European Journal of Sport Science

ISSN: 1746-1391 (Print) 1536-7290 (Online) Journal homepage: https://www.tandfonline.com/loi/tejs20

Study of mechanical characteristics of the knee extensor and flexor musculature of volleyball players

David Rodríguez-Ruiz , Dario Rodríguez-Matoso , Miriam E. Quiroga , Samuel Sarmiento , Juan Manuel García-Manso & Marzo E. Da Silva-Grigoletto

European Journal of Sport Science, September 2012; 12(5): 399–407

Routledge
Taylor & Francis Group

ORIGINAL ARTICLE

Study of mechanical characteristics of the knee extensor and flexor musculature of volleyball players

DAVID RODRÍGUEZ-RUIZ[1], DARIO RODRÍGUEZ-MATOSO[1], MIRIAM E. QUIROGA[1], SAMUEL SARMIENTO[1], JUAN MANUEL GARCÍA-MANSO[1], & MARZO E. DA SILVA-GRIGOLETTO[2]

[1]*Department of Physical Education, Universidad de Las Palmas de Gran Canaria, Las Palmas de Gran Canaria, Spain, and* [2]*Andalusian Center of Sports Medicine, Cordoba, Spain*

Abstract

The aim of the present study was to analyse differences in muscle response and mechanical characteristics of the vastus medialis, rectus femoris, vastus lateralis, and biceps femoris in elite volleyball players of both sexes using tensiomyography. To this end, 47 players of nine nationalities playing for teams in the men's and women's Spanish Superleagues were assessed. The sample comprised 22 women (age 24.6 ± 4.3 years; weight 72.14 ± 10.06 kg; height 178.40 ± 8.50 cm) and 25 men (age 25.0 ± 4.3 years; weight 88.76 ± 9.07 kg; height 194.71 ± 7.84 cm). Tensiomyography was used to assess muscular response and muscular mechanical characteristics. For this purpose, the following variables were analysed: maximum radial displacement of muscle belly and normalized response speed. The findings show, both in men and women, a higher normalized response speed score in the vastus lateralis and vastus medialis compared with the rectus femoris and biceps femoris. A marked lateral symmetry of maximum radial displacement of the muscle belly was also observed in the musculature of the lower limbs, with no statistically significant differences being detected in either men or women. There were, however, clear differences in terms of normalized response speed between male and female volleyball players: women displayed a more pronounced difference in the normalized response speed of the musculature responsible for extension (vastus medialis, rectus femoris, and vastus lateralis) and flexion (biceps femoris) of the knee joint than men. Moreover, tensiomyography proved to be a highly sensitive tool for detecting such changes.

Keywords: *Tensiomyography, volleyball, muscle*

Introduction

A key mechanical movement in volleyball is the triple extension mechanism (i.e. extension of the ankle, knee, and hip joints). This mechanism is particularly useful in a large number of technical manoeuvres, especially those involving jumping (Rodríguez-Ruiz, 1999).

The successful execution of these manoeuvres depends on the players' skill, and is governed by technical and tactical factors, as well as prevailing conditions. Another decisive factor is the learning process undergone by players during their training, by which such manoeuvres become automatic. The specialization required to reach peak performance in a particular sport calls for a standardization of training methods in order to acquire the physical and neural adaptations appropriate to the unique demands of the activity in question. Since the muscle groups that need to be trained are the same in both sexes to improve the same technical actions, this point obtains equally regardless of gender.

However, there appear to be differences in terms of morphology, muscles, and conditions that may act as qualitative variables for differentiating between the performance of the two sexes. Larger transverse sections of the muscles (Bishop, Cureton, & Collins, 1987; Ikai & Fukunaga, 1968; Laubach, 1976), greater activation of the hamstring musculature

Correspondence: D. Rodríguez-Ruiz, Department of Physical Education, Universidad de Las Palmas de Gran Canaria, Campus Universitario de Tafira s/n, 35017 Las Palmas de Gran Canaria, Spain. E-mail: drodriguez@def.ulpgc.es

ISSN 1746-1391 print/ISSN 1536-7290 online
http://dx.doi.org/10.1080/17461391.2011.568633

observable in post-jump landing, and/or the co-activation produced between the flexor and extensor musculature in the knee joint during jumps and changes of direction (Decker, Torry, Wyland, Sterett, & Steadman, 2003; Ford et al., 2006; Hewett, Ford, Myer, Wanstrath, & Scheper, 2006; Hughes, Watkins, & Owen, 2008; Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005; Lephart, Ferris, Riemann, Myers, & Fu, 2002; Malinzak, Colby, Kirkendall, Yu, & Garrett, 2001; Orishimo, Kremenic, Pappas, Hagins, & Liederbach, 2009; Padua, Arnold, Carcia, & Granata, 2005; Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007; Salci, Kentel, Heycan, Akin, & Korkusuz, 2004; Yu, Lin, & Garrett, 2006) are some of the most striking differences between men and women.

