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Hip-abductor fatigue influences sagittal plane ankle kinematics and shank muscle activity during a single-leg forward jump

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ABSTRACT

Diminished hip abductor strength decreases postural control which is a parameter that is associated with an increased risk of ankle sprains. In our study we evaluated the influence of hip abductor fatigue on sagittal plane ankle kinematics and shank muscle activity during a single-leg forward jump. Sagittal ankle plane kinematics are important in ankle sprains but less studied than frontal plane kinematics. Therefore, we evaluated differences in sagittal ankle kinematics (12-camera motion capture system) and lower limb surface electromyographic muscle activity in 20 healthy, recreationally active adults (9 females, 11 males, mean age 30.3 SD 4.0 years, mean BMI 23.6 SD 2.8 kg/m^2) before and after a hip abductor fatigue protocol (200-ms prior, at and in the 250-ms following initial contact (IC)).

After fatigue, the maximal ankle plantar-flexion angle decreased prior to IC (median 3.8° [interquartile range 0.1, 7.2], $p = 0.014$), at IC (4.1° [−0.3, 5.0], $p = 0.027$) and post IC (4.1° [−1.3, 5.0] $p = 0.036$). Gastrocnemius activity onset was delayed (−28.0 ms [−44.0, 0.0], $p < 0.01$). Average activity of the tibialis anterior increased prior to IC (pre-fatigue 19.32% [14.89, 33.45], post-fatigue 28.95% [18.49, 34.81], $p < 0.05$).

Hip-abductor fatigue influenced sagittal ankle kinematics and shank muscle activity during single-leg landings.

1. Introduction

Ankle injuries are one of the most common musculoskeletal injuries of the lower limb in sports (Petersen et al., 2013). Bridgman et al. (2003) estimated an incidence rate of 52.7–60.9 per 10,000 in the UK general population. Researchers determined that ankle injuries occur more frequently during the second half of competitions, and it was suggested that this might be due to the fatigued states of the athletes (Gabbett, 2002; Woods et al., 2003). Most non-contact ankle injuries occur during challenging movements, such as cutting, jumping and running tasks (Geiser et al., 2010).

Different explanations of ankle position and increased injury risk or injury prevention strategies are discussed in literature (Aerts et al., 2013; Kristianslund et al., 2011). Aerts et al. (2013) stated in their systematic review that several articles reported a decreased ankle plantar-flexion at IC in participants with ankle injuries. Similarly, in another study, an accidental lateral ankle sprain was recorded during a sidestep cutting of a handball player in a motion analysis laboratory (Kristianslund et al., 2011). Their recordings during the injury trial showed a more dorsi-flexed ankle position after IC compared to neutral flexion in the previous control trials of the same participant (Kristianslund et al., 2011). Therefore it seems that a position in less plantar-flexion or a dorsi-flexed position during landing is related to ankle sprains. In stiffer landing techniques (decreased passive and active flexion/extension range of motion (ROM)), the hip and ankle segments cannot sufficiently absorb the energy created during landing, consequently leading to high rates of strains on ligaments and tendons (Aerts et al., 2013; Lee et al., 2018). In healthy adults the ankle angle at

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IC primarily determines the ankle ROM (e.g. higher ankle plantar-flexion at IC, higher ankle ROM during landing) (Lee et al., 2018). However, it seems that on the one hand, a certain amount of stiffness is needed for higher performance (e.g. increased jump height, increased velocity), and on the other hand, too much or too little stiffness may be associated with bony or soft tissue injuries (Butler et al., 2003).

Due to the high incidence rate of ankle sprains (Bridgman et al., 2003) it is important to identify a modifiable risk factor to detect persons at risk of ankle sprains.

