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Gender variability in electromyographic activity, *in vivo* behaviour of the human gastrocnemius and mechanical capacity during the take-off phase of a countermovement jump

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Summary

Purpose The purpose of this study was to analyse gender differences in neuromuscular behaviour of the gastrocnemius and vastus lateralis during the take-off phase of a countermovement jump (CMJ), using direct measures (ground reaction forces, muscle activity and dynamic ultrasound).

Methods Sixty-four young adults (aged 18–25 years) participated voluntarily in this study, 35 men and 29 women. The firing of the trigger allowed obtainment of data collection vertical ground reaction forces (GRF), surface electromyography activity (sEMG) and dynamic ultrasound gastrocnemius of both legs.

Results Statistically significant gender differences were observed in the jump performance, which appear to be based on differences in muscle architecture and the electrical activation of the gastrocnemius muscles and vastus lateralis. So while men developed greater peak power, velocity take-offs and jump heights, jump kinetics compared to women, women also required a higher electrical activity to develop lower power values. Additionally, the men had higher values pennation angles and muscle thickness than women.

Conclusion Men show higher performance of the jump test than women, due to significant statistical differences in the values of muscle architecture (pennation angle and thickness muscle), lower Neural Efficiency Index and a higher amount of sEMG activity per second during the take-off phase of a CMJ.

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Introduction

The jump is facilitated by the stretch-shortening cycle (SSC) (Bosco *et al.*, 1982a,b) of musculoskeletal system, with eccentric muscle extension and the posterior concentric action of the extensors muscles of hip, knee and ankle. Most functional activities such as walking, running, stair descent, throwing and most forms of jumping meet the criteria of the SSC. The jump is considered a sporting movement and is common in many sports such as volleyball (Cook *et al.*, 2004), basketball (Malatesta *et al.*, 2003) and others. During the jump, the capacity to store and reuse high energy amounts involve a higher performance and attributed to it are the combined effects of elastic energy use and stretch reflex potentiation in the exercising muscles (Bosco *et al.*, 1982a,b). For decades, the jump has been used as an assessment system of power in the lower extremities. At present, there are multiple tests of jump, one of the important ones being the countermovement jump (CMJ). The CMJ begins with hands on hips, performing a countermovement that leads to take-off. Consequently, the action of jump is facilitated by the SSC (Bosco *et al.*, 1982a). The greatest height achieved during CMJ type, with respect to other movements in which there is not a prior stretching to the SSC, for example squat jump (SJ), is related principally with a greater muscle activation (Bosco *et al.*, 1982b), reutilization of elastic energy (Fukashiro *et al.*, 1995), decreased time to develop strength (Bobbert *et al.*, 1996), increased strength in the concentric phase of the jump (Zajac, 1993) and technical facility to execute the same (Bobbert & van Soest, 2001).

On the other hand, gender has been considered a determinant factor in the capacity to generate strength. Physiological gender differences have been observed, such as more cell androgen receptors (Kadi *et al.*, 2000), and therefore a lower sensitivity by women to hypertrophy (Folland & Williams, 2007). Several studies have found statistical differences in muscle size and other variables of muscular architecture (Chow *et al.*, 2000); these differences in the characteristics of the muscle could implicate the development of a greater strength. However, the differences between men and women are lower in the relative strength values and the greater strength of the men is due primarily to larger fibres (Miller *et al.*, 1993). Greater equality is observed (Folland & Williams, 2007) in the lower limbs as several studies found no differences between men and women with similar relative improvements both in terms of hypertrophic and strength adaptations after high-resistance system training (Cureton *et al.*, 1988; Abe *et al.*, 2000; Roth *et al.*, 2001). In this sense, Roth *et al.* (2001) observed that neither age nor gender affects muscle volume response to whole-body strength training, Abe *et al.* (2000) observed that after 12 weeks of individualized progressive heavy-resistance training the relative increases in strength, muscle thickness would appear to be similar for both men and women and Cureton *et al.* (1988) concluded that after 16 weeks of heavy-resistance training in the upper arms of both men and women, the relative magnitude of changes that occurred were similar in men and women, although the absolute changes tended to be larger in men and the relative changes in strength and muscle hypertrophy consequent to weight training are similar in men and women. Nevertheless, the men showed significantly greater CMJ jump height and peak power than women (Alegre *et al.*, 2009). Gender differences have been measured by static markers; consequently, it is interesting to describe the pattern of muscle behaviour and identify potential gender differences in movements facilitated by SSC.

