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Muscle activity during locomotion in various inclination surfaces and different running speeds.

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ABSTRACT

During dynamic activities – walking, jogging and running, muscular function is affected by running techniques and foot strike patterns, inclined surfaces and running speed. In order to assess muscle function during these activities, most studies examine certain muscles such as tibialis anterior, gastrocnemius (lateral and medial), soleus, rectus femoris, vastus (medialis and lateralis), hamstrings (biceps femoris, semimembranosus, semitendinosus), and gluteus. These muscles are commonly selected because they provide supportive and propulsive forces during running. Results of these studies may conclude to special training programs for runners in order to improve their performance.

KEYWORDS: Running; muscle activation; running surfaces; running speeds

Introduction

Running is a popular physical activity and a key element in most conditioning programs. At each running step, when the foot strikes the supporting ground, a ground reaction force (GRF) of two- or three-times body weight is generated [6] inducing shock waves that propagate throughout the locomotor system. The load resulting from ground reaction forces magnitude influences mechanical function of the musculoskeletal system and muscle activation patterns.

During dynamic activities – walking and running, muscular function is affected by running techniques and foot strike patterns, inclined surfaces and running speed. Inclined support surfaces affect the control of movement in terms of the maintenance of an

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upright posture [22], the foot strike patterns used and the related centre of pressure in anterior – posterior direction during stance, and muscles activity [24]. Sasagawa [40] assessed the active stabilization mechanisms on an inclined surface during quiet standing and found that muscle activity changed as a function of support surface conditions.

In order to assess muscle function during running, most studies examine the following muscle groups: tibialis anterior, gastrocnemius (lateral and medial), soleus, rectus femoris, vastus (medialis and lateralis), hamstrings (biceps femoris, semimembranosus, semitendinosus), and gluteus. These muscles are selected because they provide supportive and propulsive forces during running [21].

Effects of foot strike pattern and inclined surfaces on muscle activity

The work performed by muscle groups is partially affected by the foot strike pattern adopted during locomotion [1,16,50]. According to the heel and metatarsal positioning at landing, three foot strike patterns have been identified: rearfoot strike (RFS) in which the heel lands before the ball of foot, midfoot strike (MFS) in which the heel and the ball of foot lands almost simultaneously, and forefoot strike (FFS) in which the ball of foot lands before the heel [17].

Muscle activity differs depending on foot strike pattern. During level running, anterior patterns (MFS and FFS) are associated with greater plantar flexion and knee flexion at initial contact and with higher gastrocnemius lateralis activity and lower tibialis anterior and vastus lateralis activity compared to posterior patterns (RFS) [1,16,42,47,50]. When adopting a forefoot strike running technique, a more compliant ankle and stiffer knee were observed during the stance phase, resulting in a greater negative work at the ankle and a lower negative work at the knee in forefoot strike patterns compared to rearfoot strike patterns [20]. Giandolini [16] reported that adopting a midfoot strike pattern, in order to reduce loading rate during running, resulted in a higher muscular activity of the gastrocnemius lateralis during the pre-activation phase but not during the support phase. It has also been observed that in high – mileage runners the muscular activity of the gastrocnemius lateralis during the support phase was reduced compared to asymptomatic controls [4]. Probably, the pre-activation of the gastrocnemius lateralis is in fact necessary in midfoot strike running technique since the plantar flexors need to counteract the dorsiflexor moment created during the midfoot strike pattern [16].

An earlier, longer and greater plantar flexors (PF) activity, lower dorsiflexor activity, and greater biceps femoris activity have been observed when running with a forefoot strike (FFS) pattern [1,16,50]. Runners adopting a forefoot strike pattern activated their plantar flexors muscles 11% earlier and 10% longer than runners with a rearfoot strike pattern. Specifically, the activation phase of medial gastrocnemius (MG) occurred 7.7-16.3% of the gait cycle earlier and lasted on average 9.7% longer for the forefoot strike runners compared to rearfoot strike runners, at all speeds (2.5, 2.8, 3.2 and 3.5m/sec). A similar trend was observed for the activation phase of lateral gastrocnemius (LG) as well. Forefoot strike runners activated their lateral gastrocnemius muscles 7.7-13.1% of the gait cycle earlier and 6.3-14.3% longer than rearfoot strike runners at all speeds. However, calf muscles deactivation time was not influenced by running technique. This earlier and longer relative activation of the plantar flexors is likely associated with an improved capacity for elastic energy storage [1].

