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DIAGNOSTIC METHODS: CROSS-SECTIONAL STUDY

A comparison of lower limb muscle activation pattern using voluntary response index between pronated and normal foot structures during forward jump landing

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ABSTRACT

Background: Pronated of the foot is one of the important factors contributing to musculoskeletal problems affecting the lower extremities. It is known that in a pronated foot, excessive mechanical load is applied to the lower limb structures which may result in altered biomechanics and muscle activation patterns. The aim of this study was to determine changes in the muscle activation pattern of the lower extremities in individuals with pronated, compared to normal, feet, using the voluntary response index (VRI).

Methods: In this cross sectional study, 15 asymptomatic pronated foot individuals (mean age 23.27 ± 3.28 years) and 15 normal subjects (mean age 23.40 ± 3.11 years) were recruited by simple non-random sampling. Electrical activities of gluteus medius (GM), vastus lateralis (VL), vastus medialis (VM), biceps femoris, semitendinosus (ST), and medial gastrocnemius (MG) muscles were recorded during a forward jump landing task. Voluntary response index (VRI) variables, included similarity index (SI) and magnitude (Mag) were also evaluated.

Results: Muscle activity of VM ($p < 0.001$) and ST ($p = 0.010$) were significantly higher but VL ($p = 0.039$) and MG ($p = 0.001$) were significantly lower in pronated foot, compared to normal subjects. Similarity index was found to be different ($p < 0.001$) between pronated foot and healthy individuals. No significant difference was found in terms of Mag between the two groups ($p = 0.576$).

Conclusion: The altered pattern of lower limb muscle activation identified in the pronated foot during landing may be attributed to the different activation involving VL, VM, MG and ST muscles. Adaptations to the biomechanical effects, due to the pronated foot causing altered activation of VL, VM, MG, and ST muscles, results in an altered pattern of muscle activation. This change in activation pattern may harm the effectiveness of movement control processes; and might also predispose individuals with pronated feet, to injuries. It seems that an altered motor strategy with the aim of minimizing biomechanical changes, predisposes individuals to injuries. However, further large scale studies are needed to support the findings of the present study.

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1. Background

Some functional disorders in the foot region are caused by changes in the foot arches (Cote et al., 2005). The main function of foot arches is to absorb the energy that results from foot contact

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with the ground during walking and transferring forces from the body to the ground (Fiolkowski et al., 2003).

Among foot structures, the Medial Longitudinal Arch (MLA) as an important structure plays a crucial role in the transmission of forces through the foot and is very susceptible to injury. MLA plays such a role in the shock absorption and attenuation of forces transmitted to the body (Fiolkowski et al., 2003) that both the increasing and decreasing changes of these functions may place a person at the risk of injury during a physical activity (Razeghi and Batt, 2002).

Excessive pronation is a disorder that occurs due to MLA change (Cote et al., 2005). This disorder is characterized by MLA flattening and mid foot hyper mobility (Cote et al., 2005). Due to general hypermobility of foot joints and their unlocked position, proprioceptive afferents of this area are reduced, which leads to impaired postural control (Tsai et al., 2006) and increased neuromuscular system demand to stabilize and maintain the standing posture (Hertel et al., 2002).

Pronation is a three plane movement. Bone structures, ligamentous supports and intrinsic and extrinsic foot muscles are all involved in MLA maintenance and foot pronation control while walking. If there is a dysfunction in any of these elements, foot pronation increases and results in overuse Injury (Headlee et al., 2008).

Dysfunction in any of supporting intrinsic muscles of MLA (such as abductor hallucis, flexor hallucis brevis, flexor digitorum brevis, abductor digiti minimi, and dorsal interossei) may expose a person to excessive pronation (Headlee et al., 2008). Some researchers believe that in people with pronated feet, some extrinsic muscles activity such as tibialis anterior and posterior during walking, increase, while peroneus longus activity decreases, compared to that in normal subjects (Hunt and Smith, 2004). However, there is no general consensus regarding the activity of some lower limb muscles including vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), and medial gastrocnemius (MG) in pronated foot subjects. Some researchers have reported an increase in the activity of VL (Chang et al., 2012) and VM (Lee and Kim, 2014; Kim and Lee, 2013b) muscles, others reported reduced muscle activity in BF (Chang et al., 2012) and MG (Hunt and Smith, 2004; Chang et al., 2012) while some others found no difference in the activity of VL (Lee and Kim, 2014; Kim and Lee, 2013a, 2013b; Lee et al., 2013; Kim and Lee, 2013a), VM (Lee et al., 2013; Kim and Lee, 2013a), BF (Lee and Kim, 2014; Kim and Lee, 2013a, 2013b) and MG (Murley et al., 2009; Lee and Kim, 2014; Kim and Lee, 2013a, 2013b; Lee et al., 2013; Kim and Lee, 2013a). These conflicting results may arise from only regarding individual muscles, and not paying attention to their synergetic functions. In these studies, several muscles were measured, but the results discussed were not based on synergy concepts, nor was an outcome measure reported to quantify the synergetic behavior of the muscle under study.

