Journal of Electromyography and Kinesiology 23 (2013) 62–69

Contents lists available at SciVerse ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Neuromechanical adaptation induced by jumping on an elastic surface

Gonzalo Márquez [a,b,*], Xavier Aguado [c], Luis M. Alegre [c], Miguel Férnandez-del-Olmo [b]

[a] Facultad de Ciencias del Deporte y la Educación Física, Universidad Católica San Antonio, Murcia, Spain
[b] Grupo de Aprendizaje y Control del Movimiento Humano, Facultade de Ciencias do Deporte e a Educación Física (INEF Galicia), Departamento de Educación Física e Deportiva, Universidade da Coruña, A Coruña, Spain
[c] Grupo de Biomecánica Humana y Deportiva, Universidad de Castilla-La Mancha, Toledo, Spain

ARTICLE INFO

Article history:
Received 2 March 2012
Received in revised form 26 June 2012
Accepted 27 June 2012

Keywords:
Stiffness
Vertical jump
Surface
Neuromuscular control
Aftereffect

ABSTRACT

Jumping on an elastic surface produces a number of sensory and motor adjustments. This effect caused by jumping on the trampoline has been called "trampoline aftereffect". The objective of the present study was to investigate the neuromuscular response related with this effect. A group of 15 subjects took part in an experimental session, where simultaneous biomechanical and electromyographic (EMG) recordings were performed during the execution of maximal countermovement jumps (CMJs) before and after jumping on an elastic surface. We assessed motor performance (leg stiffness, jump height, peak force, vertical motion of center of mass and stored and returned energy) and EMG activation patterns of the leg muscles. The results showed a significant increase ($p \leqslant 0.05$) of the RMS EMG of knee extensors during the eccentric phase of the jump performed immediately after the exposure phase to the elastic surface (CMJ_1), and a significant increase ($p \leqslant 0.05$) in the levels of co-activation of the muscles crossing the ankle joint during the concentric phase of the same jump. Results related with motor performance of CMJ_1 showed a significant increase in the leg stiffness ($p \leqslant 0.01$) due to a lower vertical motion of center of mass (CoM) ($p \leqslant 0.005$), a significant decrease in jump height ($p \leqslant 0.01$), and a significantly smaller stored and returned energy ($p \leqslant 0.01$). The changes found during the execution of CMJ_1 may result from a mismatch between sensory feedback and the efferent copy.

1. Introduction

Adapting the stiffness of our musculoskeletal system to different surfaces is a daily process in our lives. For example, we adapt our musculoskeletal system during walking (MacLellan and Patla, 2006; Marigold and Patla, 2008), running (Ferris et al., 1998, 1999) and jumping (Ferris and Farley, 1997; Moritz and Farley, 2004, 2005). These adaptations can be explained by a simple biomechanical model, called "spring-mass model", so that when the surface stiffness decreases, the stiffness of the legs is increased, and vice versa (Ferris and Farley, 1997). Studies have shown that sudden and unexpected changes in the stiffness of the surface result in adjustments in the dynamics of the passive properties of body segments that can accommodate the stiffness of the legs immediately [52 ms] (Moritz and Farley, 2004; van der Krogt et al., 2009). These changes in stiffness appear to be associated with perceptual changes. For example, it was found that after a brief exposure of repeated jumps on an elastic surface, subjects show sensory-motor changes when they jump again on a rigid surface (Márquez et al., 2010). Repeated jumps on a trampoline cause an increase of the leg stiffness, a decrease of the height reached in the jump, an underestimation of the jump height and altered perceptual sensations, of the subsequent CMJ performed on the ground. The effects caused by jumping on the elastic surface have been called "trampoline aftereffect" (Márquez et al., 2010). Indeed, this phenomenon occurs even though the subjects are fully aware of the changes in the stiffness of the surface, suggesting the existence of a strong adaptive process.

The mechanism underlying the "trampoline aftereffect" remains unclear. Studies showing sensory and motor adaptations after the exposure to variations in the gravito–inertial force level (Lackner and Graybiel, 1980, 1981) have suggested that these effects are caused by a mismatch between the efferent copy and sensory feedback (Lackner and DiZio, 2000). This is an adaptive process that allows the generation of anticipatory motor commands to compensate for the changes occurring in the environment (Lackner and DiZio, 1994). Moreover, these adaptations have been linked to alterations in the discharge of the muscle spindles (Lackner and Graybiel, 1980, 1981), since they are essential for the limb position sense (Proske et al., 2000; Proske, 2005, 2006). Therefore, it is likely that the effect of repeated jumps on an elastic surface are associated with neuromuscular changes caused by the above mentioned factors.

* Corresponding author at: Universidad Católica San Antonio, Campus de los Jerónimos s/n, 30107 Guadalupe, Murcia, Spain. Tel.: +34 968278824; fax: +34 968278 658.
E-mail address: gmarquez@ucam.edu (G. Márquez).

1050-6411/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jelekin.2012.06.012

The aim of this study was to investigate the neuromuscular and mechanical adjustments during the CMJ performed after a brief exposure of repeated jumps on an elastic surface. Our hypothesis is that jumping on the elastic surface will produce changes in the EMG pattern and in the mechanical responses during the execution of the subsequent CMJ. This study may contribute to understanding of the neuro-mechanical adaptations induced by surfaces of different stiffness.

2. Methods

2.1. Subjects

We recruited fifteen healthy male subjects (Age: 22,2 ± 2,9 years; Weight: 73,6 ± 7,1 kg; Height: 178,3 ± 5,8 cm) from the Faculty of Sport Sciences of Toledo (Spain). Participants provided informed consent prior to participation. The experimental procedures conformed to the Declaration of Helsinki and were approved by the local ethics committee.

2.2. Material

2.2.1. Surface EMG and force platforms recordings

The test (CMJ) was performed on a 9281 CA Kistler platform (Kistler Instrument, AG, Winterthur, Switzerland) installed at ground level. Ground reaction forces (GRF) were recorded with a sampling frequency of 1000 Hz. All data were collected on a PC for further processing and analysis.