Differences in muscle activity between rearfoot and forefoot strike running patterns were also identified while running on a treadmill at a speed of 4m/sec [50]. Muscle activity was assessed just prior to and after foot contact – an instant with significant kinematic differences between strike patterns [3,29]. In accordance with other studies, results revealed that forefoot strike running pattern was associated with lower tibialis anterior and higher gastrocnemius (MG and LG) muscle activity during late swing phase, compared to rearfoot strike patterns. Additionally, the muscle activity of vastus medialis and lateral hamstrings, during late swing phase, was lower in forefoot strike runners

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compared to rearfoot strike runners. Muscle activity recorded during early stance phase presented no significant differences between forefoot and rearfoot strike patterns. The muscle activity of soleus – during the early stance phase – was lower in forefoot strike runners; however this difference was not significant. Although forefoot strike pattern is related to a greater knee flexion angle at foot contact compared to rearfoot strike pattern, rectus femoris activity during either the late swing or early stance phase presented no significant differences between foot strike patterns [50]. This finding is in contrast with the results of Shih [42] who reported that rearfoot strike runners had greater muscle activity in the rectus femoris during swing phase when adopting a forefoot strike running pattern.

Similar results about foot strike patterns and related muscle activation patterns are reported during running at inclined surfaces. Running at inclined surfaces influences lower limb joint function and muscle activity. Hill running at different slopes and varied surfaces is a commonly used method in training programs for distance runners.

Downhill running is characterized by eccentric contractions with the associated mechanical stress and consequently causes damage within the muscle fiber cytoskeleton, delayed-onset muscle soreness and decreased muscle function [30,35]. Downhill running also influences running economy and running kinematics. Chen [8] reported that running patterns were modified (step frequency was increased, ankle and knee joints range of motion was decreased) up to three days after a downhill run. Kinematic changes observed after downhill running might be due to reduced stretch reflex sensitivity and contractile failure resulting from tissue damage.

During downhill trail run, the more posterior the foot strike (rearfoot strike – RFS), the higher the tibialis anterior (TA) and vastus lateralis (VL) activities but the lower the gastrocnemius lateralis (GL) activity. Conversely, anterior patterns (MFS and RFS) are associated with higher gastrocnemius lateralis (GL) activity and lower tibialis anterior (TA) and vastus lateralis (VL) activities [16,17]. Root mean square (RMS) values from raw electromyography (EMG) signals, recorded during the 6.5km downhill run, were 28.2 ± 14.5% of RMSmax for vastus lateralis, 23.5 ± 10.3% for biceps femoris, 28.1 ± 12.0% for gastrocnemius lateralis and 35.9 ± 18.0% for tibialis anterior [17].

The lower vastus lateralis activity observed with anterior patterns may be associated with less pronounced knee extension at initial contact which may decrease vastus lateralis pre-activation [42] and /or with a negative work developed by knee extensor muscles during the braking phase [20]. In contrast, the higher vastus lateralis activity when rearfoot striking may be related to further alterations in sarcolemma excitability at knee extensors during downhill running [17].

Adopting a forefoot strike pattern during downhill running could induce greater plantar flexors fatigue and damage by increasing their recruitment, and alternatively reduce knee extensors fatigue and damage by decreasing their contribution during the energy absorption phase. Increasing plantar flexors fatigue or damage in downhill sections could affect performance in the subsequent uphill sections, where the work performed at the ankle is substantial [38]. Trail running, which is characterized by large positive and negative inclined surfaces, may mainly cause greater alterations of muscle function in plantar flexors than in dorsiflexors, as has been observed after a 5h hilly run [13].

