoto, K., Oguri, K., Matsuoka, T., & Shimizu, K. (2005). Relationship between the thickness and hemodynamics of the erector spinae muscles in various lumbar curvatures. *Clinical Biomechanics (Bristol, Avon), 20*(3), 247–253.

McGill, S. M., Grenier, S., Kavcic, N., & Cholewicki, J. (2003). Coordination of muscle activity to assure stability of the lumbar spine. *Journal of Electromyography and Kinesiology, 13*(4), 353–359.

McMeeken, J. M., Beith, I. D., Newham, D. J., Milligan, P., & Critchley, D. J. (2004). The relationship between EMG and change in thickness of transversus abdominis. *Clinical Biomechanics (Bristol, Avon), 19*(4), 337–342.

AQ7 Nevill, A. M., & Atkinson, G. (1997). Assessing agreement between measurements recorded on a ratio scale in sports medicine and sports science. *British Journal of Sports Medicine, 31*, 314–318.

Nogueira, W., Gentil, P., Mello, S. N. M., Oliveira, R. J., Bezerra, A. J. C., & Bottaro, M. (2009). Effects of power training on muscle thickness of older men. *International Journal of Sports Medicine, 30*(03), 200–204.

Pandy, M. G. (1999). Moment arm of a muscle force. *Exercise and Sport Sciences Reviews, 27*, 79–118.

Portney, L. G., & Watkins, M. P. (2000). *Foundations of clinical research. applications to practice* (2nd ed.). Upper Saddle River, NJ: Prentice Hall Health.

Roland, M., & Morris, R. (1983a). A study of the natural history of back pain. part I: Development of a reliable and sensitive measure of disability in low-back pain. *Spine, 8*(2), 141–144.

Roland, M., & Morris, R. (1983b). A study of the natural history of low-back pain. Part II: Development of guidelines for trials of treatment in primary care. *Spine, 8*(2), 145–150.

Springer, B. A., & Gill, N. W. (2007). Characterization of lateral abdominal muscle thickness in persons with lower extremity amputations. *The Journal of Orthopaedic and Sports Physical Therapy, 37*(10), 635–643.

PROOF ONLY

Stokes, M., Hides, J., Elliott, J., Kiesel, K., & Hodges, P. (2007). Rehabilitative ultrasound imaging of the posterior paraspinal muscles. *The Journal of Orthopaedic and Sports Physical Therapy, 37*(10), 581–595.

Teyhen, D. S., Gill, N. W., Whittaker, J. L., Henry, S. M., Hides, J. A., & Hodges, P. (2007). Rehabilitative ultrasound imaging of the abdominal muscles. *The Journal of Orthopaedic and Sports Physical Therapy, 37*(8), 450–466.

Tsaopoulos, D. E., Baltzopoulos, V., & Maganaris, C. N. (2006). Human patellar tendon moment arm length: measurement considerations and clinical implications for joint loading assessment. *Clinical Biomechanics (Bristol, Avon), 21*(7), 657–667.

Van Agt, H. M., Essink-Bot, M. L., Krabbe, P. F., & Bonsel, G. J. (1994). Test–retest reliability of health state valuations collected with the EuroQol questionnaire. *Social Science & Medicine (1982), 39*(11), 1537–1544.

Vilagut, G., Valderas, J. M., Ferrer, M., Garin, O., López-García, E., & Alonso, J. (2008). Interpretación de los cuestionarios de salud SF-36 y SF-12 en España: Componentes físico y mental. *Medicina Clínica, 130*(19), 726–735.

Ware, J. E., Kosinski, M., & Keller, S. D. (1998). *SF-12: How to score the SF-12 physical and mental health summary scales*. Quality Metric.

Watanabe, K., Miyamoto, K., Masuda, T., & Shimizu, K. (2004). Use of ultrasonography to evaluate thickness of the erector spinae muscle in maximum flexion and extension of the lumbar spine. *Spine, 29*(13), 1472–1477.

Williams, J. R. (2008). The declaration of Helsinki and public health. *Bulletin of the World Health Organization, 86*(8), 650–651.

PROOF ONLY