Hip-abductors, in particular the gluteus medius (GM) muscle, are important for the stabilization of the lower extremity and the pelvis during single-leg standing (Boren et al., 2011), gait (Gottschalk et al., 1989) and jumping (e.g. single-leg jumps/landings as well as drop and rebound jumps) (Kondo and Someya, 2016; Patrek et al., 2011; Powers, 2010). Several studies have investigated the effect of hip-abductor fatigue (or weakness) on single-leg balance tasks and found impaired postural control as well as a higher medial-lateral center of pressure displacement (Gribble and Hertel, 2004; Lee and Powers, 2014; Paillard, 2012; Salavati et al., 2007). Deficits of balance and postural control lead to an increased risk of ankle sprains (Fong et al., 2009) and thus, examining hip abductor strength as a modifiable parameter in relation with ankle sprains seems promising. Ankle sprains have previously been correlated with ipsilateral hip-abductor weakness (Friel et al., 2006) and a reduced vibration perception in the gluteal region (Bullock-Saxton, 1994), suggesting a direct connection between the hip-abductor muscles and ankle impairments. Contradicting findings were found for the influence of hip abductor strength as a predictor of ankle sprains. Whereas McHugh et al. (2006) found hip abductor strength not to be a risk factor for ankle sprains Powers et al. (2017) confirmed reduced isometric hip abductor strength as a predisposing factor for noncontact lateral ankle sprains.

In contrast to previous research on ankle sprains and hip abductor fatigue which mostly investigated frontal plane ankle kinematics during balance and jumping, sagittal ankle plane kinematics are barely studies. However, as ankle sprains occur during combined ankle movements, such as ankle inversion, adduction but also plantar-flexion (Petersen et al., 2013) or dorsi-flexion of the ankle (Kristianslund et al., 2011), a deeper knowledge of sagittal plane kinematics during jump landings is required to preventing and optimally treat ankle injuries.

Thus, we aimed to evaluate the influence of hip abductor fatigue on sagittal plane ankle kinematics and shank muscle activity during a single-leg forward jump.

Based on the above stated literature it was hypothesized that hip-abductor fatigue results in a decreased plantar-flexion at landing. We further hypothesized to find an increased activity of the tibialis anterior (TA) and decreased activity of the gastrocnemius (GC) muscles associated with the decreased plantar-flexion.

2. Methods

2.1. Participants

Twenty healthy, recreationally active adults, aged between 18 and 40 years were randomly recruited among the staff of the Geneva University Hospitals. Exclusion criteria included injuries of the lower extremity within the past year, chronic diseases and pain during the execution of the jumping task as well as the 30°abduction movement and medication that could potentially interfere with the ability to jump. Participants were instructed not to perform any sporting activities within the 24 h prior to testing. The study was conducted according to the Declaration of Helsinki. The local ethics committee approved the study protocol (CEREH, 13–066), and all participants provided written informed consent.

2.2. Data collection

Prior to the measurement procedure, the participants' dominant leg was identified as the leg with which he or she would kick a ball (Patrek et al., 2011). Subsequently, participants were instructed for the 25-cm (toe-to-heel distance) barefoot single-leg forward jump as well as the hip-abductor strength measurement and fatigue protocol (see section 'Tests'). Participants were given time to practice the jumps, the hip-abductor strength measurements and fatigue protocol. Because the measurement procedure had to start in a non-fatigued state, special attention was paid to the resting periods of at least five minutes between the practicing and the testing.

Participants performed the testing protocol in the following order: 1) recording of baseline surface electromyographic activity (sEMG) during the double-leg stance (to determine baseline muscle activity), 2) pre-fatigued single-leg forward jump, 3) measurement of the pre-fatigued maximal voluntary isometric contraction (MVIC) of the hip abductors of the dominant leg, 4) hip-abductor fatigue protocol, 5) measurement of the post-fatigue MVIC, 6) post-fatigue single-leg forward jump, and 7) fatigue verification MVIC to verify the participants' fatigue states at the end of the procedure. All post-fatigue tests (steps 5–7) had to be carried out within two minutes after the fatigue protocol because it was expected that full muscle strength recovery would occur within two to four minutes following the fatigue protocol (Salavati et al., 2007). Participants who exhibited more than 80% recovery from the pre-fatigue MVIC proportionately to the verification MVIC (Schwendner et al., 1995) were excluded for further analysis.