Changing foot strike pattern could modulate the eccentric work done by knee extensors and plantar flexors during downhill running, affecting this way the severity of muscle fatigue and damage observed in these muscle groups after downhill sections [17]. It is speculated that altering muscle activation patterns by switching between running techniques and foot strike patterns could better distribute the mechanical load and the muscular work done to the lower-limb muscles [1,16,42,47].

While during level running - at a constant speed - the mechanical work required by limb muscles is negligible, uphill running is characterized by increased demands for muscle mechanical work / muscle function in order to increase the body potential energy [38]. It is suggested that the most of the work necessary to perform uphill running is produced at the hip joint, while the knee and ankle joints performed similar functions at all inclines (0º, 6º, 12º). Mechanical work produced at the hip joint increased significantly with increasing running incline, as a result of either an increase in the moment of muscle force developed by hip extensors or through power transfer by knee extensors to the hip via the hamstrings [38]. Sloniger [43,44] also reported an increased muscle activity (based on MRI) in knee extensors with increasing running incline.

Muscle function during locomotion at different running speeds

Assessing muscle activation profiles during locomotion at different speeds, it appears that many muscles show a similar profile in running as in walking. During running, basic patterns of EMG activity presents an almost simultaneous activation of leg extensors. The onset of activation occurs before foot contact with the quadriceps activation being observed first, followed by the calf muscles, as a function of joint kinematics (maximum knee flexion occurs earlier than maximum ankle dorsiflexion). This part of the extensor activation goes along with a co-contraction of the hamstrings for the knee and of tibialis anterior for the ankle. Muscles activation (burst) end before toe-off, however muscle force continues for sufficient time after the end of activation to cover the complete stance phase [15].

Specifically, Gazendam & Hof [15] assessed averaged EMG patterns during locomotion at different speeds (1.25-2.25m/sec: walking and jogging, 2.5-4.5m/sec: running). EMG profiles were recorded separately for tibialis anterior (TA) and adductor magnus (AM) muscles and for the following muscle groups: 1) a quadriceps group: vastus medialis (VM), vastus lateralis (VL), and rectus femoris (RF), 2) a hamstring group: biceps femoris (BF), semitendinosus (ST) and semimembranosus (SM), 3) a calf group: soleus (SO), gastrocnemius medialis (GM), gastrocnemius lateralis (GL) and peroneus longus (PL), 4) a gluteal group: gluteus maximus (GX) and medius (GD). EMG profiles were determined by the timing (in relation to the gait cycle) and amplitude of activation.

Results revealed that during running at speeds from 2.25m/sec to 4.5m/sec, the EMG activity for the quadriceps group started before foot contact (80% of the gait cycle) and ended at about midstance (115%). Although the profiles were very similar, small differentiations were observed with speed. For the vastii muscles (VM, VL), the EMG amplitude increases for walking and jogging (speeds: 1.25-2.25m/sec), while during running at higher speeds (2.5-4.5m/sec) it presents a more constant form with higher peaks. The amplitude of activation in jogging and running is always higher than in walking. Rectus femoris (RF) presents an earlier onset of activation at about 40 - 70% before foot contact. As speed increases, the onset of activation occurs from 47% at a speed of 2.25m/sec to 37% at 4.5m/sec and EMG amplitude increases as well.

During running the EMG profiles of the hamstring group (BF, ST, SM) present two peaks. The first peak was recorded in the second half of swing, 70-100% of the gait cycle, while the second peak was recorded in stance, 6-30% of the gait cycle. Activation profiles of the three hamstring muscles presented differentiations with speed dependence. In SM both peaks appeared to be constant, while in ST both peaks increased. In BF the first peak increased, while the second peak showed maximum activity at 3m/sec and decreased at higher speeds. During walking, the same two-peaked activation pattern was recorded, with a 10% later onset of activation. The jogging profile presents the same timing pattern of walking, but with higher amplitude.