There is clearly a need for highly precise, individualized, and localized assessment of the muscle structures most commonly used in volleyball. Tensiomyography, which has been shown to be a valid non-invasive diagnostic method, requiring no effort on the part of the participant, is particularly useful in the monitoring of muscle mechanical characteristics. This technique has been used to assess the rigidity, mechanical characteristics, and contractile capacity of superficial muscles when activated by an electrical stimulus of controlled intensity (Dahmane, Djordjevic, Simunic, & Valencic, 2005; Dahmane, Djordjevic, & Smerdu, 2006; Dahmane, Knez, Valencic, & Erzen, 2000; Dahmane, Valencic, Knez, & Erzen, 2001; Pišot, Valenčič, & Šimunič & Praprontnik, 2001; Pisot et al., 2008; Simunic, 2003; Simunic, Krizaj, Narici, & Pisot, 2010; Valencic, 1990; Valencic & Knez, 1997; Valencic et al., 2000; Valencic, Knez, & Simunic, 2001). The device measures the geometrical changes (radial displacement) in the muscle belly during contraction. The measurements thus obtained, expressed in terms of the displacement of the sensor and the time that displacement takes, are used to assess muscle rigidity and muscle response time.

The aim of the present study was to use tensiomyography to assess muscle mechanical characteristics in male and female elite volleyball players and to demonstrate the validity of the method to mesure the maximum radial displacement of the muscle belly and normalized response speed, and to identify any differences between males and females in muscle response in the vastus medialis, the rectus femoris, the vastus lateralis and the biceps femoris of the same sport speciality and competitive standard.

Methods

Participants

A total of 47 players (22 women, 25 men) of nine different nationalities were assessed, all from teams in the women's and men's Superleagues in Spain (Table I). The following muscles were studied to ascertain their relative importance: vastus medialis, rectus femoris, vastus lateralis and biceps femoris.

All participants were informed of the potential risks associated with the study and signed written consent forms, approved in advance by the University of Las Palmas de Gran Canaria's Research Ethics Committee, in accordance with the guidelines set out in the Helsinki Declaration regarding research involving humans.

Measurement procedure

Tensiomyography uses a pressure sensor positioned above the belly of the muscle being investigated. The operator needs to ensure that it is placed perpendicular to the muscle belly (Valencic & Knez, 1997) and that the muscle segment to be assessed is positioned in accordance with the manufacturer's recommendations (Djordjevic et al., 2000; Gorelick & Brown, 2007; Simunic & Valencic, 2001). To trigger the contraction, a bipolar electric current is applied at incremental intensities (25, 50, 75 and 110 mA; the best response of each participant is registered), one millisecond in duration, via two electrodes located at the proximal and distal ends of the muscle, without affecting the insertion tendons (Knez & Valencic, 2000; Simunic, 2003; Valencic, 2002) and with an interval between stimuli to avoid post-tetanic activation (Belic, Knez, Karba, & Valencic, 2000; Rodríguez-Matoso et al., 2010; Simunic, 2003). The reproducibility of the method and the validity of the tensiomyography experimental protocol have been assessed in a number of studies, which have shown that it is a high-precision tool (Belic et al., 2000; Dahmane et al., 2000; Krizaj, Simunic, & Zagar, 2008; Rodríguez-Matoso et al., 2010; Simunic, 2003; Simunic & Valencic, 2001; Simunic et al., 2010; Tous-Fajardo et al., 2010).

Table I. Physical characteristics of participants

	Age (years)	Weight (kg)	Height (cm)	Body mass index ($kg \cdot m^{-2}$)
Men ($n = 25$)	25.0 ± 4.3	88.76 ± 9.07	194.71 ± 7.84	$23. \pm 1.58$
Women ($n = 22$)	24.6 ± 4.3	72.14 ± 10.06	$178. \pm 8.50$	22.63 ± 2.42

Once a particular muscle has been assessed, numerical information is generated regarding the magnitude and timing of radial displacements of transverse muscle fibres (Simunic, 2003; Valencic & Knez, 1997). The current study focused on two parameters: maximum radial displacement of the muscle belly and normalized response speed.

Maximum radial displacement of the muscle belly (D_m) refers to the radial displacement of the muscle belly expressed in millimetres. It is a measure of stiffness, and varies in each individual and each muscle group as a function of morphofunctional characteristics and the extent to which these structures have been exercised in training. Low values relative to the mean for a representative population indicate a high level of muscle tone and excess rigidity of muscle structures, while higher values indicate a lack of muscle tone or a high degree of fatigue (Dahmane et al., 2001; Hunter, Smith, Watt, Yirrell, & Galloway, 2006; Krizaj et al., 2008; Pisot et al., 2008; Quiroga et al., 2009; Rodríguez-Ruiz et al., 2009; Valencic et al., 2001).