The purpose of this study was to analyse gender differences in neuromuscular behaviour of the gastrocnemius and vastus lateralis during the take-off phase of a CMJ, using direct measures (ground reaction forces, muscle activity and dynamic ultrasound). The image recorded by the ultrasound offers the possibility to realize a morphological study through the measurement of the muscle geometric characteristics. Throughout history much attention has been provided to the distribution of the type of fibre to determinate the muscle function; however, there is no doubt this feature is also strongly determined by its architecture. It is technically known as skeletal muscle architecture and is defined as ‘the arrangement of muscle fibres within a muscle relative to the axis of force generation’ (Lieber & Fridén, 2000), where the muscle thickness and the degree of inclination and length of the muscle fibres are determined. There are numerous studies that have assessed the muscular architecture, as well as the relation between the modification of these values and strength parameters. The muscular performance in high isometric and dynamic intensity actions is based principally on the effective transmission of strength through muscular contractile elements (Bojsen-Moller *et al.*, 2005), and the fascicular geometry will determine the functional capacity of the muscles (Gans & Bock, 1965). On the other hand, the application of surface electromyography (sEMG) in the human movement studies has stimulated the development of the field known as electrophysiological kinesiology (Medved, 2001), which is considered a useful tool for understanding quantifying and assessing compound muscle action potentials (CMAP) during motor recruitment in movement disorders (Pullman *et al.*, 2000). In addition, this method allows the evaluation of muscle function during exercise and/or development of varied therapeutic procedures, such as the biofeedback or activation control system during execution of different tasks to varied intensities (Soderberg & Knutson, 2000), through synchronization of both techniques the neuromuscular pattern can be measured and can determine the muscle behaviour (muscle architecture and muscle activation) during activities in which the SSC is a key factor.

Methods

Design

A comparative description (cross-sectional study) was conducted to assess the gender differences in the take-off phase of the maximal jump.

Subjects

A non-probability sampling method was used for the sample selection. Sixty-four young adults (aged 18–25 years) participated voluntarily in this study, 35 men (174·4 ± 4·9 cm, 72·7 ± 9·4 kg, 23·3 ± 5·6 years) and 29 women (165·3 ± 5·7 cm, 61·8 ± 7·8 kg, 23·8 ± 4·1 years). The inclusion criteria included being healthy and light activity, using the International Physical Activity Questionnaire (IPAQ). Physical activity of the subjects was assessed with triaxial accelerometers (Actigraph LLC, Pensacola, FL, USA); we obtained that 96% of physical activity performed in a week was light. The exclusion criteria for both groups included any type of injury within the 6-month period prior to the study, participation in any competitive sport, sport fitness or strength training, having a medical history of neuromuscular or cardio-respiratory disease, and ingesting energy supplements and/or ergogenic aids during the study or during the 6-month period prior to the study. Ethical approval was obtained from the local university and hospital ethics committees, and all subjects gave their written informed consent prior to any testing.

Measures and procedures

Data collection for the initial evaluation was performed on two different days; on the first day, the subjects signed the informed consent documents and filled in the IPAQ. Additionally, there was a CMJ familiarization session. On the second day, anthropometric, bioimpedance and jump test data were collected.

Body composition

This consisted of measuring height (cm) and weight (kg) with the stadiometer Seca (Seca® Ltd, Hamburg, Germany). Furthermore, a lean body mass composition of legs analysis using the direct Segmental Multi-frequency Bioelectrical Impedance Analysis Method (BIA) with the Inbody 720® (Biospace, Seoul, Korea) and was performed following the manufacturer's guidelines. Thirty impedance measurements were obtained using six different frequencies (1–1000 kHz) for each of the two segments (right leg and left leg) using the tetrapolar 8-point tactile electrode system.

Jump test (CMJ)

In the jump test, one electromyography system, one force platform and two ultrasound probes were synchronized with an external trigger signal during the take-off phase of a CMJ. The firing of the trigger allowed data collection of vertical ground reaction forces (GRF), electromyographic activity (sEMG) and dynamic ultrasound recording of the gastrocnemius of both legs.

All subjects underwent a familiarization session 48 h previous to the assessment, which consisted in performing the CMJ with real-time feedback. Before data collection, the subjects carried out a 15-min warm-up, consisting of ergometer 839E (Monark, Varberg, Sweden) cycling at an intensity of 50–75 W and 80–90 rpm for 10 min, 5 min of stretching of lower extremities and six jumps (three submaximal and three maximum jumps). Next, the subjects performed two sets of three maximal jumps and analysed were those of higher flight time of each set. Muscle architecture and muscle activation values of the right lateral gastrocnemius and left medial gastrocnemius were collected in the first set of and left lateral gastrocnemius and right medial gastrocnemius in the second set of the jumps. The rest between each jump was 60 s and 2 min between sets. The trials were considered valid when subjects performed them maximally and with an appropriate technique (Linthorne, 2001).