The EMG profile of the calf group (SO, GM, GL, PL) showed a single activation peak, similar to the quadriceps peak but with 10% later onset of activation. Muscles activity started shortly before stance (86%) and ended before toe-off (125%). It seems that during running, an almost simultaneous activation of quadriceps and calf group is observed which is associated with an energy absorption and production process. In contrast, during walking the activation peak was recorded at the end of stance (26-55%) as such impact absorption and push-

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off are separated in time and done separately by quadriceps and calf. With increasing running speed from 2.25-4.5m/sec, the activation amplitude of soleus and peroneus longus remained constant, while gastrocnemius medialis and lateralis amplitude increased at about 40%.

The gluteus muscles (GX, GD) profile, recorded during running, showed two peaks. The first peak is similar for both gluteus maximus and medius, and its timing occurs from 88% to 118% of the gait cycle. A constant amplitude for GD is appeared, while the amplitude of activation linearly increases with speed in GX. The second peak is observed at mid-wing (60-84% of the gait cycle) for the GX, and at the transition from stance to swing (30-50%) for the GD. Both muscles activation amplitude increased with speed. Walking patterns appeared to be similar with those of running, with the exception of GX second peak which was lower and the amplitude of GD which was lower as well.

The EMG activity of the tibialis anterior (TA) extended over the complete swing phase. During running, it started before toe-off (27%) and ended abruptly at heel contact (100%), with a peak in final swing at 90%. In walking, TA activity started later and extended into stance, with a peak at heel contact.

During running at speeds higher than 3m/sec, the EMG activity for the adductor magnus (AM) shows three peaks: in midstance (18%), in midswing (68%) and in final swing (90%). At lower running speeds, EMG activity is low and irregular. The walking profile is different from running, presenting peaks at foot contact (0%) and toe-off (57%).

A study [2] for the hip flexors (iliacus, psoas, sartorius, rectus femoris and tensor fasciae latae) activity during running revealed that all hip flexors were active from about 30-65% of the gait cycle. The rectus femoris activation recorded slightly later (45-65%) which is in accordance with the results of Gazendam and Hof [15], suggesting that RF function is more as a hip flexor than as part of quadriceps (knee extensor). Psoas showed a second peak in late swing, 80-100%. Tensor fasciae latae activity was recorded during stance and early swing (0-50%), supporting the idea of not being a hip flexor. The activation amplitude of iliacus and psoas sharply increased with running speed.

Running speed appears to "interact" with leg muscles contribution to joint and body segment accelerations during dynamic locomotion [9]. Activation patterns of calf muscles (medial gastrocnemius and lateral gastrocnemius) were affected by running speed. When running on a motorized treadmill, runners activated and deactivated both medial (MG) and lateral (LG) gastrocnemius muscles earlier in the step as they run faster (running speed: 2.5, 2.8, 3.2 and 3.5m/sec). Additionally, the activation amplitudes of medial and lateral gastrocnemius increased with increasing running speed (Ahn et al., 2014).

Kyrolainen [26] assessed electromyographic (EMG) activity of the leg muscles (gluteus maximus, vastus lateralis, biceps femoris, gastrocnemius and tibialis anterior) and the ground reaction forces, in 17 elite male middle–distance runners, during running at different speeds. The results showed that the averaged EMG activities of all the muscles increased with increasing running speed, especially in the pre-contact and braking phases.

As running speed increased from 3.5-7 m/sec, the ankle plantarflexors (soleus and gastrocnemius) were mainly responsible for generating higher vertical support forces during ground contact, contributing this way in step length increment. At higher running speeds –above 7m/sec, peak forces developed by soleus and gastrocnemius decreased, while hip muscles – iliacus and psoas combined (ILPSO), gluteus maximus, hamstrings and rectus femoris – generated increased forces and contributed in a vigorous acceleration of hip and knee joints during swing phase, increasing this way step frequency [9].