To assess kinematics during the jumps, participants were equipped with 10 reflective markers on the dominant leg and six additional markers on the upper body (Davis et al., 1991; Gutierrez-Farewik et al., 2006), which were tracked with a sampling rate of 100 Hz using a 12-camera motion capture system (type MX3 +, Vicon, Oxford, UK). The sEMG of the gluteus medius (GM), peroneus longus (PL), lateral gastrocnemius (GC) and tibialis anterior (TA) muscles were recorded via a bipolar surface EMG (sEMG) system (Aurion Zero Wire, Milan, IT) using fixed 20 mm inter-electrode (silver/silver chloride) spacing, input impedance of 10 MOhms, a common mode rejection ratio of 90 dB, and signal to noise ratio > 50 db. The sEMG raw signals were sampled at 1000 Hz. A gain of 1000 was used to increase signal amplitude of EMG; a 12 bit A/D converter produced an output in a digital format. Data was stored using the Nexus VICON software in C3D format. After skin preparation by local, gentle abrasion, shaving if necessary and disinfection with alcohol, the surface electrodes were placed on GM, PL, GC and TA in accordance with the SENIAM guidelines (Hermens et al., 2000).

The instant of the IC was defined using a force plate (AMTI, Watertown, MA, US, sampling rate: 1000 Hz).

2.3. Tests

2.3.1. Single-leg forward jump

Participants were asked to stand on the dominant leg and then to perform a 25-cm single-leg forward jump onto the force plate and to stabilize the jump for five seconds after landing.

2.3.2. Hip-abductor fatigue protocol

The hip-abductor fatigue protocol was performed twice in a row (round one and round two) until complete fatigue of the hip abductors was achieved. Participants were positioned in a side-lying position with the non-dominant leg placed at 45° of hip and 90° of knee flexion to ensure a stable position (Patrek et al., 2011) and to avoid compensation (Fig. 1a) (Widler and Glatthorn, 2009). Participants were asked to abduct the dominant leg and to touch the bar (corresponding to 30° of abduction) at a rate of 60 times per minute. When they were no longer able to keep up with this rhythm or to reach the 30° abduction bar two times in a row (Patrek et al., 2011), they were allowed to rest for 30 s (round one). Thereafter, the protocol was repeated (round two) to

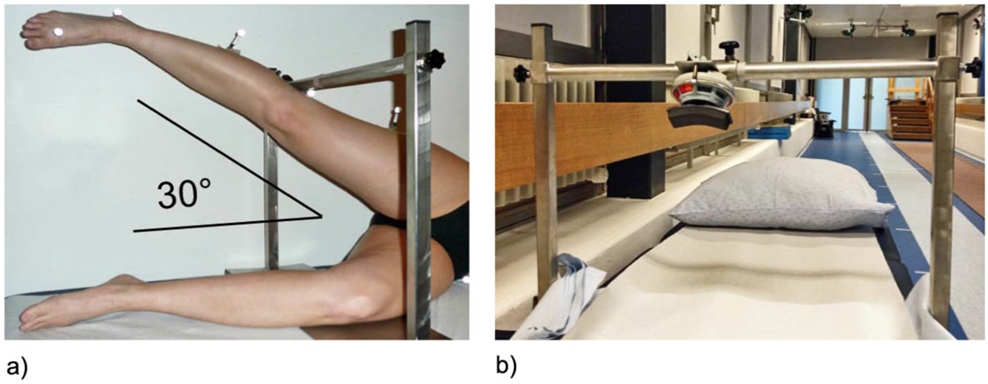

Fig. 1. (a) adjustable frame with abduction bar to guarantee 30° hip abduction during the fatigue protocol; (b) adjustable frame with abduction bar and adjustable dynamometer to measure the MVIC.

ensure that the hip abductors were completely fatigued. Round two was stopped according to the same criteria as round one, thereafter the participant directly proceeded to the measurement of the post-fatigue MVIC. No recovery was allowed after the second round of the fatigue protocol. During the testing procedure strong verbal encouragement was given.