Ground reaction forces (GRF)

Subjects performed a CMJ on a Kistler 9253B11 force platform (Kistler AG, Suiza). Vertical reaction forces were sampled at 500 Hz. Variables obtained from each maximum jump were as follows: the vertical take-off velocity (V_{to}; m s^{-1}), peak power of the take-off phase (P_{peak}; W kg^{-1}) and jump height (h; cm).

Muscle electrical activity (electromyography – sEMG)

One pair of bipolar Ag/AgCl surface electrodes (Ambu® blue sensor N-00-S, Balleurp, Denmark) were placed on the lateral and medial gastrocnemius of both legs (LG_{right}, LG_{left}, MG_{right} and MG_{left}) (interelectrode distance 10 mm) and the vastus lateralis of the quadriceps of both legs (VL_{right} and VL_{left}) following the sEMG for non-invasive assessment of muscles (SENIAM) guidelines (Hermens *et al.*, 2000). To reduce input impedance, subjects' skin was shaved and cleaned with denatured 70% alcohol. Electromyographic activity was analysed with 8-channel electromyography ME 6000TE (Mega Electronics, Kuopio, Filandia), with filter length band 8–500 Hz. The signal was transmitted to a computer at a sampling rate of 1 kHz. The signal was low pass filtered to a frequency of 500 Hz ($EMG_{rms;}$ μV), which was integrated (iEMG; μV s) and finally selected signal developed during the take-off phase of the CMJ. Finally, the electromyographic relative value was obtained based on the maximum peak sEMG obtained in the take-off phase (EMG_{rms}; % and iEMG; %) of the jump. The Neural Efficiency Index was calculated (NEI; μV W^{-1}), average of the EMG_{rms} of the four gastrocnemius was divided by the average power developed during the take-off phase of the CMJ.

Dynamic ultrasound (muscle architecture)

For the measurement of the behaviour of the muscle fibre, a real-time, B-mode computerized ultrasound system (LOGIQ P5 Premium; GE Healthcare, USA) was used with a linear array probe of 7·5–12 MHz wave frequency to obtain longitudinal ultrasonic images of the medial gastrocnemius and lateral gastrocnemius during CMJ. The probe was positioned on the most prominent bulge of the muscle of the medial gastrocnemius and a 1/3 of the line between the head of the fibula and the heel in the lateral gastrocnemius using a foam fixation designed for this purpose.

Ultrasound frames. Two frames from the take-off were analysed from each jump. Frame 1: prior to knee flexion moment and frame 2: last moment of contact with the platform. In each frame pennation angle (α1 and α2), muscle thickness (Th1 and Th2) and angular velocity ((α2–α1) time of the take-off^{-1}); velocity of the thickness ((th2–th1) time of the take-off^{-1}) were calculated. The length of the fibre (L_f) was calculated with the recommendations of other studies (Blazevich *et al.*, 2003): $L_{f\ =\ muscle\ thickness/sin\ (pennation\ angle)}$ (L_f1, in the frame 1; L_f2, in the frame 2), and subsequently shortening velocity was calculated ((L_f1–L_f2) • time of the take-off^{-1}).

Moreover, muscle architecture of vastus lateralis of the quadriceps was analysed on a static standing position before the maximum jumping test. The image was recorded at a 66% distance from the line of the superior anterior iliac spine to the lateral side of the patella, with the ultrasound probe placed in the sagittal plane and perpendicular to the skin.

Statistical analysis

Statistical analysis was performed with the Statistical Package for the Social Sciences (SPSS, version 19, SPSS Inc, Chicago, IL, USA). Standard descriptive statistics were performed (mean and standard deviations). Data normality was tested with the Shapiro–Wilk tests. In addition, for variables that showed a normal distribution, an independent sample t-test was applied. However, the U Mann–Whitney (independent samples) was applied for variables that did not show a normal distribution. A significance level of $P \leq 0{\cdot}05$ was set.

Results

No statistically significant differences were found between men and women in the amount of physical activity. No statistically significant differences were observed between in the GRF of the maximum jumps of the set 1 and 2.

Body composition

Statistically significant differences between men and women were observed in body composition variables. However, no statistically significant gender differences were found in the relative values of body composition (Table 1).