Unlike the traditional examination of electrical activities, by which individual muscles are compared between the groups at any given time, all the muscles involved in a task are evaluated by the Voluntary Response Index (VRI), which provides objective and quantitative information about the collective behavior of a muscular system (Lee et al., 2004). This vector-based analysis method comprises two components: Magnitude (Mag), which indicates an overall electrical activity outcome obtained from all the muscles during a task performance and Similarity Index (SI), which represents the similarity coefficient of the electromyographic activity pattern of the muscles compared to a prototype pattern obtained from healthy individuals (Lee et al., 2004).

2. Objectives

Considering the fact that most muscle electrical activities in a pronated foot have been investigated in walking and running, it seems necessary to investigate the activation patterns of the main muscles in the lower limbs in terms of the values of their activity and also the VRI during a challenging task such as forward jump landing. Forward jump is a functional dynamic task with both active and passive mechanisms that mainly contribute to the control of posture and transmission of impact forces during performance. Therefore, this study aimed to compare the activation pattern of some global muscles of the lower extremities including gluteus medius (GM), semitendinosus (ST), VL, VM, BF and MG in pronated and normal foot structures using VRI during a forward jump landing task.

3. Materials and methods

3.1. Participants

In this cross-sectional study, 30 individuals (15 pronated and 15 normal foot subjects) were recruited according to the inclusion and exclusion criteria. Theses 30 individuals were selected out of 92 volunteers visited following an announcement on the university campus. Inclusion criteria included age between 20 and 30 years old and body mass index (BMI) between 22 and 25 kg/m^2. Pronated foot structures were determined based on the angles of MLA and rear foot to leg (RL). The MLA angles of less than 134° and between 134° and 150° were considered for a pronated and normal foot, respectively. Moreover, RL angles in a pronated and normal foot were considered to be greater than 9° and between 3° and 9°, respectively. Individuals with professional athletic activities, scoliosis, discopathy, low back pain and deformities in the knees, history of orthopedic and neurological disorders in the past six months, and the use of any substances that may affect postural control in the 48 h prior to tests were excluded from the study.

The study protocol was approved by the Ethics Committee of the Ahvaz Jundishapur University of Medical Sciences (Ahvaz, Iran). All subjects were given written information about the aims of the study and upon agreement to participate were asked to sign a consent form. Subjects were also informed that there was no harm in this study and they were free to leave the study at any time.

3.2. Sampling method

The participants were selected from students at the Ahvaz Jundishapur University of Medical Sciences through simple, nonrandom sampling method. After testing 10 individuals in each group, the sample size was calculated at a 5% level of significance and with a power of 80%, which led to a sample size of at least 15 individuals in each group.

3.3. Data collection

In this study, all measurements were taken by the single investigator and the intra-tester reliability of the procedures for measuring MLA and RL angles and EMG parameters were investigated during a pilot study on 10 subjects through two sessions of 3 trials during two separate days.

MLA and RL angles were measured for the dominant foot of each subject. The dominant leg of subjects were determined using a dominant leg questionnaire (Tsepis et al., 2004). The subjects were instructed to stand relaxed on both feet, while their two ankle joint centers were as far apart as the anterior superior iliac spines. MLA angle was reconstructed from the intersection of two lines connecting the medial malleolus and the medial aspect of the first metatarsal head to the navicular tuberosity. The intersection of the longitudinal bisecting line of the calcaneus and the longitudinal bisecting line of the distal one-third of the leg forms an acute angle called RL. A foot was classified as a pronated foot when the RL angle was >9° and MLA angle was <134°. The RL angle of 3-9° and MLA angle of 134–150° were considered for a normal foot (Jonson and Gross, 1997).