2.3.3. Assessment of MVIC

Hip-abductor strength was quantified by measuring the MVIC in the side-lying position. Participants pushed in a 10° hip-abduction position against a dynamometer (Hogganhealth, microFET2® wireless, US) that was fixed to a custom-built, adjustable frame (Fig. 1b). The dynamometer was placed 5 cm proximal to the knee joint gap (Click Fenter et al., 2003). This measurement setting was previously shown to be valid and reliable (Click Fenter et al., 2003; Widler and Glatthorn, 2009). To determine the MVIC, participants were asked to abduct the dominant leg, push against the dynamometer as hard as possible and hold the contraction for 5 s. Participants were thereby instructed not to externally rotate the leg, to keep it straight and to have the hip in a neutral to slightly extended position to avoid compensation with other muscle groups (Jacobs et al., 2005; Patrek et al., 2011; Widler and Glatthorn, 2009). The MVIC measurement session at baseline consisted of three repetitions, whereby the highest value was retained for the analysis (Widler and Glatthorn, 2009). For the post-fatigue MVIC as well as the verification MVIC, only one trial was performed to complete the entire testing procedure within two minutes.

2.4. Data reduction

Sagittal-plane ankle kinematics were established according to the Plug-in Gait model using the software Nexus 1.8.5 (Vicon, Oxford, UK).

The sEMG signals were high-pass filtered with a cut-off frequency of 30 Hz (fourth-order Butterworth) (Patrek et al., 2011), full-wave rectified and subsequently low-pass filtered with a cut-off frequency of 6 Hz (fourth-order Butterworth) using a custom-built MATLAB routine (version R2012a, The MathWorks, MA, USA). We then normalized the sEMG to the peak sEMG value recorded during the pre-fatigue single leg jump (Chapman et al., 2010).

The kinematic and EMG data were analysed within a 200 ms window prior to the IC, at the moment of the IC and within a 250 ms window after the IC (Carcia and Martin, 2007). The following parameters were extracted: maximum (position of the ankle that is most into the dorsi-flexed direction) and minimum (position of the ankle that is most into the plantar-flexed position) sagittal-plane ankle angles with their respective occurrence times, as well as the peak and average sEMG activity of GM, PL, GC and TA with their respective occurrence times. Muscle onset time was calculated as the moment where the EMG signal exceeded five standard deviations of the mean baseline sEMG activity (Patrek et al., 2011) assessed by the baseline sEMG during the double-leg stance.

Positive kinematic values of the ankle in the sagittal plane are designated to dorsi-flexed positions, negative values to plantar-flexion.

2.5. Statistical analysis

Statistical testing was carried out using SPSS® version 22.0 for Mac (IBM Chicago, IL, USA). As data were not normally distributed (Shapiro-Wilk test, $p \leq 0.05$), differences due to the hip-abductor fatigue protocol as well as the sub analyses between males and females were investigated using the Wilcoxon signed-rank test with the significance level set at $p \leq 0.05$.

3. Results

A 34 years-old female participant had to be excluded due to a fatigue recovery of 83.6%. Therefore, all analyses were based on 19 participants (female-male ratio: 8/11, mean age: 30.3 SD 4.0 years, mean body mass index [BMI]: 23.6 SD 2.8 kg/m^2), whereby 17 participants indicated the right leg as the dominant leg. No differences were found between males and females for the kinematic and muscle activity parameters.

3.1. Hip-abductor fatigue

In the first round of the fatigue protocol, the participants were fatigued after a median time of 343 s [25th and 75th percentile; Q_{25}: 225, Q_{75}: 456], and in the second round of the fatigue protocol after 190 s [81, 300]. All participants completed the jump tests within 101 s [95, 106] and therefore fulfilled the criterion of performing all post-fatigue tests within two minutes. Between pre-fatigue (280.3 N [244.7, 356.0]) and post-fatigue MVIC (106.8 N [84.6, 155.7]), the force decreased by 62% ($p < 0.001$). At the verification MVIC (173.5 N [142.4, 213.6]) at the end of the tests, the participants showed on average still 38% less force as compared with the pre-fatigue values ($p < 0.001$).

3.2. Ankle kinematics

Following the fatigue protocol, the maximal ankle angle prior to IC decreased by 3.8° [0.1, 7.2] and at IC by 4.1° [−0.3, 5.0] towards a less plantar-flexed position ($p = 0.014$ and $p = 0.027$ respectively) (Table 1, Fig. 2). After IC, a decrease of the minimal ankle angle of 4.1° [−1.3, 5.0] in a less plantar-flexed position ($p = 0.036$) was observed.