Vertical ground reaction force

Men showed a significantly greater CMJ jump h, P_{peak} and V_{to} than women (differences between means: 7·3 W kg^{-1}, P = 0·000; 0·31 m s^{-1}, P = 0·000; 5·7 cm, P = 0·000, respectively) (Fig. 1).

sEMG data, LG_{right} and LG_{left}: No statistically significant differences in the values of electrical activation and production were found in the lateral gastrocnemius. MG_{right} and MG_{left}: Significantly higher values in variable of EMG_{rms} (%) of women of the medial gastrocnemius (Fig. 4) were observed (MG_{right}; P = 0·006, MG_{left}; P = 0·016). VL_{right} and VL_{left}: In the vastus lateralis of the quadriceps (right and left) of men and women, the difference between EMGrms and iEMG was

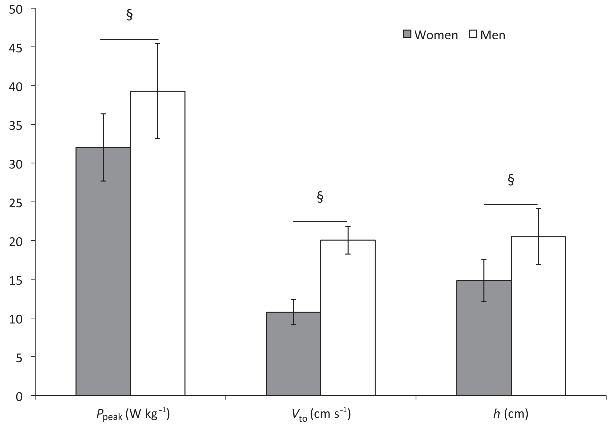

Figure 1 Mean (±SD) values of the ground reaction forces $^{§}P<0{\cdot}001$. P_{peak}: peak power of the take-off phase; V_{to}: the vertical take-off velocity and h: jump height.

statistically significant (Figs 2 and 3). Men were found greater in EMG_{rms} (VL_{right}; P = 0·001), iEMG (VL_{left}; P = 0·018, VL_{right}; P = 0·000) and iEMG% (VL_{left}; P = 0·018, VL_{right}; P = 0·000). Men were lower in EMG_{rms} % (VL_{right}; P = 0·028).

The Neural Efficiency Index (NEI) of the men and women was significantly different (P<0·05). Women were found to have greater NEI than men (NEI_{women}; 0·49 ± 0·15, NEI_{men}; 0·37 ± 0·15; P = 0·005).

Dynamic ultrasound

Statistically significant differences were found in muscle architecture of the medial gastrocnemius for the MG_{right} in the α2 (P = 0·039), with greater values for men compared with women. Furthermore, differences were obtained in Th2 (P = 0·042). Pennation angles of the LG were greater in men, and the differences were significant in the LG_{right} and LG_{left} in α1 (LG_{right}; P = 0·016; LG_{left}, P = 0·047) and α2 (LG_{right}; P = 0·031, LG_{left}; P = 0·054). Muscle thickness was significantly greater in the LG_{right} and LG_{left} in Th1 (LG_{right}; P = 0·007) and Th2 (LG_{right}; P = 0·009, LG_{left}: P = 0·012) (Figs 4 and 5). In fibre length, no statistically significant differences were found in any of the gastrocnemius analysed. No statistically significant gender differences were found in the resulting velocities.

Table 1 Mean (±SD) values of body composition.

	Women (*n* = 29)	Men (*n* = 35)	*P*
Musculoskeletal mass (kg)	23·94 ± 2·4	32·77 ± 2·6	0·001
Fat mass (kg)	17·14 ± 5·8	14·83 ± 8·0	0·198
Lean Body Mass (kg)	41·06 ± 3·7	54·71 ± 4·1	0·001
Lean Body Mass of right leg (kg)	6·93 ± 0·8	9·25 ± 0·7	0·001
Lean Body Mass of right leg (%)	98·48 ± 6·8	101·57 ± 6·8	0·074
Lean Body Mass of left leg (kg)	6·91 ± 0·8	9·15 ± 0·7	0·001
Lean Body Mass of left leg (%)	98·09 ± 6·7	100·50 ± 6·3	0·141