Electromyographic activity was recorded from the soleus (SOL), gastrocnemius medialis (GM), tibialis anterior (TA), vastus lateralis (VL), rectus femoris (RF) and biceps femoris (BF) of the right leg (Fig. 1), using pre-gelled bipolar surface Ag–AgCl electrodes (Blue Sensor, Ambu. Inc.). The electrodes were connected to a wireless data acquisition system of eight channels (Noraxon Telemyo 2400T USA). EMG activity was recorded at a 1000 Hz sampling rate. All signals were amplified and filtered with a bandwidth from 10–500 Hz, where each channel has an input impedance >100 MOhm, common mode rejection ratio >100 dB and a gain = 1000. All data were stored on a PC using the program Myoresearch XP (Noraxon Inc. USA) for off-line processing and analysis.

2.2.2. Properties of the elastic surface

The elastic surface consisted of a mini-trampoline (Gimnova), with a jump area of 0.60 m × 0.60 m connected to 32 springs along the outer edge, resulting in a linear stiffness of 14 kN/m. The stiffness of the surface was tested using a static load test (up to 2000 N, see Arampatzis et al., 2001). The linear regression between the surface displacement and the force was significant (r^2 = 0.99).

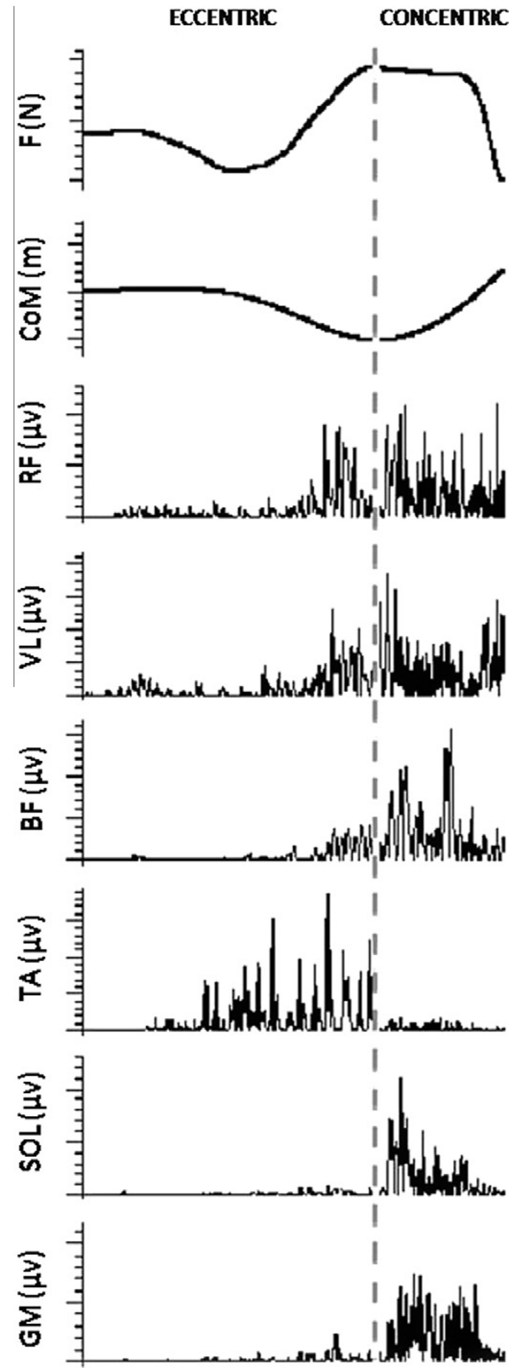

Fig. 1. Example of kinematics and EMG recordings during CMJ performance.

2.3. General procedures

2.3.1. Subject preparation

Electrodes were placed over the muscle belly along the longitudinal axis of muscle fibers, with ±2 cm inter-electrode distance, placing the reference electrode in the head of the fibula (Hortobagyi et al., 2009). Cables were secured with an adhesive tape and elastic mesh to prevent possible artifacts caused by movement. Electrodes were placed according to SENIAM guidelines.

2.3.2. Jump test (CMJ)

The subjects were instructed to start in an upright position, rapidly squat, and then jump into the air with maximal effort. The hands were akimbo throughout the test in order to eliminate the effect of arm swing during the performance of each jump. During the squat phase of the movement, the angular displacement of the knee was standardized so that the subjects were required to bend their knees to approximately 90°. A 90° knee bend was merely a reference value and not an excluding criterion. For a more detailed description about CMJ performance see Bosco et al. 1983.

2.3.3. Repetitive jumps or exposure phase to the elastic surface

During the exposure phase on the elastic surface, the subjects were required to jump keeping their hands on their hips. In order to equate the number and rate of jumps, the subjects jumped in synchronization with a metronome at a rate of 1 Hz during 1 min. This was of importance since the jumping frequency has been shown to affect the leg stiffness (Farley et al., 1991; Hobara et al., 2010). This 1 Hz rate was chosen from pilot experiments that showed that this rate was observed when people performed self-paced jumps at low intensity on the trampoline.

2.3.4. Protocol

One experimental session was conducted, starting with a standardized warm-up protocol to ensure that the subject performed vertical jumps with maximal effort and without risk of injury. At the end of the warm-up session, each subject performed two maximal CMJs on the force platform, with an inter-trial interval of 30 s. We used the average of the two jumps as baseline (CMJ_{bsl}). Then, the subjects performed a minute of repeated jumps (1 Hz) on the elastic surface. Immediately after the exposure phase, they perform three new CMJs on the force platform (CMJ_1–CMJ_3), with an interval of 30 s between attempts. The subjects jumped inside an indoor facility with their eyes open and with their body oriented to the same direction at all times. Thus, the visual cues were kept constant.

2.4. Data processing and analysis

Vertical acceleration (from the GRF) was evaluated in order to obtain the vertical velocity and displacement of the CoM, using the double integration method (Cavagna, 1975). The height of the jump was obtained from the velocity value at the moment of take-off using the following equation:

$$H = v^2/2g,$$

where v is the take-off velocity and g the gravitational acceleration. Leg stiffness (K_{leg}) during the CMJ was defined as:

$$F_{peak}/\Delta L,$$

where F_{peak} is the peak GRF (which correspond to the lowest position of the CoM), and ΔL is the vertical displacement of the CoM from the starting position to the lowest position (Ferris and Farley, 1997; Liu et al., 2006).