During level running at moderate speed, hip muscles generate low forces which might reflect a strategy for minimizing metabolic energy cost [38] on the basis of the design of the musculoskeletal system which has been shaped by the need to produce force economically [39,45]. However, during very fast level running (at an exercise intensity equivalent to 115% of peak oxygen uptake), a very high

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level of activity of all of the hamstrings, gluteal and adductor muscles was observed [43]. During uphill running at high speed, the vastus medialis and lateralis and the rectus femoris muscles found to be more active compared to level slow running [49].

Liebenberg [28] investigated how lower extremity muscles are influenced by body weight support during running at different speeds. Muscle activity from the biceps femoris, rectus femoris, tibialis anterior and gastrocnemius was recorded during running on a treadmill, which provided body weight support, at different speed and body weight conditions. Results revealed that muscle activity (average EMG and root mean square EMG) decreased as body weight decreased for all muscles, without however changing muscle activity patterns, and increased across speed for all muscles.

Comparison between treadmill and over-ground running

Treadmills have often been used to investigate human locomotion (walking and running) and to evaluate performance parameters. Treadmill running is a popular training method for distance runners, as it is characterized by decreased ground reaction forces [36] and less stress / load propagated to their bodies compared to over-ground running. When running on a treadmill, the supporting ground (the treadmill belt) is moving relatively to subjects centre of mass (CM), which is opposite to real world bipedal locomotion where subjects centre of mass moves relatively to the supporting ground [33]. As such, many studies have investigated the differences between over-ground / field and treadmill conditions, attempting to answer the question whether over-ground locomotion could be interpreted and related in light of the measurements performed on treadmill.

Comparing over-ground and treadmill running, it was found that in both conditions running step was quite similar. However, differences concerning the kinematic and kinetic parameters were observed [36]. The average speed for instrumented treadmill running (3.80m/sec) was similar compared to the average over-ground running speed (3.84m/sec). The cadence (number of steps / min) was significantly higher and the step time and step length were significantly shorter for the instrumented treadmill running condition. Concerning the angular kinematics, peak knee angles were significantly different between treadmill and over-ground running [36]. The above findings are similar with the results from previous studies [11,41,46]. Elliott & Blanksby [11] reported a shorter unsupported (flight) phase, decreased step length and increased cadence in moderate speeds (3.3-4.8 m/sec) when running on a treadmill compared to over-ground running. Frishberg [14], comparing over-ground (mean velocity 8.54 ±0.09 m/sec) and treadmill (mean velocity 8.46 ±0.13 m/sec) sprinting, found no significant differences in step parameters (frequency, length, support time, flight time) between the two conditions, however, he reported differences in segmental kinematics. When sprinting on a treadmill, the thigh of the support leg was more erect at contact and moved with a slower angular velocity, whereas the shank of the support leg was less erect at contact and moved with a greater range of motion and angular velocity. It has also been reported that when running on a treadmill the foot position at landing is flatter than when running over-ground [34]. McKenna & Riches [31], assessing sprinting kinematics, reported no fundamental differences between field and treadmill conditions.

In contrast, Morin et al. [33] reported that 100m sprint performance parameters were different between treadmill and field conditions, resulting in a lower performance on the treadmill compared to field sprint running. Specifically, the maximal running speed variable was significantly lower on treadmill (Smax = 6.90 ± 0.39 m/sec) compared to the running speed obtained on the track (Smax = 8.84 ± 0.51 m/sec). Nevertheless, the value of treadmill maximal running speed is comparable with the values recorded in previous studies (ranging from 6.10m/sec, [7]), to 11.1m/sec, [48]). Additionally, the variables assessed determining 100m sprint performance – the 100m time and the corresponding mean 100m speed, and the time required for acceleration – are associated with a significantly lower

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performance when running on a treadmill than on the track. However, the time to reach maximal running speed and deceleration time presented no significant differences between field and treadmill.

Differences in kinetic parameters were also observed, comparing treadmill and over-ground running. In treadmill running, the ground reaction forces (GRF) components (peak propulsive force and peak medial force) were significantly reduced, which is associated with the reduced knee moments recorded. Nevertheless, the higher ankle moments and preserved power recorded support the preservation of push-off during treadmill running [36], finding which has been observed in treadmill walking as well [37].