No differences were found for maximum angle occurrence time, minimum angle and minimum angle occurrence time prior to IC as well as maximum angle, maximum angle occurrence time and minimum angle occurrence time after IC.

Table 1
Kinematic results for maximal/minimal ankle angles, and maximal/minimal ankle angle occurrence time's pre-fatigue/post-fatigue −200 ms before, at the IC and +250 ms after the IC.

		Pre-fatigue	Post-fatigue	
Time point	Ankle variables	Median [Q_{25}, Q_{75}]	Median [Q_{25}, Q_{75}]	P-value
200 ms window prior to IC	Max angle (°)	−8.0 [−13.2, 3.9]	−3.1 [−6.6, 2.7]	0.014*
	Max angle occurrence time (ms)	−50 [−130, 0]	−100 [−200, 0]	0.373
	Min angle (°)	−17.2 [−25.4, −6.4]	−11.7 [−18.2, −9.2]	0.070
	Min angle occurrence time (ms)	−60 [−200.0, −40.0]	−150 [−180.0, −30.0]	0.602
At IC	Angle at landing (°)	−9.6 [13.8, 2.0]	−6.0 [−10.5, 1.7]	0.027*
250 ms window after IC	Max angle (°)	18.9 [16.7, 22.3]	17.2 [15.9, 21.6]	0.778
	Max angle occurrence time (ms)	160.0 [140.0,230.0]	150.0 [130.0,250.0]	0.815
	Min angle (°)	−9.6 [−13.8, 0.6]	−6.0 [−10.5, −0.6]	0.036*
	Min angle occurrence time (ms)	0 [0, 0]	0 [0, 0]	1.00

* $p < 0.05$, significant difference pre- to post-fatigue. Negative values: plantar-flexion, positive values: dorsi-flexion of the ankle. IC: initial contact, Q_{25}: 25th percentile, Q_{75}: 75th percentile

3.3. Muscle activity

The normalized sEMG data for GM, TA, GC and PL as well as the muscle activity onset and the peak occurrence times are presented in Table 2. A later onset was observed for the activity of the GC muscle (pre-to post-fatigue difference: 28.0 ms [0.0, −44.0], $p < 0.01$). In addition, TA average activity prior to IC increased after the hip abductor fatigue protocol (pre- to post-fatigue difference: 4.2% [−2.9, 23.3], $p < 0.05$). The normalized sEMG activity curves for pre- and post-fatigue are presented in Fig. 3. No further differences for the muscle activity parameters were found.

4. Discussion

This study's aim was to assess the effect of hip-abductor fatigue on sagittal-plane ankle kinematics and shank muscle activity during a single-leg forward jump. Overall, the participants showed a significant reduction in ankle plantar-flexion at landing after hip-abductor fatigue. In addition, we observed a later onset of GC activity and an increased TA activity.

These findings confirmed our hypothesis, which predicted a decreased plantar-flexion position. It might be that with the decreased plantar-flexion at landing participants adopted a stiffer landing technique (decreased active ROM) after hip-abductor fatigue, which was previously reported to be associated with a higher risk of lower-limb injuries due to the decreased absorption and energy dissipation of the forces generated during jump landings (Aerts et al., 2013; Lee et al., 2018).

The decreased plantar-flexion of the ankle during jump landings was also observed in a previous study (Webster et al., 2016). In contrast to the above mentioned studies (Aerts et al., 2013; Friel et al., 2006), Webster et al. (2016) postulated that the decreased ankle plantar-flexion at IC was an injury prevention strategy, as ankle injuries mostly occur in positions with ankle inversion, adduction and plantar-flexion (Petersen et al., 2013). They interpreted the decreased plantar-flexion at landing as a strategy for preventing ankle sprains, as the dorsi-flexed position of the ankle brings the lateral ligament into a position with less injury potential (Caulfield and Garrett (2002)).