In addition, we assessed the stored and returned energy in the muscles during the eccentric and concentric phase of the CMJ. The energy stored (ES) was defined as the integral of force – displacement curve from the starting position to the maximum displacement of CoM. The energy returned (ER) for the lower limb muscles during the concentric phase, was defined as the integral of the force – displacement curve from the maximum displacement of CoM to take-off. These energy changes were calculated using the following equations:

$$ES = \int_{t0}^{t1} F(t) \cdot v(t)dt$$

$$ES = \int_{t1}^{t2} F(t) \cdot v(t)dt$$

where $F(t)$ is the force–time curve measured by the platform; $v(t)$ is the velocity time curve of the CoM; t_0 is the time at the beginning of CMJ; t_1 is the time at the lowest position of the CoM; and, t_2 is the time at take-off.

The EMG signals were band-pass filtered (10–500 Hz), and then full wave rectified. The root mean square (RMS) of the eccentric and concentric phase of each muscle studied (RF, VL, BF, TA, SOL, GM) was calculated. The mean RMS value describes the gross innervation input of a selected muscle for a given task (e.g. CMJ) and it is less sensitive to duration differences of the analyzed intervals (Basmajian and De Luca, 1985; De Luca, 1997; Konrad, 2005).

Muscle co-activation is the simultaneous activity of agonist and antagonist muscles acting around a joint (Kellis et al., 2003). According to Hortobagyi et al. (2009), to calculate the co-activation level the different phases of the movement and specific functions of each muscle, need to be taken into account. In order to compute this parameter for the eccentric and concentric phase of the CMJ, the following equation was applied:

$$\text{Co-activation } (\%) = (\text{RMS EMG}_{antagonist}/\text{RMS EMG}_{agonist}) \times 100.$$

2.5. Statistical analysis

Analysis of variance with repeated measures (ANOVA-RM) was performed with trial (CMJ_{bsl}, CMJ_1–CMJ_3) as a main factor. The ANOVA-MR was performed for the following variables: K_{leg}, ΔL, F_{peak}, jump height, ES, ER, RMS of eccentric and concentric phase of each muscle studied (RF, VL, BF, TA, SOL, GM), co-activation level in the eccentric phase (SOL/TA, GM/TA, BF/RF and BF/VL) and the concentric phase (TA/SOL, TA/GM, BF/RF and BF/VL).

Post hoc analysis was performed using paired t test with Bonferroni correction and the statistical significance was set at $p \leqslant 0.05$. None of the data violated the normality requirements necessary to conduct parametric statistical tests. All statistical tests were performed using SPSS 15.0 (SPSS Inc, Chicago, Illinois, USA).

3. Results

3.1. Mechanical behavior

For the leg stiffness, the ANOVA-RM showed a significant effect ($F = 4.547$, $p = 0.022$). After repeated jumps on the elastic surface, K_{leg} increased significantly in the CMJ_1, compared with CMJ_{bsl} ($p = 0.006$; Fig. 2A) and recovered baseline levels in the CMJ_2, since there was no difference between this jump and CMJbsl.

The analysis of vertical motion of the CoM showed a similar pattern to leg stiffness. The ANOVA-MR revealed a significant main effect for trial ($F = 10.476$, $p \leqslant 0.001$). Post-hoc comparisons showed that ΔL was significantly lower in the CMJ_1 and CMJ_2 compared with CMJ_{bsl} ($p \leqslant 0.001$ and $p = 0.007$, respectively; Fig. 2C), but returned to baseline in the CMJ_3. Furthermore in CMJ_3, ΔL was significantly higher than the CMJ_1 ($p \leqslant 0.05$).

In relation to peak force, the ANOVA-RM showed no significant changes (see Fig. 2D).

In the analysis of the jump height, the ANOVA-MR showed a significant main effect ($F = 4.651$, $p = 0.007$; Fig. 2B). After repeated jumps on the trampoline, the height reached in the CMJ_1 decreased significantly compared with CMJ_{bsl} ($p = 0.006$). There were no significant differences between CMJ_2, CMJ_3 and CMJ_{bsl}.

In relation to the stored energy, the ANOVA-RM showed a significant effect of trial ($F = 5.480$, $p = 0.012$). This parameter decreased significantly in the CMJ_1 and CMJ_2, compared with CMJ_{bsl} ($p = 0.013$ and $p = 0.006$, respectively; Fig. 2E). However, there were no differences between the CMJ_{bsl} and CMJ_3, indicating a rapid recovery of baseline values. The analysis of the returned energy also indicated a significant main effect ($F = 11\ 901$, $p \leqslant 0.0001$). The post hoc comparisons showed that after the exposure of the elastic surface, the returned energy during the concentric phase decreased significantly in the CMJ_1 and CMJ_2 in relation to CMJ_{bsl} ($p \leqslant 0.0001$ and $p = 0.006$, respectively; see Fig. 2F). In the CMJ_3 the RE values return to baseline, since there were no differences between this jump and CMJ_{bsl}.

3.2. EMG recordings

The RMS EMG analysis of the eccentric phase showed a significant main effect of trial for the rectus femoris ($F = 5.502$, $p = 0.014$) and vastus lateralis ($F = 4.621$, $p = 0.007$). In the case of the RF, the RMS of the CMJ_1 was significantly higher than that of CMJ_{bsl} and CMJ_3 ($p = 0.025$ and $p = 0.005$, respectively; see Fig. 3A). The VL