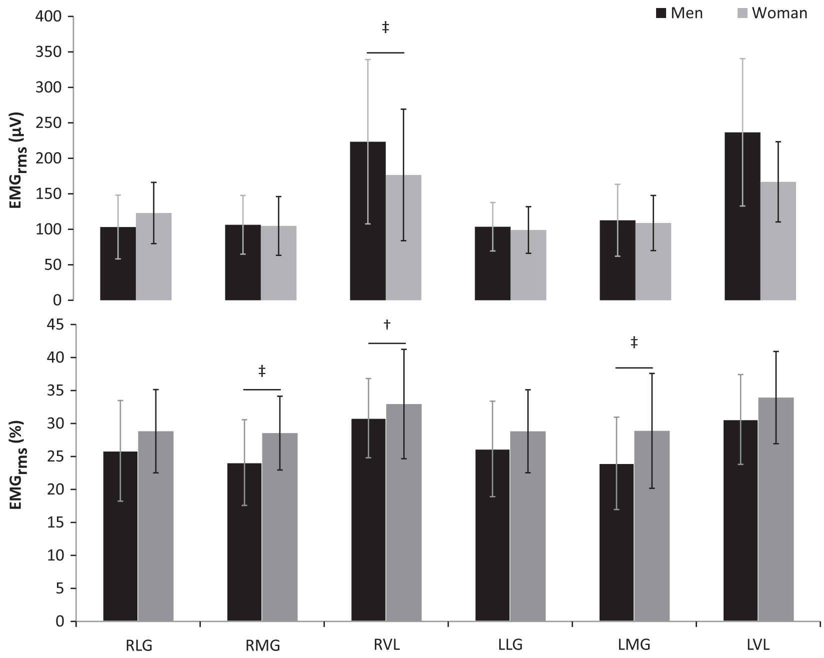

Figure 2 Root-mean-square values (Mean ± SD) of the electromyographic signal (EMG_{rms}). RLG, right lateral gastrocnemius; RMG, right medial gastrocnemius; RVL, right vastus lateralis; LLG, left lateral gastrocnemius; LMG, left medial gastrocnemius; LVL, left vastus lateralis $^{\dagger}P<0{\cdot}05$, $^{\ddagger}P<0{\cdot}01$.

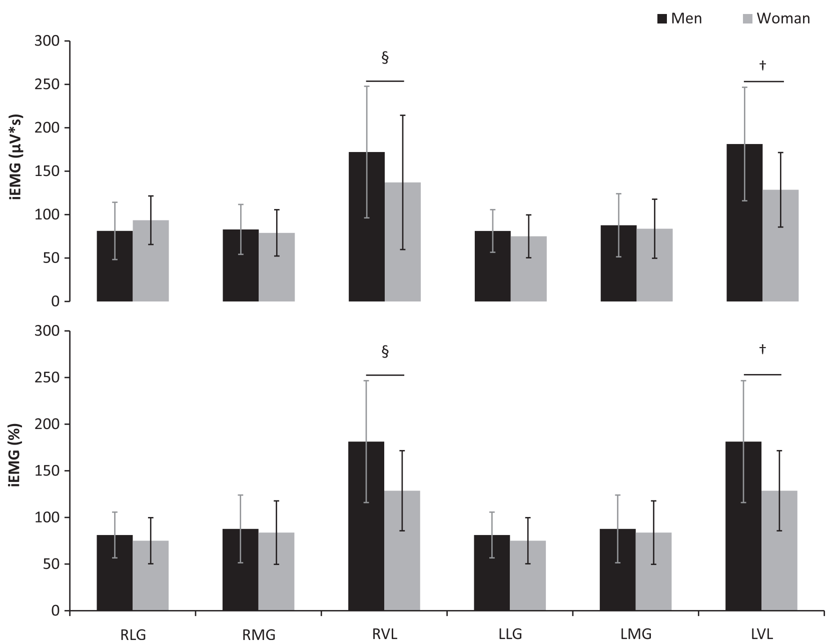

Figure 3 Values (Mean ± SD) of the Integrated of the electromyographic signal (iEMG). RLG, right lateral gastrocnemius; RMG, right medial gastrocnemius; RVL, right vastus lateralis; LLG, left lateral gastrocnemius; LMG, left medial gastrocnemius; LVL, left vastus lateralis $^{\S}P<0{\cdot}001$; $^{\dagger}P<0{\cdot}05$.

Ultrasound of the vastus lateralis

Men showed significantly greater thickness in the vastus lateralis (VL_{right} women 1·91 ± 0·18 cm, VL_{right} men 2·17 ± 0·40 cm, P = 0·001; VL_{left} women 1·94 ± 0·22 cm, VL_{right} men 2·13 ± 0·33 cm, P = 0·011), in the pennation angle of the left vastus lateralis (women 15·0 ± 2·7°, men 16·6 ± 3·4°, P = 0·052) and in the fibre length of the right vastus lateralis (women 6·77 ± 1·51 cm, men 8·04 ± 2·4 cm, P = 0·014) compared with women.