The normalized response speed (V_{rn}) represents the relationship between the difference in the displacement between 10% and 90% of D_m (Δd_r) and the increase in muscle contraction time (Δt_c) between these two values (equation 1). Valencic and Knez (1997) report that to be able to compare the scores obtained from different muscles, it is necessary to normalize this time rise. This is done by dividing equation (1) by the D_m for each muscle (equation 2). The authors report that ($\triangle d_r$) is equal to 0.8 per D_m. Therefore, the normalized response speed will be equal to 0.8 divided by the increase in muscle contraction time between 10% and 90% of D_m (equation 3) (Figure 1):

$$V_r = \Delta d_r / \Delta t_c \quad (\text{mm} \cdot \text{s}^{-1}) \qquad (1)$$

$$V_{rn} = V_r / D_m = (\Delta d_r / \Delta t_c)/D_m \quad (\text{mm} \cdot \text{s}^{-1}/\text{mm}) \qquad (2)$$

$$V_{rn} = 0.8/t_c \quad (\text{mm} \cdot \text{s}^{-1}) \qquad (3)$$

Statistical analysis

Normal distribution of the data was initially checked using the Kolmogorov–Smirnov test. For the comparative analysis, an analysis of variance (ANOVA) of one factor was performed on the parameters obtained for vastus medialis, rectus femoris, vastus lateralis, and biceps femoris, in both men and women, with a Bonferroni multiple comparisons test. Statistical significance was set at an alpha of 0.05. To compare biceps femoris means for men and women, a *t*-test for independent samples was used. All statistical analyses were performed using the SPSS v.17 statistics package (SPSS Inc., Chicago, IL, USA).

Results

Mean normalized response speed in both men and women was higher for vastus lateralis and vastus medialis than for rectus femoris and biceps femoris (Figures 1 and 2). However, women displayed a much more pronounced difference in normalized response speed between the vastus medialis, rectus femoris, and vastus lateralis compared with the Biceps Female (BF) (Figure 2).

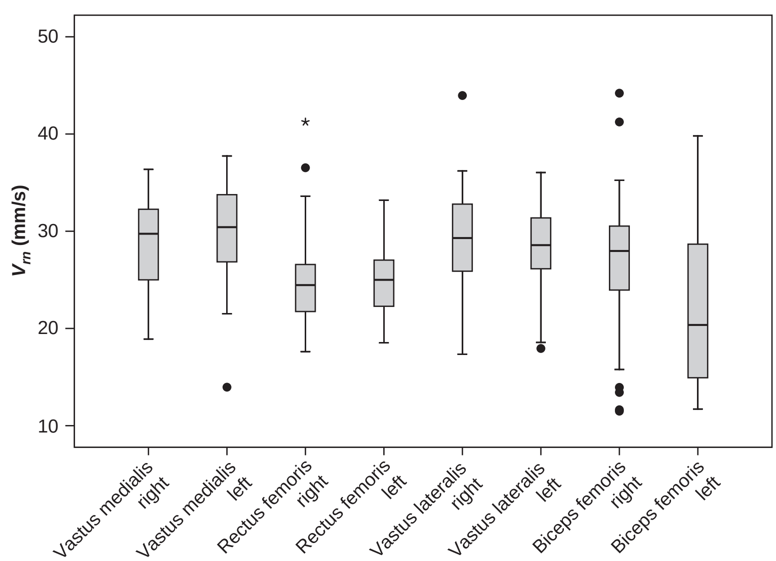

Figure 1. Mean normalized response speed (V_{rn}) for vastus lateralis, rectus femoris, vastus medialis and biceps femoris in the right and left legs of male volleyball players (mm · s^{-1}).

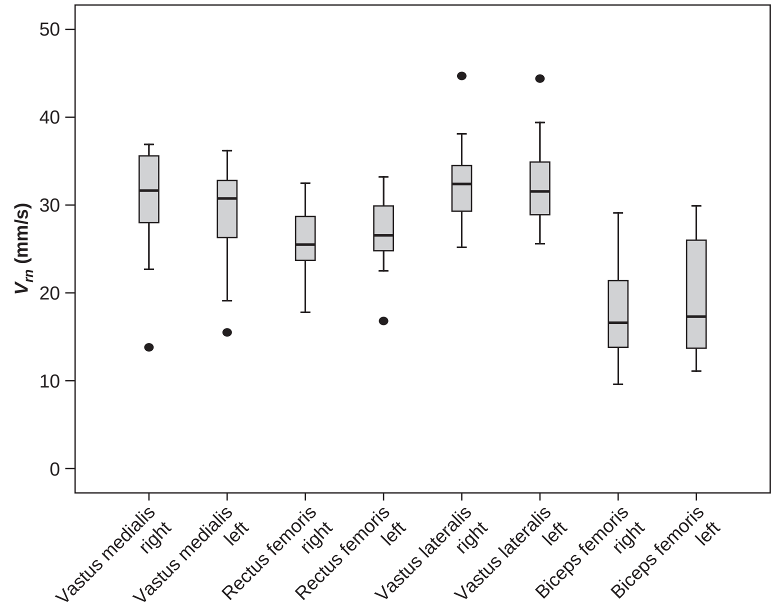

Figure 2. Mean normalized response speed (V_{rn}) for vastus lateralis, rectus femoris, vastus medialis and biceps femoris in the right and left legs of female volleyball players (mm · s^{-1}).