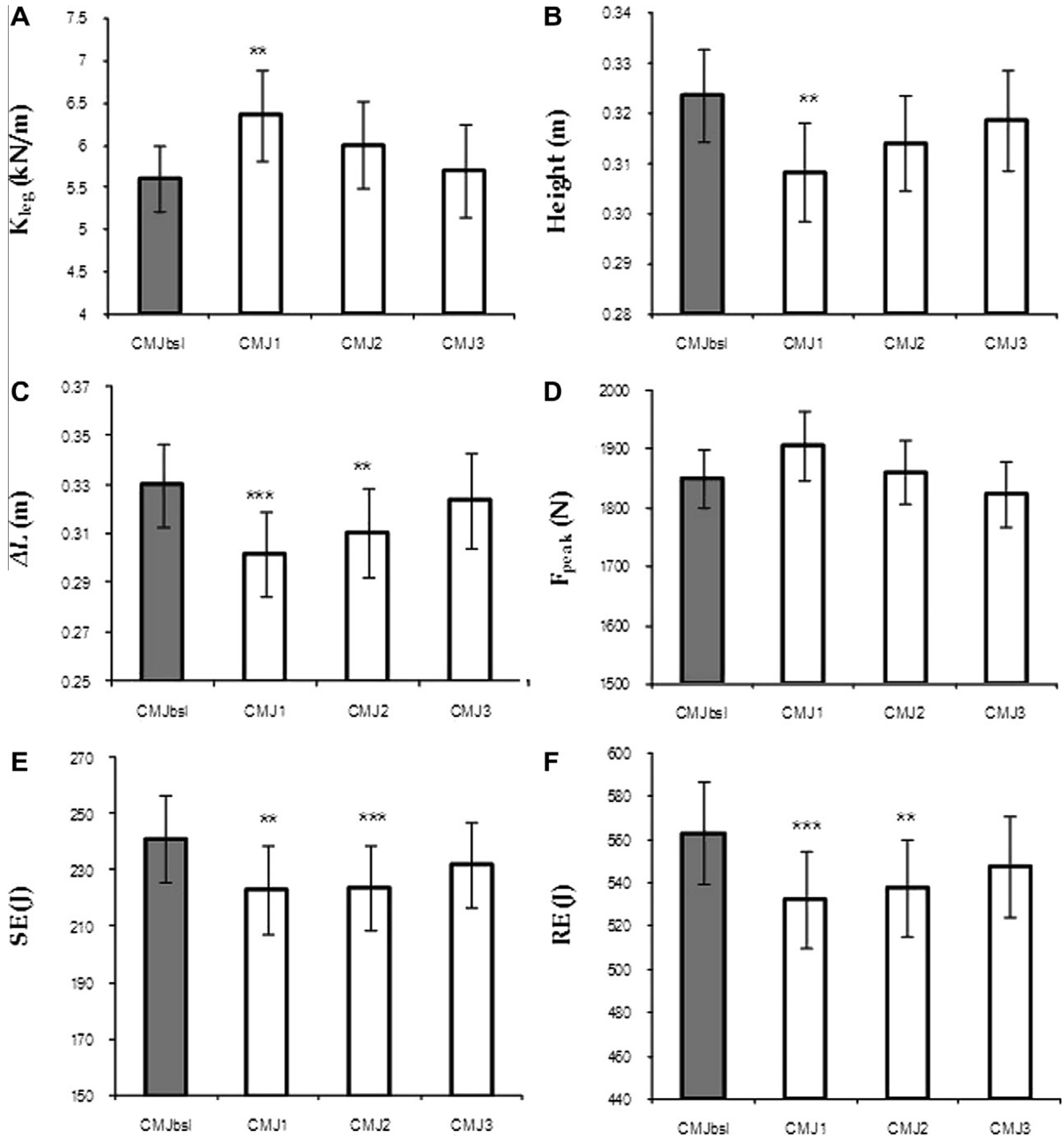

Fig. 2. Mean (±SE) of leg stiffness (A), height of jump (B), vertical motion of CoM (C), force peak (D), stored energy (E) and returned energy (F) of CMJ's performed before (grey bar) and after (white bars) the exposure to the elastic surface jumping. (∗) significant differences with CMJ_{bsl}. $^{*}p \leqslant 0.05$; $^{**}p \leqslant 0.01$; $^{***}p \leqslant 0.001$.

muscle showed similar results, showing that the RMS EMG of CMJ_1 increased significantly in relation to CMJ_{bsl}, CMJ_2 and CMJ_3 ($p = 0.022$, $p = 0.004$ and $p = 0.007$, respectively; Fig. 3B). CMJ_2 and CMJ_3 showed no significant differences compared with CMJ_{bsl}, indicating that after the CMJ_1, activation of knee extensors in the eccentric phase returned to baseline. In the case of the EMG activation of biceps femoris, tibialis anterior, soleus and medial gastrocnemius no statistical differences were observed. The RMS EMG analysis of the concentric phase showed no significant changes in any of the studied muscles.

The analysis of co-activation level of agonist–antagonist muscle pairs during the eccentric phase revealed no significant changes (see Table 1). However, during the concentric phase, the ANOVA-RM showed a significant effect for the pairs TA/SOL ($F = 7.329$, $p = 0.004$) and TA/GM ($F = 3.470$, $p = 0.025$). Post hoc analysis revealed that in the CMJ_1, the co-activation level of the pair TA/SOL were significantly higher than in the CMJ_{bsl}, CMJ_2 and CMJ_3 ($p = 0.012$, $p = 0.003$ and $p = 0.027$, respectively; Fig. 4C). Furthermore, in the case of TA/GM pair, the co-activation level increased significantly in the CMJ_1 in relation to the values found in the CMJ_3 and CMJ_{bsl} ($p = 0.035$ and $p = 0.029$, respectively; see Fig. 4D).

4. Discussion

The main findings of this study demonstrate that after repeated jumps on an elastic surface, neuromuscular adaptations are observed during the execution of the first jump performed