Discussion

The purpose of this study was to investigate gender differences in muscle architecture and electrical activity of human gastrocnemius and vastus lateralis of the quadriceps as well as differences in jump performance during the take-off phase of the CMJ.

In our results, statistically significant gender differences were observed in the jump performance, which appear to be based on differences in muscle architecture and the electrical

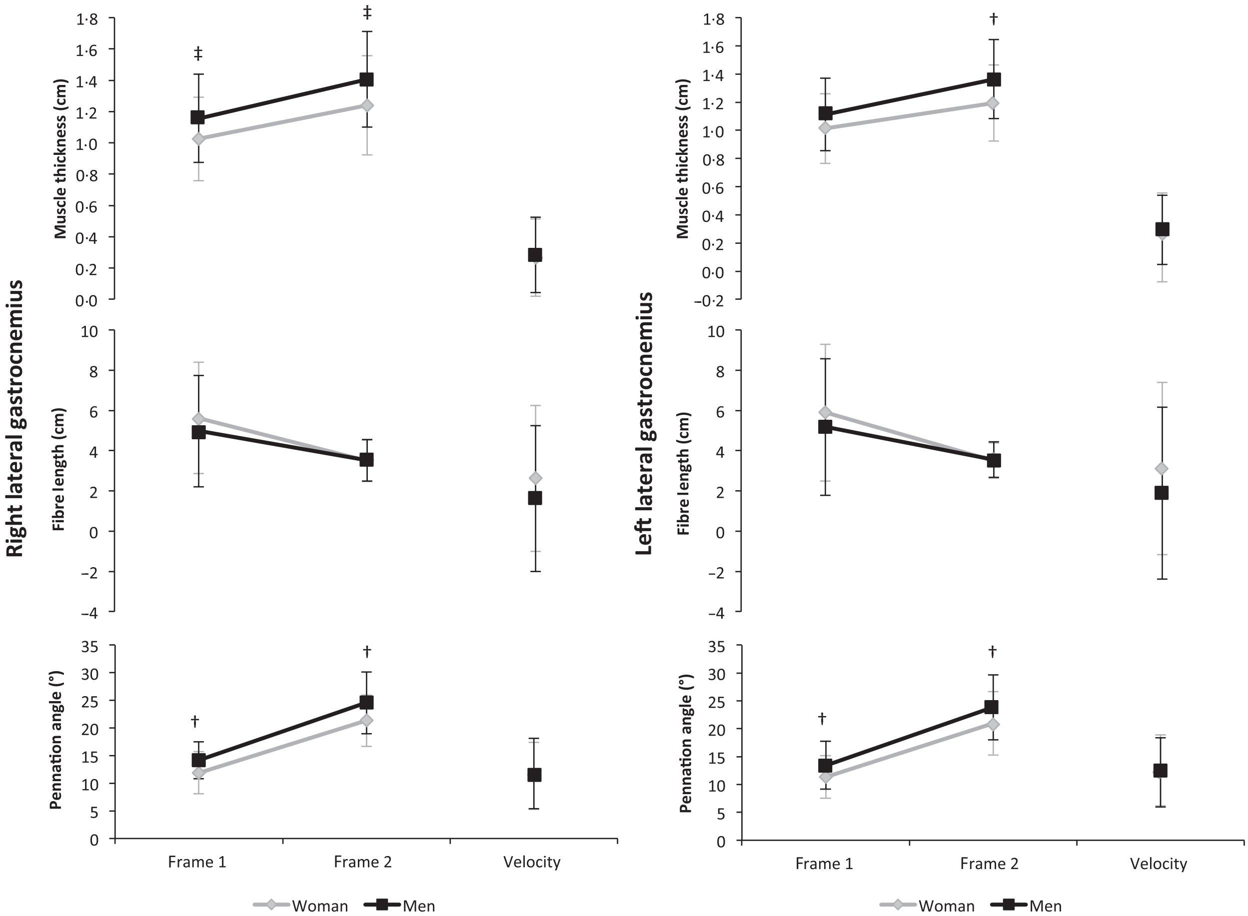

Figure 4 Behaviour of the muscle fibre in the lateralis gastrocnemius (Mean $\pm$ SD) $^{\dagger}P<0{\cdot}05$, $^{\ddagger}P<0{\cdot}01$.