A data acquisition unit (Biometrics Data Log, Oxford Ltd, UK) was used to measure the muscle activity.

After skin preparation, sEMG electrodes (Ag/AgCl circular electrodes separated by 2 cm) were placed parallel to the muscle fibers. The electrodes were applied over the GM, VL, VM, BF, ST, and MG muscles based on the SENIAM protocol (Hermens et al., 2000). A force platform (Bertec 4060-08, Bertec Inc, Columbus, Ohio) was used to detect the initial contact and stabilization time after landing. A participant was asked to jump forward on both legs with a maximum effort with his/her arms crossed on the chest (Hagins et al., 2007), while landing on the dominant leg and maintaining his/her balance without opening the arms, touching the ground with his/her non-landing foot, or stepping with the landing foot. The participant was then asked to jump 60% of their maximum jump length (marked previously on the ground). This latter jump was considered as the main task and normalized by the former jump done with the maximum effort. The participants performed the tests barefoot and if they were unable to keep the balance, test was repeated. Also for the subjects' familiarization, they practiced the forward jump twice before the main tests. All the tests were repeated 3 times with 3 min of rest interval to avoid fatigue. The data were captured at a sampling rate of 1000 Hz for EMG and 100 Hz for the force plate for 10 s.

3.4. Data analysis

The surface EMG data obtained from the initial foot contact to the time of stabilization was considered for further analysis. The stabilization time was calculated based on the force-plate data. The time at which the anterior-posterior COP first went continuously below the mean +3SD of the steady-state single-leg stance for at least 200 ms was considered as the time of stability. The most stable second starting from second 4 after a heel contact was considered as the steady-state single-leg stance. The average value of the Root Mean Square (RMS, millivolt) obtained from 3 successful forward jump landings (Pappas and Carpes, 2012) was used to evaluate the VRIs and compare the activation level between the two study groups. In the examination of VRIs, RMSs of all the muscles were considered as a vector called a Response Vector (RV) with 6 response elements corresponding to 6 tested muscles. An average of the RVs across all the healthy subjects (n = 15) was applied as a Prototype Response Vector (PRV). The Euclidian norm of the RVS was considered as the magnitude of the total muscle activity.

The RVs of the pronated foot subjects were calculated in the same manner and finally compared with their PRVs (Lee et al., 2004). The SI of the muscle activity was calculated as a cosine similarity (the angle between 2 vectors found by their inner products as shown in Equation (1)), and the SIs of both groups were finally compared (Lee et al., 2004). The SIs had the values of 0–1, while 1 indicated a maximum similarity (see equation (1)).

$$\mathrm{SI} = \frac{\sum_i (RV_i PRV_i)}{|RV||PRV|} \tag{1}$$

3.5. Statistical analysis

Statistical analysis was performed using SPSS version 21.0 (SPSS Inc., Chicago, IL, USA). Descriptive statistical methods, including dispersion and central tendency were used to describe the variables. One-sample Kolmogorov-Smirnov test was applied to check the normal distribution of the data. The intra-tester reliability of the variables was assessed with intra-class correlation coefficient (ICC), standard error of measurement (SEM), and minimal detectable change (MDC). Independent-samples *t*-test was also utilized for comparisons between the two groups. The level of significance was set at $p < 0.05$.

4. Results

Thirty subjects (15 males and 15 females) consisting of 15 pronated foot and 15 normal subjects with mean values for the following variables; age of 23.33 ± 3.14 years, weight of 65.87 ± 6.86 kg, height of 167.33 ± 9.25 cm and BMI of 23.47 ± 0.98; participated in the present study. No significant differences in age, weight, height or BMI were found between the two groups ($p > 0.05$ in all instances). Sample characteristics are shown in Table 1. The MLA and RL angles were significantly different between pronated and normal groups ($p = 0.001$ for both) (see Table 1).

The intra-tester reliability measurement for the studied variables was good to excellent. The ICC, SEM, and MDC values were obtained as follows: MLA angle (ICC = 0.88, SEM = 2.50°, MDC = 4.90°), RL angle (ICC = 0.73, SEM = 1.40°, MDC = 2.74°), RMS of GM (ICC = 0.72, SEM = 6.37, MDC = 8.25), VL (ICC = 0.73, SEM = 4.71, MDC = 9.24), VM (ICC = 0.78, SEM = 7.74, MDC = 15.17), BF (ICC = 0.81, SEM = 5.13, MDC = 7.89), ST (ICC = 0.82, SEM = 5.53, MDC = 10.84), and MG (ICC = 0.85, SEM = 7.82, MDC = 15.33).