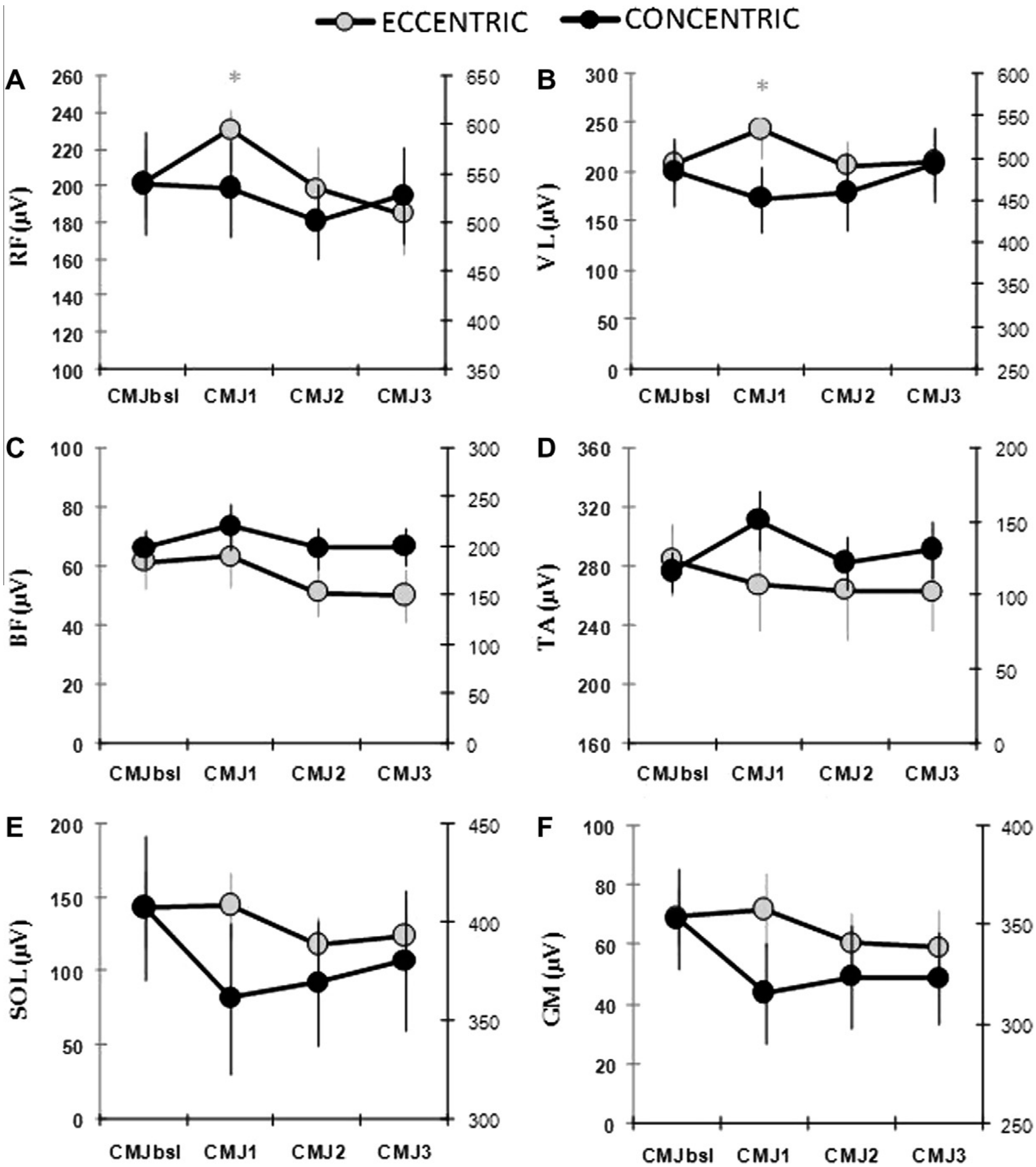

Fig. 3. Mean (±SE) RMS values of eccentric (grey circles) and concentric (black circles) phase of the muscles RF (A), VL (B), BF (C), TA (D), SOL (E) and GM (F) during the CMJ's performed before (CMJ_{bsl}) and after (CMJ_{1-3}) the exposure to the elastic surface jumping. Left scale (grey) corresponds with RMS eccentric phase and right scale (black) corresponds with RMS concentric phase. (*) Eccentric RMS amplitude of CMJ_1 was greater than CMJ_{bsl} in the muscles RF and VL. $^*p \leqslant 0.05$.

on the rigid surface. These changes in neuromuscular activity seem to be related with the adjustments in the mechanics of the jump.

It is well known that during the jumps on elastic surfaces, subjects increase the leg stiffness to offset the decrease in surface stiffness, improving mechanical efficiency and reducing energy cost (Ferris and Farley, 1997; Kerdok et al., 2002). These adjustments during jumps on surfaces of different stiffness are achieved through adjustments made in the dynamics of the CoM (Ferris and Farley, 1997; Moritz and Farley, 2004, 2005). In line with this are studies showing that subjects adjust leg stiffness for their first step on a new surface during running on different stiffness surfaces (Ferris et al., 1998, 1999). Several studies reported instantaneous changes in the leg stiffness during the landing on both expected and unexpected surfaces (Moritz and Farley, 2004; van der Krogt et al., 2009). This rapid change in leg stiffness (52 ms after landing) may be due to a passive mechanism and not due to neural feedback (Moritz and Farley, 2004). However, after repeated jumps on an elastic surface, the subjects showed an increase in the leg stiffness in the subsequent jump on a rigid surface. This increase is a consequence of exposure to elastic surfaces, since previous findings have shown that after repeated jumps on a hard surface leg stiffness is not affected (Márquez et al., 2010). Moreover, in the present study, we provide evidence that only one trial is necessary to adjust the stiffness of the legs on the new surface. Thus, it is unlikely that a passive mechanism is involved.

Table 1
Mean (±SD) of co-activation values (%) during eccentric and concentric phase of the muscle pairs crossing knee and ankle joint during the CMJs performed before (CMJ_{bsl}) and after (CMJ_{1-3}) the exposure to the elastic surface jumping.