Statistically significant differences were observed in men between left biceps femoris and left vastus lateralis ($P < 0.05$). There were also significant differences between right vastus lateralis and left vastus lateralis ($P < 0.01$). Greater muscular imbalances were found in women players, with significant right versus left differences in normalized response speed for vastus medialis ($P < 0.05$), rectus femoris ($P < 0.001$) and biceps femoris ($P < 0.001$). There were also significant differences between biceps femoris and vastus medialis ($P < 0.05$), and between biceps femoris and vastus lateralis ($P < 0.005$) in the left leg.

In men, significant differences in maximum radial displacement of the muscle belly (Figure 3) were observed between vastus medialis and rectus femoris ($P < 0.005$), between vastus medialis and biceps femoris ($P < 0.005$), between vastus lateralis and rectus femoris ($P < 0.05$), and between vastus lateralis and biceps femoris ($P < 0.005$) in the right leg, and between vastus medialis and rectus femoris ($P < 0.001$) and vastus lateralis and rectus femoris ($P < 0.005$) in the left leg. Comparison of right and left legs revealed no statistically significant differences.

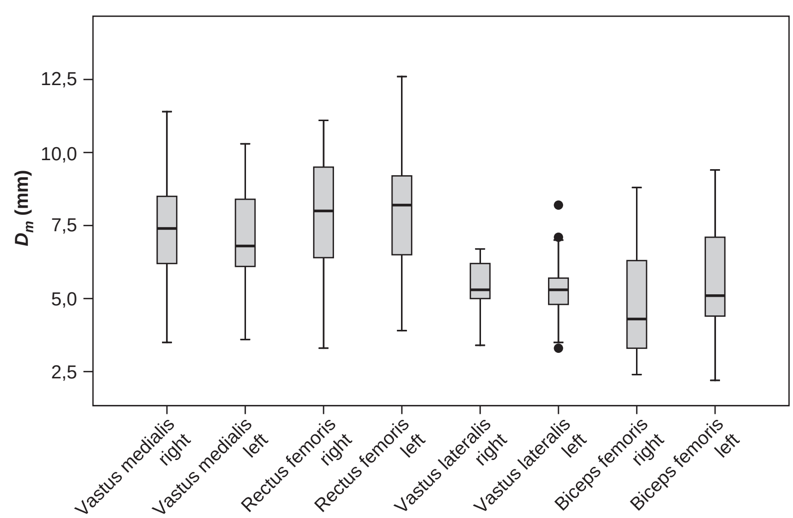

Figure 3. Mean maximum deformation (D_m) for vastus lateralis, rectus femoris, vastus medialis and biceps femoris in the right and left legs of male volleyball players (mm).

There were no significant differences in mean maximum radial displacement of the muscle belly for women (Figure 4).

Comparison of normalized response speed for biceps femoris in men and women (Figure 5) revealed that men displayed significantly ($P < 0.001$) higher values, as well as greater muscular rigidity ($P < 0.005$) (Figure 6) in the right leg.

Discussion

In the present study, there were clear muscle-response differences between male and female volleyball players. These differences were especially marked in relation to the response speed in the muscles responsible for extension (vastus lateralis, rectus femoris and vastus medialis) and flexion (biceps femoris) of the knee joint. A similar difference was evident in terms of muscle rigidity, with men having lower maximum radial displacement of the muscle belly, which was especially pronounced for the BF.

The findings showed, both for men and women, a higher normalized response speed for vastus lateralis and vastus medialis compared with rectus femoris and biceps femoris (Figures 1 and 2). This could be due to two mechanisms. First, to the particular characteristics of the type of jump used in manoeuvres specific to volleyball (jump serve, block and shot). The need to coordinate the jump action with the trajectory of the ball and the height of the net forces the player to execute a jump with a small amount of hip flexion, so responsibility for the main action of extending the knee falls on the vastus medialis and vastus lateralis. Similar findings have been reported by Salci et al. (2004) and Hughes et al. (2008) in studies of gender-related differences in volleyball players. Second, it could be due to the morphological and functional characteristics of muscles undergoing specific adaptive changes in volleyball players, due to the particular demands of this sport and the manoeuvres habitually performed by players. For example, statistically significant differences were observed in men between left biceps femoris and left vastus lateralis ($P < 0.05$). There were also significant differences between right and left vastus lateralis ($P < 0.01$). In women players, there were significant differences between biceps femoris and vastus medialis ($P < 0.05$), and between biceps femoris and vastus lateralis ($P < 0.005$) in the left leg. These differences are due principally to the specific spike jump of the right-handed male and female players.