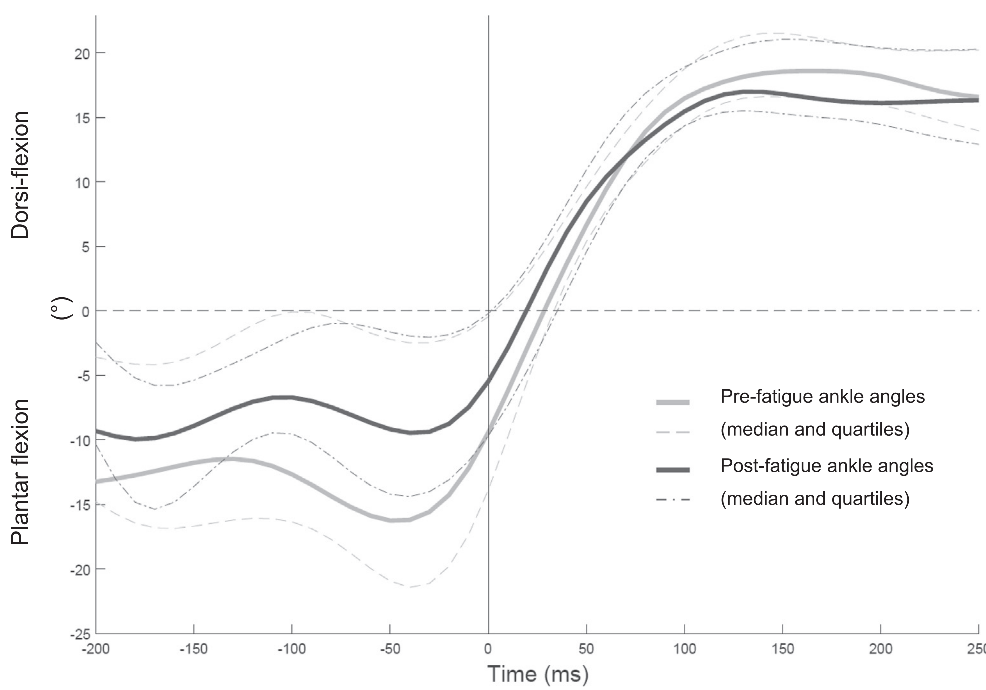

Fig. 2. Ankle kinematics, medians and quartiles of pre-fatigue (light grey with Q_{25} and Q_{75} in dashed light grey) and post-fatigue (dark grey with Q_{25} and Q_{75} in a dark grey dash-dotted line) ankle angles during the timeframe of 200 ms before IC to 250 ms after IC.

Table 2
sEMG activity for peak and average in the 200 ms window pre initial contact (IC), at IC and in the 200 ms after IC. The sEMG peak, average and at IC are normalized to the peak value reached during the pre- fatigue trial for gluteus medius, tibialis anterior, gastrocnemius lateralis and peroneus longus; and presented in %.