The VRI characteristics of pronated foot subjects compared to normal subjects showed a statistically significant difference in SI ($p < 0.001$). No significant difference was found in terms of Mag between the two groups ($p = 0.576$) (see Fig. 1). RMS between the groups (that is, across all muscles) showed that muscle activity of VM ($p < 0.001$) and ST ($p = 0.010$) were higher but VL ($p = 0.039$) and MG ($p = 0.001$) were significantly lower in the pronated foot compared to normal subjects. In addition, the findings showed that

Table 1
Sample characteristics.[a,b]

Variables	Foot type		
	Pronated	Normal	P. value
Number of subjects	15	15	
Gender (male/female)	7/8	8/7	
Age (year)	23.27 (3.28)	23.40 (3.11)	0.91
Weight (kg)	66.80 (6.38)	64.93 (7.42)	0.46
Height (cm)	167.67 (9.77)	167.00 (9.04)	0.84
BMI (kg/m^2)	23.73 (0.95)	23.21 (0.97)	0.15
MLA angle (degree)	126.13 (4.32)	142.07 (3.97)	< **0.001***
RL angle (degree)	13.73 (2.31)	6.73 (1.03)	< **0.001***

* Statistically significant.

[a] Values are presented as mean (SD).

[b] Abbreviation: kg: kilograms; cm: centimeters; BMI; body mass index; m: meters; MLA: medial longitudinal arch; RL: rear-foot to leg.

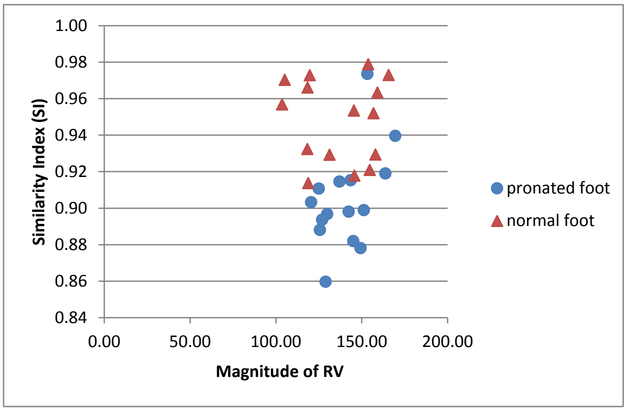

Fig. 1. Voluntary response index obtained from pronated and normal foot structures. While the magnitude of RV is not statistically different between two groups, subjects with pronated foot demonstrated lower values of SI compared to the normal group.

Table 2
SI, Mag, muscle activity of GM, VL, VM, BF, ST and MG in pronated vs normal subjects.[a,b]

Variables	Foot type		
	Pronated	Normal	P. value
SI	0.90 (0.006)	0.94 (0.005)	< **0.001***
Mag	140.86 (3.82)	137.07 (5.50)	0.576
GM	63.87 (5.20)	54.20 (5.89)	0.229
VL	44.00 (4.95)	58.60 (4.55)	**0.039***
VM	68.27 (2.35)	42.40 (4.24)	< **0.001***
BF	43.47 (4.85)	51.00 (6.51)	0.362
ST	63.60 (5.10)	43.33 (5.24)	**0.010***
MG	41.20 (4.19)	65.27 (4.62)	**0.001***

* Statistically significant.

[a] Values are presented as mean (SE).

[b] Abbreviation: SI: similarity index; Mag: magnitude; GM: gluteus medius; VL: vastus lateralis; VM: vastus medialis; BF: biceps femoris; ST: semitendinosus; MG: medial gastrocnemius.

there were no significant differences in GM ($p = 0.229$) and BF ($p = 0.362$) muscles between groups (see Table 2).

5. Discussion

In this study, the pattern of muscle activity of the lower limbs were investigated using VRI in both printed and normal foot groups. It was observed that Mag of both groups had no significant difference with each other, but the SI of the pronated foot group was less than that of the normal group, which may be due to higher activity of VM and ST muscles and the lower activity of VL and MG muscles in pronated foot group as opposed to the control group.