In the present sample, differences in normalized response speed between knee extensors and flexors were more marked in women (Figure 2). A number of researchers have attributed this to a difference in the activation of the muscles concerned, noting that when women execute a minor flexion of the knee, they perform the jumping motion using mainly the quadriceps, while men execute this movement with a more intense activation of the quadriceps and hamstrings (Decker et al., 2003; Hughes et al., 2008; Lephart et al., 2002; Malinzak et al., 2001; Padua et al., 2005; Yu et al., 2006). There was no appreciable difference, for either sex, between left and right legs

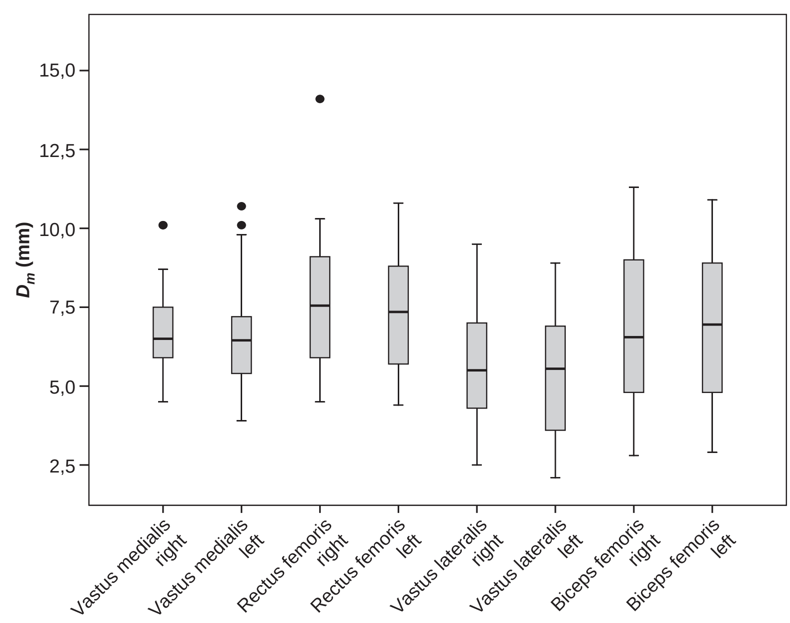

Figure 4. Mean maximum deformation (D_m) for vastus lateralis, rectus femoris, vastus medialis and biceps femoris in the right and left legs of female volleyball players (mm).

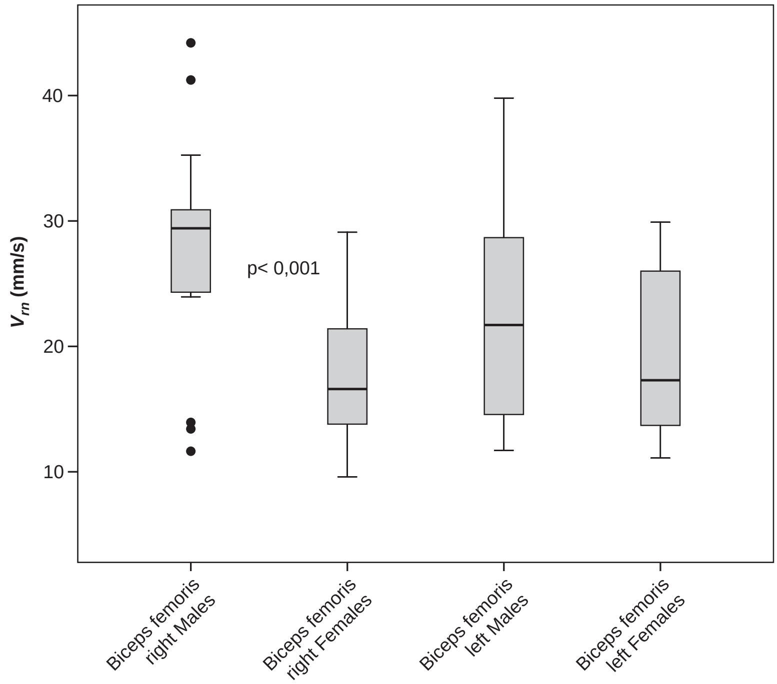

Figure 5. Comparison of mean normalized response speed (V_{rn}) of the biceps femoris in the right and left legs of male and female volleyball players (mm · s^{-1}).

in terms of the relationship between the normalized response speed of the quadriceps and hamstrings.

As might be expected, morphological differences were observed between male and female volleyball players of the same age and standard of performance. The shape and proportions of the pelvis, as well as the position of the bony structures of the lower limb, are especially important in this sport. Hip width and external tibia rotation prompt flexion–extension of the knee, leading to a higher probability of injury