However, Kram [25], attempting to measure the vertical and anterior – posterior ground reaction forces in a treadmill running condition, reported that when running either on a treadmill or overground at the same speed the GRF components were very similar, suggesting that the underlying biomechanics are identical.

It is suggested that familiarity with treadmill running tend to influence biomechanical characteristics of running [27], however, adaptations to treadmill locomotion differ between individuals [34].

As ground reaction forces are decreased while running either on an instrumented treadmill [36] or on a positive - pressure treadmill [23], it is expected some muscles to require less intensities of activation since metabolic cost is reduced [18,19]. According to Hunter's [23] findings, who investigated changes in muscle activation for various lower limb muscles while running on a positive – pressure treadmill at different amounts of body weight support, most of the lower limb muscles showed decreases in activation as more body weight was supported. Specifically, the two vastii muscles (medialis and lateralis) and rectus femoris activities decreased dramatically as more body weight was supported. Peroneus longus activity presented a significantly descending trend with body weight support; however, the amount of this decrease was lower compared to other muscles.

While reduced ground reaction forces may contribute to lower intensity's activation for certain muscles during stance, during the swing phase this decreased activation is not observed for all muscle groups. When using positive – pressure treadmill, compared to a traditional treadmill, some muscle activation patterns may not be altered during the swing phase. During this part of gait cycle, the activity of hip adductors appeared to be relatively unchanged as different amounts of body weight were supported [23], which could be explained by the fact that during the swing phase the function of hip adductors is to keep the swing leg moving in the forward direction [15]. During early stance, the medial and lateral hamstrings remained unchanged as well - independently of body weight condition. Although this phase is related to supporting body weight, it appears that the hamstrings are less involved in body support than expected. However, high muscle activation is necessary in order to produce the appropriate horizontal forces required in running, which were not decreased by the positive – pressure treadmill [23].

It is suggested that when using a treadmill and allowing subjects to accelerate the belt voluntarily, it is possible to interpret – not to reproduce – running performance and evaluate inter-subject differences [33].

Conclusion

During dynamic locomotion, muscular function is affected by running techniques and foot strike patterns, inclined surfaces and running speed. The foot positioning at landing influences running technique and muscle activation patterns. Running at varied inclined surfaces affect lower limb joint function and the corresponding muscle activity. Additionally, it is reported that running speed "interacts" with leg muscles contribution to joint and body segment accelerations during dynamic locomotion, affecting this way muscle activation patterns. Taking into consideration these determinants of running performance and the fact that training adaptation differs between individuals; the above-mentioned parameters should be combined effectively in order to design suitable and beneficial training programs for

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professional and recreational athletes. Many training programs include running on a treadmill which is characterized by decreased ground reaction forces and less stress / mechanical load propagated to athletes' bodies compared to over-ground running, and is speculated that this training method could provide an over-distance running benefit.

Conflict of interest:
The authors declared no conflicts of interest.

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ΠΕΡΙΛΗΨΗ

Κατά τη διάρκεια δυναμικών αθλημάτων τρεξίματος, μικρών ή μεγάλων αποστάσεων, η μυϊκή λειτουργία εξαρτάται από την τεχνική τρεξίματος, το είδος βάδισης του αθλητή, την κλίση των επιφανειών τρεξίματος αλλά και την αναπτυσσόμενη ταχύτητα. Οι σύγχρονες εργομετρικές μελέτες εξετάζουν συγκεκριμένες μυϊκές ομάδες και πως αυτές ανταποκρίνονται στις ανωτέρω μεταβλητές. Σκοπός είναι ο σχεδιασμός εξατομικευμένων προπονητικών τεχνικών βελτίωσης της αθλητικής απόδοσης άρα και επίδοσης ανάλογα με το είδος του τρεξίματος.

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: τρέξιμο, μυϊκή δραστηριότητα, επιφάνειες κλίσης, ταχύτητα