In the present study, there was no significant difference between the two groups in terms of their Mag. This suggests that the total amount of muscle activity was similar in both groups, and that the resultant amount of weakness and strength of the muscles involved in the task are the same in both pronated and normal people. This does not necessarily mean that there is weakness and strength similarity in the same muscles in both groups. However, a decrease in the activity of one muscle in the pronated foot group may be compensated for by an increase in the activity of another in the same group. Therefore, the resultant value of muscle activity is the same in both groups without having any similarity in terms of activity pattern. Unlike Mag, the two groups had significantly different SI, which suggests that the pattern of muscle activity is different between the two groups; and that different muscles showed no similar electrical activity in the two groups during forward jump landing. Comparing the muscle activity values of different muscles in the two groups revealed that the activity of VM and ST muscles in pronated foot group was higher than that in the normal group; whereas the muscle activity values of VL and MG in the pronated foot was lower than that of normal group. While the activity of BF and GM muscles were not significantly difference between the groups, their values in the pronated foot were lower and higher than those of the normal group, respectively.

Generally, the results of the present study are consistent with those of Lee and Kim (2014),Kim and Lee (2013b) in VM and BF muscles, with Hunt and Smith (2004), Chang et al. (2012). in MG muscle, with Kim and Lee (2013a) in BF muscle and are inconsistent with Chang et al. (2012), Lee and Kim (2014), Kim and Lee (2013b), Lee et al. (2013), Kim and Lee (2013a) in VL muscle, with Lee et al. (2013), Kim and Lee (2013a) in VM muscle, with Chang et al. (2012). in BF muscle, with Lee and Kim (2014), Kim and Lee (2013b), Lee et al. (2013), Kim and Lee (2013a), Murly et al (Murley et al., 2009).in MG muscle.

The different results obtained might be due to the lower demanding tasks tested in those studies, which mainly dealt with the lower extremity muscle activation during the associated low-load tasks like walking, but not those of higher loads like jump landing. Lee and Kim examined the activation of the lower limb muscles in 30 subjects consisting of 15 subjects each with pronated and 15 with normal foot, at different gait velocities on an ascending slope. At all studied speeds, the VM muscle activity in the pronated foot was more than in the normal group, while muscle activities of VL, BF and MG were similar between the two groups (Lee and Kim, 2014). Similarly, Kim and Lee examined lower limb muscles activity in 30 subject with pronated and normal foot (15 per group) at different gait speeds and observed that at all studied speeds, the VM muscle activity was higher in the pronated foot but there was no significant difference between the muscle activity of VL, BF and MG between the two groups (Kim and Lee, 2013b). Chang et al. examined sEMG of lower limbs in 10 people with pronated foot and 10 normal subjects during double leg drop landing and concluded that VL muscle activity was higher in pronated foot than in normal group while MG and BF muscle activity was lower in both groups (Chang et al., 2012). Hunt and Smith compared EMG parameters of lower limb in the stance phase of walking in people with pronated and normal foot and concluded that the MG muscle activity in pronated foot was lower than in normal individuals (Hunt and Smith, 2004). Lee et al. examined lower limb muscle activation on single leg standing in 11 pronated foot and 12 normal individuals and observed that electrical activity of VL, VM, and MG muscles is the same in both groups (Lee et al., 2013). Kim and Lee examined the activity of some lower limb muscles of 30 pronated foot and normal people (15 per group) in walking on different slopes and concluded that at all studied slopes, the electrical activity of VL, VM, BF and MG muscles was similar in both groups (Kim and Lee, 2013a). Murley et al. compared electrical activity of some lower limb muscles during walking in 30 pronated foot and 30 normal people and concluded that EMG activity of MG muscle was not different in the two groups (Murley et al., 2009).

Among extensor muscles of the knee, the role of VM is much more pronounced than the other extensors. Particularly, due to weakness of the ankle plantar flexors, people with pronated foot receive more load on their VM muscle than normal people (Neumann, 2002). Therefore, this muscle has to show more activity during landing in pronated foot than in normal people to control landing shock as well as excessive knee flexion which are occurred to compensate for ankle plantar flexors weakness. In addition, it has been shown that pronated foot is associated with excessive internal rotation of the lower limb during running (Nigg et al., 1993).