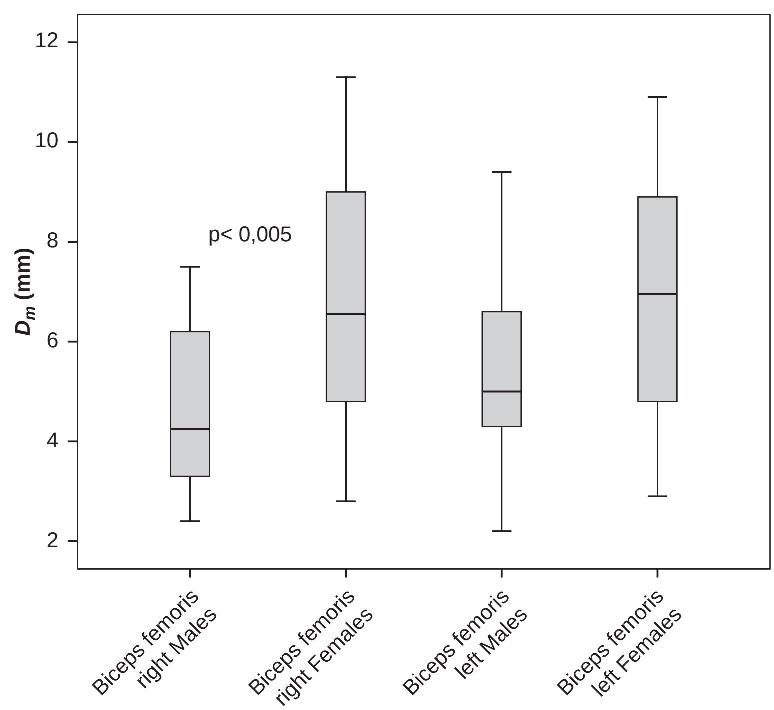

Figure 6. Comparison of mean maximum deformation (D_m) of the biceps femoris in the right and left legs of male and female volleyball players (mm).

among women (Bergstrom, Brandseth, Fretheim, Tvilde, & Ekeland, 2001; Forde, 2005; Huston, Greenfield, & Wojtys, 2000).

These structural differences, combined with differences in mechanical response (normalized response speed and maximum radial displacement of the muscle belly) of the vastus lateralis, vastus medialis and biceps femoris observed in the present study, indicate the possible development of a certain instability in the knee joint, perhaps adversely affecting the application of forces in the jump (Boden, Dean, Feagin, & Garrett, 2000; Hughes et al., 2008; Olsen, Mykelbust, Engebretsen, & Bahr, 2004) and increasing the risk of injury on landing (Decker et al., 2003; Ford et al., 2006; Hewett et al., 2006; Kernozek et al., 2005; Lephart et al., 2002; Orishimo et al., 2009; Pappas et al., 2007; Salci et al., 2004).

It is therefore advisable to establish exercises that teach a better landing technique, and to include in training regimes a number of compensatory exercises designed to improve knee stability, favouring the alignment of loads on the joints and reducing the risk of injury (Chappell & Limpisvasti, 2008; Hewett et al., 2005; Hughes, Watkins, Owen, & Lewis, 2007; Myer, Ford, McLean, & Hewitt, 2006; Orishimo et al., 2009).

In contrast to the general population, the volleyball players in the present study displayed a significant lateral symmetry in maximum radial displacement of the muscle belly in the lower-limb muscles, with no significant gender-related differences. However, significant differences were found between left and right legs for normalized response speed: vastus lateralis ($P < 0.01$) in men, and vastus medialis ($P < 0.05$), rectus femoris ($P < 0.001$) and biceps femoris ($P < 0.001$) in women. These differences are due to the specific volleyball skills.

Conclusion

The results show, in both men and women, a higher normalized response speed in the vastus lateralis and vastus medialis compared with the rectus femoris and biceps femoris. A significant lateral symmetry in maximum radial displacement of the muscle belly was notable in lower-limb muscles, with no significant differences between the sexes. There were, however, clear differences in terms of muscle response between male and female volleyball players: the women show a more pronounced difference in normalized response speed of the musculature responsible for extension (vastus medialis, rectus femoris and vastus lateralis) and flexion (biceps femoris) of the knee joint than the men. Moreover, tensiomyography proved to be a highly sensitive tool for detecting such changes.

It is therefore advisable to establish exercises that teach a better landing technique, and to include in training regimes a number of compensatory exercises designed to improve knee stability, favouring the alignment of loads on the joints and reducing the risk of injury.

References

Belic, A., Knez, N., Karba, R., & Valencic, V. (2000). Validation of the human muscle model. In *Proceedings of the 2000 Summer Computer Simulation Conference,* 16–20 July 2000, Vancouver, British Columbia. Session 1: Issues on Whole Body Modeling.

Bergstrom, K. A., Brandseth, K., Fretheim, S., Tvilde, K., & Ekeland, A. (2001). Activity-related knee injuries and pain in athletic adolescents. *Knee Surgery, Sports Traumatology, Arthroscopy*, *9*, 146–150.

Bishop, Ph., Cureton, K., & Collins, M. (1987). Sex difference in muscular strength in equally-trained men and women. *Ergonomics*, *30*, 675–687.

Boden, B. P., Dean, G. S., Feagin, J. A., & Garrett, W. E. (2000). Mechanisms of anterior cruciate ligament injury. *Orthopedics*, *23*, 573–578.

Chappell, J. D., & Limpisvasti, O. (2008). Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *American Journal of Sports Medicine*, *36*, 1081–1086.

Dahmane, R., Djordjevic, S., Simunic, B., & Valencic, V. (2005). Spatial fiber type distribution in normal human muscle: Histochemical and tensiomyographical evaluation. *Journal of Biomechanics*, *38*, 2451–2459.

Dahmane, R., Djordjevic, S., & Smerdu, V. (2006). Adaptive potential of human biceps femoris muscle demonstrated by histochemical, immunohistochemical and mechanomyographical methods. *Medical and Biological Engineering and Computing*, *44*, 999–1006.