	CMJ_{bsl}	CMJ_1	CMJ_2	CMJ_2
Eccentric				
BF/RF	30.54 (±17.35)	27.45 (±17.73)	25.80 (±17.57)	27.28 (±15.88)
BF/VL	29.48 (±14.14)	25.90 (±13.82)	24.76 (±16.65)	23.92 (±11.65)
SOL/TA	50.15 (±31.95)	54.29 (±28.20)	44.90 (±30.73)	47.28 (±37.45)
GM/TA	24.45 (±14.53)	26.90 (±19.22)	22.95 (±17.37)	22.44 (±20.26)
Concentric				
BF/RF	36.75 (±14.46)	41.32 (±19.08)	39.67 (±16.05)	37.96 (±15.09)
BF/VL	40.98 (±15.26)	48.88 (±23.49)	43.28 (±16.95)	40.63 (±20.65)
TA/SOL	28.76 (±17.68)	41.88 (±25.36)	33.33 (±18.94)	34.59 (±20.59)
TA/GM	33.20 (±19.94)	47.94 (±35.17)	37.98 (±24.44)	40.75 (±21.87)

Increased stiffness in the CMJ_1 is the result of a lower vertical motion of the CoM during the countermovement, since the peak force remained unchanged. The adjustment in ΔL could result from changes in the discharge rate of muscle spindles. This hypothesis is supported by the fact that during the execution of CMJ_1, the RMS EMG of the eccentric phase of knee extensors (VL and RF) increases significantly. These changes may be due to increased sensitivity of muscle spindles, resulting in a lower ΔL during the countermovement. One possible explanation is that, during the downward movement of the CoM in repetitive jumps performed on the elastic surface, subjects require a higher level of activation in the extensor muscles (anti-gravity) than in normal gravity [1G] (Lackner and Graybiel, 1981), due to increased body weight by a higher level of gravito–inertial acceleration (3-4 G, Sovelius et al., 2008). Moritz and Farley (2005) suggest that hoppers activate their leg extensors muscles 1.5–2-fold higher during stand phase of the jumps performed on very soft elastic surfaces than in stiff surfaces since the legs remain nearly isometric. Therefore, during the first jump on the rigid surface the motor commands could be unbalanced with the afferent signals as a result of the previous exposure to the elastic surface.

According to Nicol et al. (2006), increased stiffness is associated with increased responsiveness to stretch by muscle spindles, which results in a facilitation of the stretch reflex activation. Currently, it has been shown that these effects are related with a phenomenon called "thixotropy", which affects the behavior of the intrafusal fibers (Axelson and Hagbarth, 2001; Hagbarth and Nordin, 1998). This phenomenon is caused by the formation of new cross-bridges between the actin and myosin filaments by conditioning effect of a given muscle (e.g. eccentric work or a sustained contraction). This may cause a higher intrinsic stiffness of intrafusal fibers, resulting in changes in the discharge pattern of primary afferent terminals and thus changing the balance in the α-γ co-activation (Proske et al., 1993). This phenomenon was found to disappear after a short and intense muscle contraction (Axelson and Hagbarth, 2001). It is possible that repeated jumps on the elastic surface (characterized by high eccentric loading and low degree of stretch) influence the fusimotor system dynamics, inducing the changes observed during the execution of CMJ_1. The effect disappears in subsequent jumps (CMJ_2 and CMJ_3) and a return to baseline is observed.

The results of this study show a decrease in jump height in the CMJ performed immediately after the jumping exposure to the elastic surface. The jump height depends on mechanical, metabolic and neuromuscular factors (Asmussen and Bonde-Petersen, 1974; Bosco et al., 1982; Kubo et al., 1999; Voigt et al., 1995). However, a parameter that affects substantially the vertical jump height is the accumulation of energy during the stretching of a muscle, which is then returned during concentric work (Cavagna et al., 1968; Cavagna, 1977; Asmussen and Bonde-Petersen, 1974; Bosco et al., 1982; Komi and Bosco, 1978). Our results are consistent with these findings, since we found a significant decrease in the stored and returned energy during the execution of CMJ_1, which is reflected in a lower jump height.

Other factors affecting the height of the CMJ are the amplitude of the stretch during the eccentric phase and the co-contraction of antagonistic muscles (Komi, 1984; Aura and Komi, 1986). If we

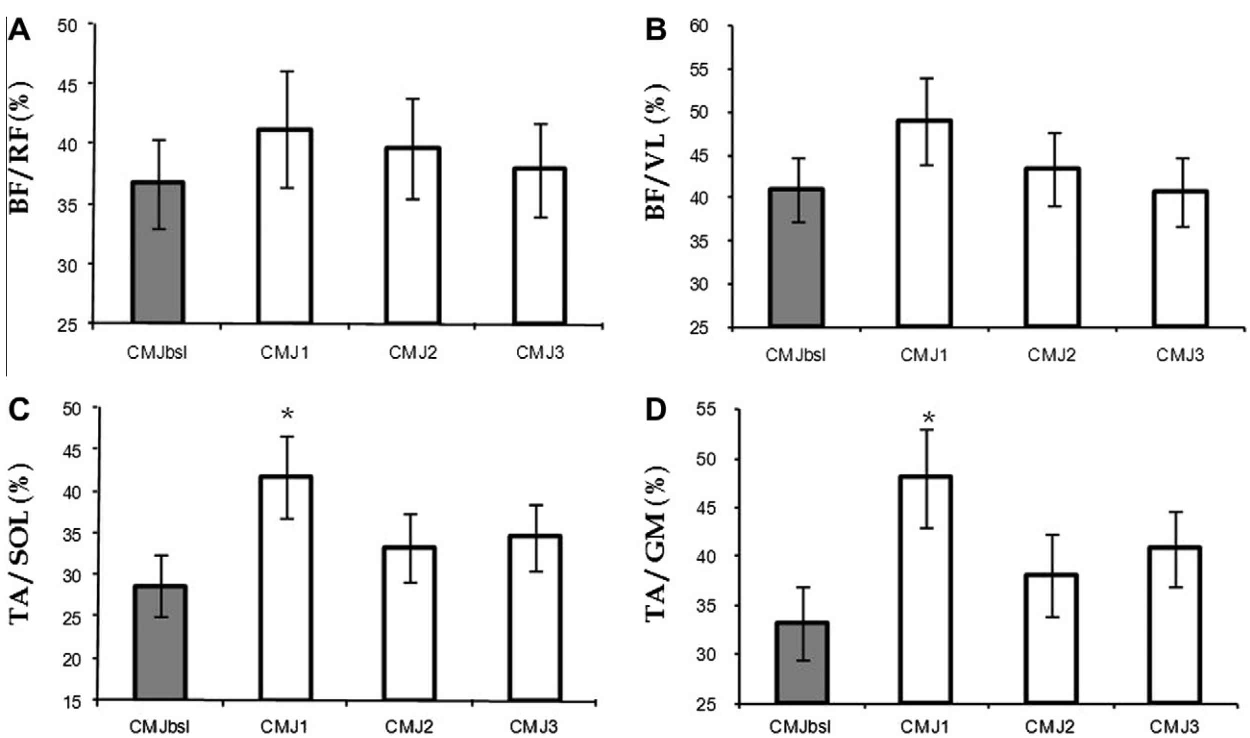

Fig. 4. Mean (±SE) of co-activation level (%) of the concentric phase of the muscles pairs BF/RF (A), BF/VL (B), TA/SOL (C) and TA/GM (D) during the CMJs performed before (grey bar) and after (white bars) the exposure to the elastic surface jumping. (*) significant differences compared with CMJ_{bsl}. $^*p \leqslant 0.05$.