Internal rotation of the lower limb causes patellar lateralization which finally leads to patellar maltracking and patellofemoral pain syndrome (Tiberio, 1987). This seems to be one of the causes of VM hyperactivity and VL inhibition with the aim of avoiding patellar maltracking. It is known that in the frontal plane, rear foot eversion is associated with knee valgus (Williams et al., 2001) which results in the compression of the lateral compartment of the knee (Tiberio, 1987). Therefore, medial side muscles of the knee, including VM and ST has to show more activity to control the valgus whereas the lateral side muscles of the knee including VL and BF should be inhibited to reduce the intensity of the valgus force.

The major role of the ankle plantar flexors during walking is stabilizing the knee and ankle to avoid an excessive rotation (Sutherland et al., 1980). Thus, the decreased activities of ankle plantar flexor muscles, including the MG observed in our study might be due to the kinematic changes in the lower limb joints in the pronated compared to the normal feet.

However, they experienced a functional change due to the mechanical changes in the lower limb joints resulting from excessive pronation (Sutherland et al., 1980). It seems that the difference between the muscle activities of the subjects with a pronated foot was due to a neuromuscular adaptation aimed at reducing the load exerted on the MLA (Murley et al., 2009).

The magnitudes of muscle activation in the pronated and normal groups did not reveal a significant difference between the two groups though its value in the group of a pronated foot was higher than in the group of a normal foot. There is increasing evidence suggesting that the proximal musculature dysfunction of the lower limb depends on distal limb function. In other words, foot structure can affect proximal structures such as the hip and pelvic. Therefore, due to excessive pronation, there will be functional shortening in lower limb and an increase in the internal rotation of the limb which promotes the anterior pelvic tilt. This in turn, increases the strain on the pelvic and hip including iliopsoas, piriformis and gluteal muscles (Bird and Payne, 1999). On the other hand, biomechanical changes associated with lumbopelvic dysfunction that include adduction and internal rotation of the femur and knee valgus (Willson et al., 2005) would cause gravity line to be placed inside the subtalar joint, and consequently these changes will be necessarily accompanied by excessive pronation. In addition, a study conducted on the kinetics of the lower limb reflecting the dependency of knee and ankle torque on hip torque (Bobbert and Van Zandwijk, 1999) can also confirm these claims. All these mechanisms may explain the related injuries and the relationship between excessive pronation and GM muscle dysfunction. All these statements support the hypothesis of the different levels of GM activity between the two groups. The contradiction seen in our outputs may have resulted from the small size of the sample as a limitation in our study. In the present study, the inclusion criteria urged us to choose the individuals with further MLA and RL angles compared to those detected with common pronated feet, thus dealing with more severe foot pronations. Conservative inclusion criteria based on MLA and RL angles were chosen to ensure the differences between the two groups is terms of foot pronation.

Moreover, ignoring some important muscles, such as lateral gastrocnemius due to a limited number of sEMG channels could be considered as another limitation of the study. The strength of this study, however, was that unlike the studies conducted on the foot structures, only one method was used to select the foot structure to be evaluated on a single plane, which might lead to contradictory findings in the different studies dealing with this issue. However, to address this shortcoming in the present study, the foot structure was assessed in both sagittal (MLA angle) and frontal (RL angle) planes, and if both angles confirmed pronated or normal foot, the person would enter the experiment. Therefore, the subjects were grouped with higher precision and this may be one of the main reasons for reaching a significant difference in most variables between the two groups. Furthermore, in previous studies tasks such as standing, walking and running were often used for comparison between different foot structures, but these tasks were less likely to provide sufficient perturbation to identify the differences between different structures in all studied parameters. In this study in order to overcome this drawback, the challenging task of forward jump landing (one-leg landing), which is more likely to provide the required perturbation was used.

The study results showed that the changed muscle activation pattern detected in patients with pronated foot during landing is a result of the differences in activation of VL, VM, ST and MG muscles. This represents a changed movement strategy in order to minimize biomechanical changes exerted on the lower limbs which make them more susceptible to musculoskeletal injuries.

Future studies are recommended to replicate this study before and after the use of therapeutic interventions such as corrective foot orthosis, or strengthening exercises particularly in intrinsic foot muscles also coordinative exercises to better determine the impact of these interventions on EMG parameters due to pronated foot.

Conflicts of interest

None.

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