Dahmane, R., Knez, N., Valencic, V., & Erzen, I. (2000). Tensiomyography, a non-invasive method reflecting the percentage of slow muscle fiber in human skeletal muscles. In *Book of Abstracts: Life Sciences 2000*, 28 September to 1 October, Gozd Martuljek, Slovenia, pp./str. 29.

Dahmane, R., Valencic, V., Knez, N., & Erzen, I. (2001). Evaluation of the ability to make non-invasive estimation of muscle contractile properties on the basis of the muscle belly response. *Medical and Biological Engineering and Computing*, *39*, 51–55.

Decker, M. J., Torry, M. R., Wyland, D. J., Sterett, W. I., & Steadman, J. R. (2003). Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. *Clinical Biomechanics*, *18*, 662–669.

Djordjevic, S., Valencic, V., Knez, N., Dahmane, R., Jurcic-Zlobec, B., Bednarik, J., (2000). Contractile properties of skeletal muscles of two groups of sportsmen – sprinters and cyclists measured by tensiomyography. Paper presented to the 2000 Pre-Olympic Congress, Brisbane, Australia, Abstract 220.

Ford, K. R., Myer, G. D., Smith, R. L., Vianello, R. M., Seiwert, S. L., & Hewett, T. E. (2006). A comparison of dynamic coronal plane excursion between matched male and female athletes when performing single leg landings. *Clinical Biomechanics*, *21*, 33–40.

Forde, F. A. (2005). *Analysis of knee mechanics during the squat exercise: Differences between females and males* (Doctoral thesis). University of Florida.

Gorelick, M. L., & Brown, J. M. (2007). Mechanomyographic assessment of contractile properties within seven segments of the human deltoid muscle. *European Journal of Applied Physiology*, *100*, 35–44.

Hewett, T. E., Ford, K. R., Myer, G. D., Wanstrath, K., & Scheper, M. (2006). Gender differences in hip adduction motion and torque during a single-leg agility maneuver. *Journal of Orthopaedic Research*, *24*, 416–421.

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S., Colosimo, A. J., van den Bogert, A. J., et al. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes. *American Journal of Sports Medicine*, *33*, 492–501.

Hughes, G., Watkins, J., & Owen, N. (2008). Gender differences in lower limb frontal plane kinematics during landing. *Sports Biomechanics*, *7*, 333–341.

Hughes, G., Watkins, J., Owen, N., & Lewis, M. (2007). Gender differences in knee kinematics during landing from volleyball block jumps. *Human Movement Studies*, *53*, 1–20.

Hunter, A. M., Smith, I. J., Watt, J. M., Yirrell, Ch., & Galloway, S. D. (2006). The effect of massage on force production and tensiomyography. *Medicine and Science in Sports and Exercise*, *38*, S27.

Huston, L. J., Greenfield, M. L., & Wojtys, E. M. (2000). Anterior cruciate ligament injuries in the female athlete: Potential risk factors. *Clinical Orthopaedics and Related Research*, *372*, 50–63.

Ikai, M., & Fukunaga, T. (1968). Calculation of muscle strength per unit cross-sectional area of the human muscle by means of ultrasonic measurement. *Internationale Zeitshrift für Angewande Physiologie*, *26*, 26–32.

Kernozek, T. W., Torry, M. R., Van Hoof, H., Cowley, H., & Tanner, S. (2005). Gender differences in frontal and sagittal plane biomechanics during drop landings. *Medicine and Science in Sports and Exercise*, *37*, 1003–1012.

Knez, N., & Valencic, V. (2000). In *Proceedings of the Ninth Electrochemical and Computer Science Conference ERK 2000,* 21–23 September 2000, Portoroz, Slovenia. Ljubljana: IEEE Region 8, Slovenian section IEEE, Vol. B, pp. 301–304.

Krizaj, D., Simunic, B., & Zagar, T. (2008). Short-term repeatability of parameters extracted from radial displacement of muscle belly. *Journal of Electromyography and Kinesiology*, *18*, 645–651.

Laubach, L. L. (1976). Comparative muscular strength of men and women: A review of the literature. *Aviation, Space and Environmental Medicine*, *47*, 534–542.

Lephart, S. M., Ferris, C. M., Riemann, B. L., Myers, J. B., & Fu, F. H. (2002). Gender differences in strength and lower extremity kinematics during landing. *Clinical Orthopaedics and Related Research*, *401*, 162–169.

Malinzak, R. A., Colby, S. M., Kirkendall, D. T., Yu, B., & Garrett, W. E. (2001). A comparison of knee joint motion patterns between men and women in selected athletic tasks. *Clinical Biomechanics*, *16*, 438–445.

Myer, G. D., Ford, K. R., McLean, S. G., & Hewett, T. E. (2006). The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *American Journal of Sports Medicine*, *34*, 445–455.

Olsen, O. E., Mykelbust, G., Engebretsen, L., & Bahr, R. (2004). Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *American Journal of Sports Medicine*, *32*, 1002–1012.