		Gluteus medius			Tibialis anterior			Gastrocnemius lateralis			Peroneus longus		
		Pre-fatigue	Post-fatigue	p value	Pre-fatigue	Post-fatigue	p value	Pre-fatigue	Post-fatigue	p value	Pre-fatigue	Post-fatigue	p value
		Median	Median		Median	Median		Median	Median		Median	Median	
		Q_{25}, Q_{75}	Q_{25}, Q_{75}		Q_{25}, Q_{75}	Q_{25}, Q_{75}		Q_{25}, Q_{75}	Q_{25}, Q_{75}		Q_{25}, Q_{75}	Q_{25}, Q_{75}	
Onset		−169.0 −200.0, −75.0	−175.0 −200.0, −30.0	0.25	−136.0 −200.0, −73.3	−113.5 −200.0, −47.5	0.53	−131.0 −175.5, −105.5	−105.0 −132.0, −71.0	**0.01***	−110.0 −143.0, −48.0	−106.0, −182.0, −57.0	0.48
200 ms window prior to IC	Peak (%)	87.3 69.5, 100.0	88.8, 35.0, 197.6	0.30	52.8 34.6, 100.0	62.4 42.3, 135.2	0.06	94.1 56.7, 100.0	64.1 43.4, 100.8	0.87	55.3 41.7, 69.9	49.6 35.7, 8.5	0.97
	Time peak (ms)	−64.0 −126.0, −30.5	−100.0 −120.5, −50.3	0.47	−188.0 −200.0, −25.5	−174.0 −184.0, −155.0	0.28	−26.0 −50.0, −8.5	−35.5 −65.3, −29.0	0.07	−42.5 −62.5, −20.3	−31.0 −63.0, −18.3	0.22
	Mean (%)	41.0 32.1, 51.5	41.7 20.8, 81.2	0.55	19.3 14.9, 33.5	29.0 18.5, 34.8	**0.04***	33.9 21.1, 41.2	21.4 14.4, 37.5	0.11	23.7 18.4, 31.0	22.1 15.3, 31.4	0.15
At IC	(%)	38.2 31.4, 64.5	36.0 17.6, 64.5	0.81	32.6 20.7, 34.3	21.8 12.1, 33.0	0.26	46.6 25.9, 72.7	37.6 14.7, 70.2	0.55	33.5 26.9, 44.0	31.1 19.2, 49.2	0.52
250 ms window after IC	Peak (%)	100.0 84.5, 100.0	113.1 48.7, 308.4	0.09	100.0 97.0, 100.0	106.0 50.7, 191.3	0.21	100.0 75.3, 100.0	101.9 37.6, 142.8	0.42	100.0 100.0, 100.0	84.5 62.1, 164.4	0.90
	Time peak (ms)	42.0 33.0, 57.0	50.0 34.0, 84.0	0.63	161.0 88.0, 225.0	152.0 107.0, 190.0	0.71	82.0 43.0, 146.0	73.0 65.0, 134.0	0.63	121.0 78.0, 151.0	103.0 69.0, 149.0	0.46
	Mean (%)	40.7 33.7, 51.4	51.9 19.9, 119.5	0.08	43.4 37.2, 48.6	45.6 26.0, 77.1	0.16	35.9 28.4, 45.4	36.3 16.7, 54.9	0.75	48.4 40.7, 55.2	46.7 27.0, 61.9	0.78

Q_{25}: 25th percentile, Q_{75}: 75th percentile.
* = $p < 0.05$.

The question whether kinematic changes observed after hip-abductor fatigue are rather injury endangering or just a preventive strategy remains open. The non-examined kinetic changes as well as the absence of knee, hip and trunk kinematics in our study do not yet allow a final conclusion about this issue.

After hip abductor fatigue the later onset of the GC muscle activity as well as the increased TA average activity prior to IC lead to a less plantar-flexed position at landing. The TA is the muscle that is most responsible for the dorsi-flexion of the foot (Webster et al., 2016). Corresponding to our findings, Webster et al. (2016) also found a higher post-fatigue activation of the TA and no significant changes for the PL. However, Lee and Powers (2014) found an increased PL activation and no significant difference of TA in the participants classified in the weak hip-abductor group compared with their participants with strong hip abductors. Nevertheless, they observed an increase in TA activity in the weak hip-abductor group, but this change was not statistically significant. The difference of their results and ours may be the result of a more challenging jumping task in our study compared with the balance task performed in their study (Lee and Powers, 2014). Our participants further had to react to hip-abductor fatigue that was induced directly