activation of the gastrocnemius muscles and vastus lateralis. So while men developed greater peak power, velocity take-offs and jump heights, jump kinetics compared to women, women also required a higher electrical activity to develop lower power values. Additionally, the men had higher values pennation angles and muscle thickness than women, suggesting that muscle hypertrophy (Kawakami *et al.*, 1993) involves statistically significant differences between men and women in the kinetic jump. These results agree with those found by Ikemoto *et al.* (2006) in the gender differences in the maximal power and the properties of the power curve, the maximal muscle power appeared at 30–50% maximum voluntary contraction in males, and at 20–40% MVC in females. Also in the results of Edwen *et al.* (2013), they found significant differences in the peak power in all age ranges between woman and men (18–81 years). Consequently, the ability to generate power during SSC is independent of age, but gender is a determining factor and maximal SSC power production. This fact was observed to converge between genders when approaching old age. Laffaye *et al.* (2013) observed gender differences between the eccentric and concentric phases of the jump, also men showed significantly greater CMJ jump height and peak power than women (Alegre *et al.*, 2009). In this sense, in our study we have observed statistically significant differences in the mechanical CMJ variables between men and women. The increased capacity of men to develop power may be due to the total amount of muscle tissue that men accumulate in the lower extremities. (Abe *et al.*, 2003). In this respect, in our study the men showed greater amount of lean body mass in the left and right leg and more total musculoskeletal mass, but these differences disappear in the relative body composition.

Secondly, these gender differences are observed also in the electrical activation of the muscle, the women showed greater EMG_{rms} (%) of the medial gastrocnemius and right vastus lateralis but lower iEMG (μV s) of the right and left vastus lateralis, and these values in men could facilitate rate of force development. Cioni *et al.* (1994) showed gender differences in the spectral parameters power spectrum of the sEMG, they were studied during voluntary muscle contractions, the sex differences and the mean values of the median power frequency were lower in women than in men, these differences may be due to anatomical gender differences. According to Winter & Brookes (1991), the electromechanical delay in women (44·9 ms) was significantly longer than in men (39·6 ms). In this sense, in our study significant gender differences were observed in the sEMG pattern, the men develop a greater mean EMGrms (μV) value than women in the right quadriceps and a