take into account the results found in the first jump performed after exposure to the elastic surface, they reflect a lower ΔL, and an increase in the co-activation level of muscles crossing the ankle joint (TA, SOL and GM) during the concentric phase. Previous studies have demonstrated that high levels of co-activation are associated with an increased stiffness of the ankle joint (Dyhre-Poulsen et al., 1991; Nielsen et al., 1994,Weiss et al., 1988), and reduced efficiency during motion control (Falconer and Winter, 1985). Our results are in line with the findings of Farley and Morgenroth (1999) showing that ankle stiffness offsets the perturbation due to a decrease in surface stiffness. The recovery of the coactivation after the CMJ1 it may be explained by a forward model theory of motor control (Taube et al., 2012; Márquez et al., 2010). According with this theory, an internal model can be updated by comparing the predicted and actual outcome of a motor command (Wolpert and Flanagan, 2001). In our study the subjects could use the error between the predicted and actual sensory feedback occurred in the first CMJ after the trampoline, in order to update their internal model for the next jump. This could explain the decrease in the co-activation during the CMJ2 and CMJ2 and, as a result, the recovery of the height jump due to a more efficient work of the ankle-joint. According to Hof et al. (2002), a lower elasticity (or higher stiffness) of the muscle-tendon complex of the ankle joint, reduces the amount of mechanical work developed during the plantar flexion that occurs in the final phase of the vertical jump. The fact that the ankle behaves less efficiently due to an increase of its stiffness, could result in lower angular velocity and a lower mechanical moment during the concentric phase, which would compromise the final performance (Bobbert et al., 1986).

In summary, the current results show that repetitive jumps on an elastic surface lead to mechanical and neuromuscular changes in a subsequent countermovement jump performed on a stiff surface. These changes involve an increase in the activation of the knee extensor muscles during the braking phase and increased co-activation of the ankle joint muscles during the push-off phase.

References

Arampatzis A, Bruggemann GP, Klapsing GM. Leg stiffness and mechanical energetic processes during jumping on a sprung surface. Med Sci Sports Exerc 2001;33:923–31.

Asmussen E, Bonde-Petersen F. Storage of elastic energy in skeletal muscles in man. Acta Physiol Scand 1974;91:385–92.

Aura O, Komi PV. Effects of prestretch intensity on mechanical efficiency of positive work and on elastic behavior of skeletal muscle in stretch-shortening cycle exercise. Int J Sports Med 1986;7:137–43.

Axelson HW, Hagbarth KE. Human motor control consequences of thixotropic changes in muscular short-range stiffness. J Physiol 2001;535:279–88.

Basmajian JV, De Luca CJ. Muscles alive. Their functions revealed by electromyography. Baltimore, USA: Williams & Wilkins; 1985.

Bobbert MF, Huijing PA, Van Ingen Schenau GJ. An estimation of power output and work done by the human triceps surae muscle-tendon complex in jumping. J Biomech 1986;19:899–906.

Bosco C, Komi PV, Tihanyi J, Fekete G, Apor P. Mechanical power test and fiber composition of human leg extensor muscles. Eur J Appl Physiol 1983;51:129–35.

Bosco C, Viitasalo JT, Komi PV, Luhtanen P. Combined effect of elastic energy and myoelectrical potentiation during stretch-shortening cycle exercise. Acta Physiol Scand 1982;114:557–65.

Cavagna GA. Force platforms as ergometers. J Appl Physiol 1975;39:174–9.

Cavagna GA. Storage and utilization of elastic energy in skeletal muscle. Exerc Sport Sci Rev 1977;5:89–129.

Cavagna GA, Dusman B, Margaria R. Positive work done by a previously stretched muscle. J Appl Physiol 1968;24:21–32.

De Luca CJ. The use of surface electromyography in biomechanics. J Appl Biomech 1997;13:135–63.

Dyhre-Poulsen P, Simonsen EB, Voigt M. Dynamic control of muscle stiffness and H reflex modulation during hopping and jumping in man. J Physiol 1991;437:287–304.

Falconer K, Winter DA. Quantitative assessment of co-contraction at the ankle joint in walking. Electromyogr Clin Neurophysiol 1985;25:135–49.

Farley CT, Blickhan R, Saito J, Taylor CR. Hopping frequency in humans: a test of how springs set stride frequency in bouncing gaits. J Appl Physiol 1991;71:2127–32.

Farley CT, Morgenroth DC. Leg stiffness primarily depends on ankle stiffness during human hopping. J Biomech 1999;32:267–73.

Ferris DP, Farley CT. Interaction of leg stiffness and surfaces stiffness during human hopping. J Appl Physiol 1997;82:15–22.

Ferris DP, Liang K, Farley CT. Runners adjust leg stiffness for their first step on a new running surface. J Biomech 1999;32:787–94.

Ferris DP, Louie M, Farley CT. Running in the real world: adjusting leg stiffness for different surfaces. Proc Biol Sci 1998;265:989–94.

Hagbarth KE, Nordin M. Postural after-contractions in man attributed to muscle spindle thixotropy. J Physiol 1998;506(Pt 3):875–83.

Hobara H, Inoue K, Muraoka T, Omuro K, Sakamoto M, Kanosue K. Leg stiffness adjustment for a range of hopping frequencies in humans. J Biomech 2010;43:506–11.

Hof AL, Van Zandwijk JP, Bobbert MF. Mechanics of human triceps surae muscle in walking, running and jumping. Acta Physiol Scand 2002;174:17–30.