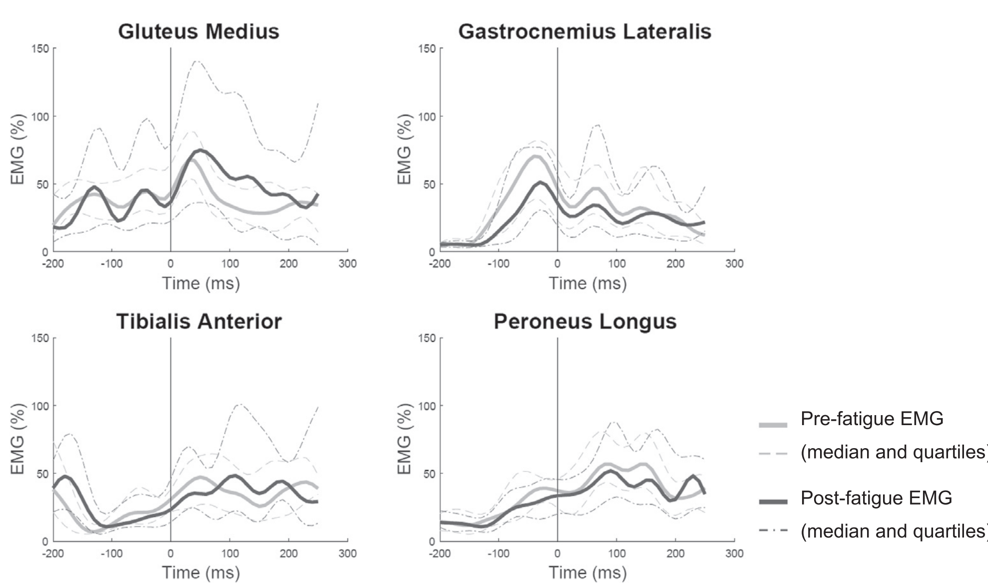

Fig. 3. sEMG curves for gluteus medius, tibialis anterior, gastrocnemius lateralis and peroneus longus during the timeframe of 200 ms before IC to 250 ms after IC, pre- (light grey with Q_{25} and Q_{75} in dashed light grey) and post-fatigue (dark grey with percentiles Q_{25} and Q_{75} in dark dash-dotted grey).

before the jump, might resembling muscle fatigue occurring during sporting tasks, whereas their participants may have found compensation strategies due to their permanent hip-abductor weakness.

A strength of this study is the examination of an ankle sprain-related, sport-specific landing task. Second, we checked if our participants remained fatigued for at least 80% of the pre-fatigue MVIC. Therefore, we can confirm that the changes in EMG activity and ankle kinematics were due to hip-abductor fatigue. Further, in previous studies, the influence of hip-abductor fatigue was often assessed retrospectively, and it was a challenge to know if the observed changes of hip-abductor strength led to ankle sprains or if the changes occurred to protect the ankle after hip-abductor weakness. In our study, we assessed the same participants before and after a hip-abductor fatigue protocol. Consequently, we were able to examine the direct influence of hip-abductor fatigue and sagittal-plane ankle kinematics as well as sEMG activities. Finally, the normalization of our sEMG data to the peak sEMG activity pre-fatigue is a good and adequate evaluation technique for amplitude comparisons within the same subject, in a short time interval and the same experimental conditions without changes to the sEMG electrodes (Halaki and Ginn, 2012). However, it limits the direct comparison of our results to other studies using different normalization methods.

A limitation was the assessment of the ankle kinematics on the sagittal plane only, whereas ankle sprains occur in combined ankle movements (Petersen et al., 2013). The small kinematic changes assessed with a three-dimensional motion analysis system also remains a limitation. When interpreting our significant but small ($< 5^{\circ}$) kinematic changes, the potential measurement error of 2° that McGinley et al. (2009) stated should, as well as in other studies, be considered for the clinical interpretation of the study results.

Furthermore, we did not distinguish between the recreationally performed sport activities of our participants. The jump and landing strategies could be influenced by this fact and be a source of bias. The push-off phase, although not assessed in our study, is also an important element of a jump and might has influenced the landing. Our small sample size might also have influenced the study results. Finally, for some participants, an unanticipated movement task, instead of the single-leg forward jump, would have created even more realistic situations occurring during sport activities (side step, cutting, unanticipated jumps), in which ankle sprains occur and would have provoked more dynamic movements and may have led to larger kinematic and EMG changes after hip-abductor fatigue.

The influence of hip-abductor fatigue on ankle sprains should further be studied. A prospective trial would allow insight into further mechanisms and/or muscle weaknesses that should be trained by physical therapists to prevent future ankle sprains. Assessing not only kinetic and kinematic changes of the ankle but also those of the knee, hip and trunk while examining potential injury risk/mechanisms of the ankle would help to better understand the landing strategies that participants adopt.

In conclusion, induced hip-abductor fatigue resulted in a significant decrease of plantar-flexion and in a later onset of GC muscle activity during a single-leg forward jump. In addition, the TA muscle average activity before the IC increased. Therefore, it can be postulated that hip-abductor fatigue influences the sagittal plane position of the ankle during challenging tasks. Whether these changes lead to an increased injury risk or, on the contrary, to possible injury prevention cannot yet be concluded with these findings.

5. Authorship

All authors substantially contributed to the conception of the study, analyses and interpretation of the data, drafting and revising this article. All authors read and approved the final manuscript.

Conflict of interest

The authors state no conflict of interest.

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