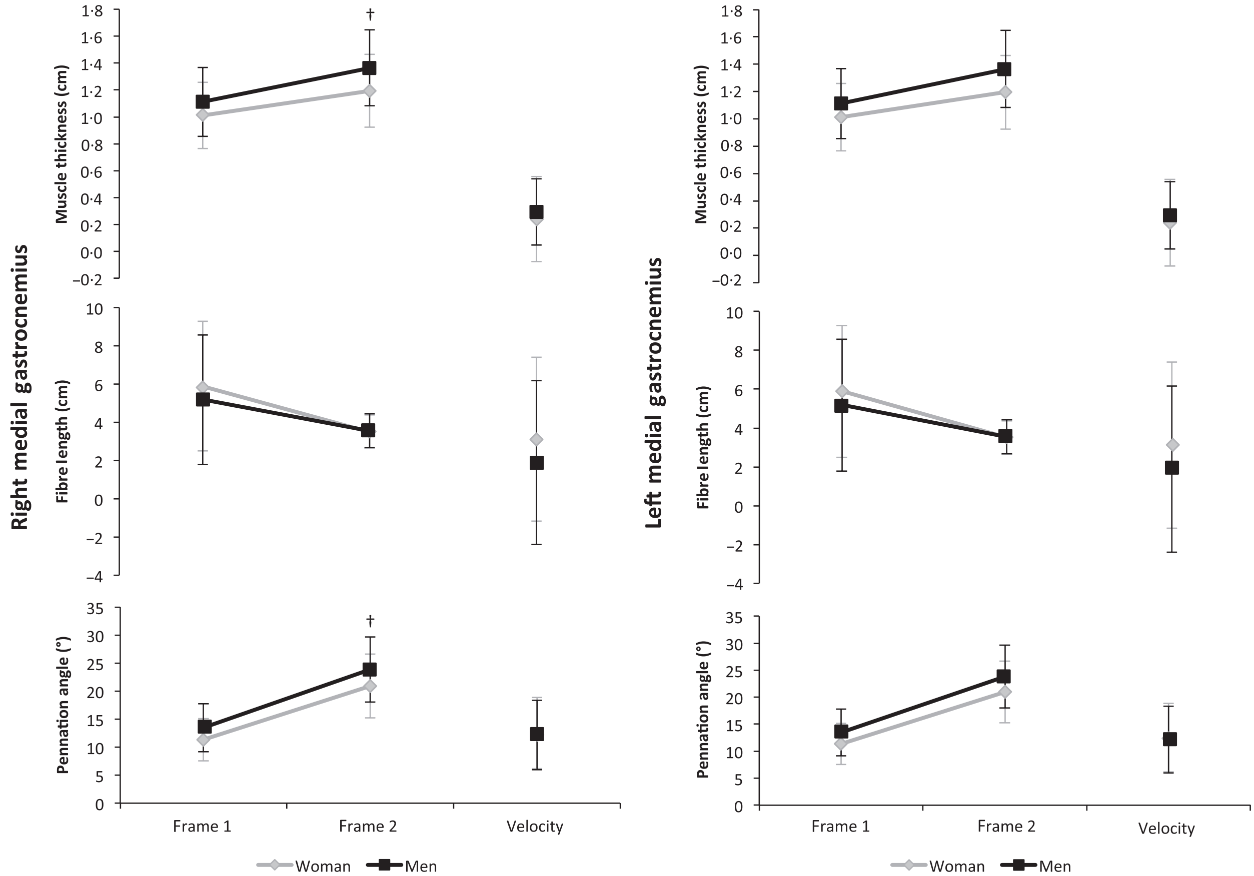

Figure 5 Behaviour of the muscle fibre in the medialis gastrocnemius (Mean ± SD) $^{\dagger}P<0{\cdot}05$.

lower relative value compared to its peak in the lateral gastrocnemius. Also, men generate a greater amount of sEMG activity per second in the vastus lateralis of the quadriceps (right and left) than women. On the other hand, neural index of efficiency and statistically significant higher values were observed in women compared to men, a greater neural activity to develop lower power values. In the case of women, a higher electrical activity in relation to its peak value is needed to generate a lower power, which is reflected in the index of neuromuscular efficiency. In exchange, in men, the electrical activity of the vastus lateralis of the quadriceps (iEMG) is greater.

The performance of the CMJ is attributed to a combination of elastic energy use and muscle activation (Bosco *et al.*, 1982a) during stretch-shortening cycle (SSC) (Cavagna, 1977; Bosco *et al.*, 1982b). Several studies have analysed muscle architecture "live" recording the dynamic ultrasound images during different types of jumps (Finni *et al.*, 2000). However, they have not found studies that analyse the influence of gender and dynamic muscular architecture during movements facilitated by the SSC. Skeletal muscle function design is based primarily on muscle architectural properties and is only slightly influenced by fibre properties (Burkholder *et al.*, 1994). Chow *et al.* (2000) showed it is evident that there are distinct gender-based differences in the muscle architecture of normal human soleus and gastrocnemius muscles, and these differences have interesting ramifications with respect to muscle performance. In our research, in the muscle architecture, statistically significant differences in the lateral gastrocnemius between men and women were observed. Men had higher values in the angles of pennation and greater muscle thickness in the lateral gastrocnemius and the vastus lateralis. Most contractile tissue in men in the extensor muscles of the knee and ankle (greater muscle thicknesses and pennation angles) could explain the capacity to develop a greater amount of electrical activity per second. Alegre *et al.* (2009) found similar results; they showed statistically significant differences in the thickness of the gastrocnemius muscle (medial and lateral) and vastus lateralis, pennation angle in the vastus lateralis and lateral gastrocnemius and fascicle length in the vastus lateralis and medial gastrocnemius. Another factor in the gender differences in the performance is the viscoelastic properties of tendon structures. The women have a lower stiffness and hysteresis of tendon than men, and these differential tendon properties might provide an explanation for the gender differences observed in muscle function and stretch-shortening cycle exercises (Kubo *et al.*, 2003).

In the current study, an *in vivo* neuromuscular system was introduced to assess movements in which the SSC occurs. Whereas the jump is a frequent sporting movement in many sports, we think that the information obtained in our study of neuromuscular could be useful to improve the performance jump of men and women in different sports, examining the different phases of the jump permits the existence of observing deficiencies in certain muscle groups for which can be targeted specifically in training. On the other hand, as the muscle tears are very common in jumpers and sprinters (Chan *et al.*, 2012) information obtained in our study may also be useful to reinforce the mechanisms and different muscle susceptibility to injury and therefore help reduce injuries as both the gastrocnemius muscle and the quadriceps muscles are frequently injured a lot in the sport. Finally, the study could give information to monitor and enhance athletic performance, being a tool for the assessment and monitoring of explosive strength and power.

In conclusion, we can determine that men show higher performance of the jump test than women, due to significant statistical differences in the values of muscle architecture (pennation angle and thickness muscle), lower Neural Efficiency Index and a higher amount of sEMG activity per second during the take-off phase of a CMJ. Future studies should analyse the sEMG and muscle architecture in the jump phase (concentric and eccentric) and the statistical correlation between neuromuscular performance and jump performance.

Conflict of interest

The authors have no conflict of interests.

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