Hortobagyi T, Solnik S, Gruber A, Rider P, Steinweg K, Helseth J, et al. Interaction between age and gait velocity in the amplitude and timing of antagonist muscle co-activation. Gait Posture 2009;29:558–64.

Kellis E, Arabatzi F, Papadopoulos C. Muscle co-activation around the knee in drop jumping using the co-contraction index. J Electromyogr Kinesiol 2003;13:229–38.

Kerdok AE, Biewener AA, McMahon TA, Weyand PG, Herr HM. Energetics and mechanics of human running on surfaces of different stiffnesses. J Appl Physiol 2002;92:469–78.

Komi PV. Physiological and biomechanical correlates of muscle function: effects of muscle structure and stretch-shortening cycle on force and speed. Exerc Sport Sci Rev 1984;12:81–121.

Komi PV, Bosco C. Utilization of stored elastic energy in leg extensor muscles by men and women. Med Sci Sports 1978;10:261–5.

Konrad P. The ABC, of EMG. A practical introduction to kinesiological electromyography. USA: Noraxon INC; 2005.

Kubo K, Kawakami Y, Fukunaga T. Influence of elastic properties of tendon structures on jump performance in humans. J Appl Physiol 1999;87:2090–6.

Lackner JR, Dizio P. Rapid adaptation to Coriolis force perturbations of arm trajectory. J Neurophysiol 1994;72:299–313.

Lackner JR, DiZio PA. Aspects of body self-calibration. Trends Cogn Sci 2000;4:279–88.

Lackner JR, Graybiel A. Visual and postural motion aftereffects following parabolic flight. Aviat Space Environ Med 1980;51:230–3.

Lackner JR, Graybiel A. Illusions of postural, visual, and aircraft motion elicited by deep knee in the increased gravitoinertial force phase of parabolic flight. Evidence for dynamic sensory-motor calibration to earth gravity force levels. Exp Brain Res 1981;44:312–6.

Liu Y, Peng CH, Wei SH, Chi JC, Tsai FR, Chen JY. Active leg stiffness and energy stored in the muscles during maximal counter movement jump in the aged. J Electromyogr Kinesiol 2006;16:342–51.

Márquez G, Aguado X, Alegre LM, Lago A, Acero RM, Fernandez-del-Olmo M. The trampoline aftereffect: the motor and sensory modulations associated with jumping on an elastic surface. Exp Brain Res 2010;204:575–84.

MacLellan MJ, Patla AE. Adaptations of walking pattern on a compliant surface to regulate dynamic stability. Exp Brain Res 2006;173:521–30.

Marigold DS, Patla AE. Visual information from the lower visual field is important for walking across multi-surface terrain. Exp Brain Res 2008;188:23–31.

Moritz CT, Farley CT. Human hopping on very soft elastic surfaces: implications for muscle pre-stretch and elastic energy storage in locomotion. J Exp Biol 2005;208:939–49.

Moritz CT, Farley CT. Passive dynamics change leg mechanics for an unexpected surface during human hopping. J Appl Physiol 2004;97:1313–22.

Nicol C, Avela J, Komi PV. The stretch-shortening cycle: a model to study naturally occurring neuromuscular fatigue. Sports Med 2006;36:977–99.

Nielsen J, Sinkjaer T, Toft E, Kagamihara Y. Segmental reflexes and ankle joint stiffness during co-contraction of antagonistic ankle muscles in man. Exp Brain Res 1994;102:350–8.

Proske U. What is the role of muscle receptors in proprioception? Muscle Nerve 2005;31:780–7.

Proske U. Kinesthesia: the role of muscle receptors. Muscle Nerve 2006;34:545–58.

Proske U, Morgan DL, Gregory JE. Thixotropy in skeletal muscle and in muscle spindles: a review. Prog Neurobiol 1993;41:705–21.

Proske U, Wise AK, Gregory JE. The role of muscle receptors in the detection of movements. Prog Neurobiol 2000;60:85–96.

Sovelius R, Oksa J, Rintala H, Huhtala H, Siitonen S. Neck muscle strain when wearing helmet and NVG during acceleration on a trampoline. Aviat Space Environ Med 2008;79:112–6.

Taube W, Leukel C, Gollhofer A. How neurons make us jump: the neural control of stretch-shortening cycle movements. Exerc Sport Sci Rev 2012;40(2):106–15.

van der Krogt MM, de Graaf WW, Farley CT, Moritz CT, Richard Casius LJ, Bobbert MF. Robust passive dynamics of the musculoskeletal system compensate for unexpected surface changes during human hopping. J Appl Physiol 2009;107:801–8.

Voigt M, Simonsen EB, Dyhre-Poulsen P, Klausen K. Mechanical and muscular factors influencing the performance in maximal vertical jumping after different prestretch loads. J Biomech 1995;28:293–307.

Weiss PL, Hunter IW, Kearney RE. Human ankle joint stiffness over the full range of muscle activation levels. J Biomech 1988;21:539–44.

Wolpert DM, Flanagan JR. Motor prediction. Curr Biol 2001;18:R729–32.

Gonzalo Márquez received his Ph.D. at the University of A Coruña in 2011. Currently, he is Assistant Professor at the Faculty of Sports Sciences in the Catholic University of Murcia (Spain). His main research interest is the integration of neurophysiology and biomechanics to highlight neurophysiological mechanisms of motor control and motor learning.

Xavier Aguado received his Ph.D. at the University of Barcelona in 1995. He is Professor at the Faculty of Sports Sciences in Toledo (Spain) and is the Head of the Biomechanics Lab at the University of Castilla-la-Mancha. His main research interest is the Sport Biomechanics.

Luis M. Alegre received his Ph.D. at the University of Castilla-La Mancha in 2004. He is Associate Professor at the Faculty of Sports Sciences in Toledo (Spain). His main research interests are the acute and chronic adaptations of the muscle-tendon unit to physical activity.

Miguel Fernandez-del-Olmo received his Ph.D. at the University of A Coruña in 2001. He is the Head of the Motor Control and Learning Research Group at the University of A Coruña and is Associate Professor at the Sports Sciences Faculty. His main research interests are the mechanism involved in the human motor control and learning from the neurophysological and behavioural perspectives.