Orishimo, K. F., Kremenic, I. J., Pappas, E., Hagins, M., & Liederbach, M. (2009). Comparison of landing biomechanics between male and female professional dancers. *American Journal of Sports Medicine*, *37*, 2187–2193.

Padua, D. A., Arnold, B. L., Carcia, Ch. R., & Granata, K. P. (2005). Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *Journal of Motor Behaviour*, *37*, 111–125.

Pappas, E., Hagins, M., Sheikhzadeh, A., Nordin, M., & Rose, D. J. (2007). Biomechanical differences between unilateral and bilateral landings from a jump: Gender differences. *Clinical Journal of Sports Medicine*, *17*, 263–268.

Pisot, R., Narici, M. V., Simunic, B., De Boer, M., Seynnes, O., Jurdana, M., et al. (2008). Whole muscle contractile parameters and thickness loss during 35-day bed-rest. *Journal of Applied Physiology*, *104*, 409–414.

Pišot, R., Valenčič, V., Šimunič, B., & Praprontnik, U. (2001). Influence of biomechanical properties of particular skeletal muscles on child motor development. In *Proceedings of the International Sport Medicine Conference,* 26–29 September 2001, (pp. 176–177). Trinity College Dublin.

Quiroga, M. E., Rodríguez-Ruiz, D., Rodríguez-Matoso, D., Sarmiento, S., Losa, J., de Saá, Y., et al. (2009). Evaluación de las características mecánicas del músculo mediante la tensiomigrafía. Estudio de casos. In *VIII Congreso Internacional sobre Entrenamiento en Voleibol. Junta de Castilla y León.* 10–12 October 2009, Valladolid, España.

Rodríguez-Matoso, D., Rodríguez-Ruiz, D., Sarmiento, S., Vaamonde, D., Da Silva-Grigoletto, M. E., & García-Manso, J. M. (2010). Reproducibility of muscle response measurements using tensiomyography in a range of positions. *Revista Andaluza de Medicina del Deporte*, *3*(3), 81–86.

Rodríguez-Ruiz, D. (1999). *Efectos de tres modelos de entrenamiento de la fuerza para la mejora de la capacidad de salto en jugadores de Voleibol de máximo nivel* (Doctoral thesis). Universidad de Las Palmas de Gran Canaria.

Rodríguez-Ruiz, D., Quiroga, M. E., Rodríguez-Matoso, D., Sarmiento, S., Losa, J., De Saá, Y., et al. (2009). Aplicación de la tensiomiografía (tmg) en jugadores de voleyplaya: Estudio de caso. In O. Usabiaga, J. Castellano, & J. Etxebeste (Eds.), *Investigando para innovar en la actividad física y el deporte* (pp. 121–130). Voitoria, Spain: Ed. Gidekit.

Salci, Y., Kentel, B. B., Heycan, C., Akin, S., & Korkusuz, F. (2004). Comparison of landing maneuvers between male and female college volleyball players. *Clinical Biomechanics*, *19*, 622–628.

Simunic, B. (2003). *Model of longitudinal contractions and transverse deformations in skeletal muscles*. Doctoral thesis, University of Ljubljana.

Simunic, B., Krizaj, D., Narici, M., & Pisot, R. (2010). Twitch parameters in transversal and longitudinal biceps brachii response. *Annales Kinesiologiae*, *1*, 61–80.

Simunic, B., & Valencic, V. (2001). In *Proceedings of the Xth Electrochemical and Computer Science Conference*, 24–26 September 2001, Portoroz, Slovenia. IEEE Region 8, Slovenian Section IEEE, Vol. B, pp. 363–366.

Tous-Fajardo, J., Moras, G., Rodríguez-Jiménez, S., Usacha, R., Daniel Doutresa, M., & Maffiuletti, N. A. (2010). Inter-rater reliability of muscle contractile property measurements using non-invasive tensiomyography. *Journal of Electromyography and Kinesiology*, *20*, 761–766.

Valencic, V. (1990). Direct measurement of the skeletal muscle tonus. In *Advances in external control of human extremities* (pp. 575–584). Belgrade: Nauka.

Valencic, V. (2002). *Method for selective and non-invasive detection of skeletal muscles contraction process*. International Application

Published under the Patent Cooperation Treaty (PCT). N° WO 02/074167 A1.

Valencic, V., Djordjevic, S., Knez, N., Dahmane, R., Coh, M., Jurcic-Zlobec, B., et al. (2000). Contractile properties of skeletal muscles: Detection by tensiomyographic measurement method. In *2000 Pre-Olympic Congress*, Brisbane, Australia, Abstract 507.

Valencic, V., & Knez, N. (1997). Measuring of the skeletal muscles' dynamic properties. *Artificial Organs*, *21*, 240–242.

Valencic, V., Knez, N., & Simunic, B. (2001). Tensiomyography: Detection of skeletal muscle response by means of radial muscle belly displacement. *Biomedical Engineering*, *1*, 1–10.

Yu, B., Lin, C. F., & Garrett, W. E. (2006). Lower extremity biomechanics during the landing of a stop-jump task. *Clinical Biomechanics*, *21*, 297–305.