Contents Lists is Available Online
International Journal of Motor Control and Learning (IJMCL)
Journal Homepage: www.ijmcl.com

The Effects of Heel Spring on Lower Limb Muscular Activity and Running Economy

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Keywords

Running Economy
Heel Positions
Insoles
Muscular Activity
Muscle Tendon Units (MTU)

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Received: 2021/11/01
Accepted: 2022/02/10
Published: 2022/02/19

Abstract

Objective: Running economy (RE) is a performance variable for distance runners. It can be affected by parameters such as equipment, running technique and surface. It has been shown that substantial mechanical energy will return by shoe integrated and that energy could be stored in the Muscle Tendon Units (MTU). The purpose was to investigate the influence of three difference heel positions induced by insoles on lower limb muscular activity and VO_2 and RE (performance variable) changes during steady state running. It was hypothesized that with decreasing heel spring a linear increase in RE would be observed.

Methods: Fifteen healthy trained male runners were tested on a treadmill submaximal pace while surface electromyography (EMG) from nine muscles of leg and thigh, the VO_2 by spirometry and kinematics by 2D video camera was measured. Subjects had to run in three insoles Up Heel (UH) (14 mm heel spring), Flat insole/Heel (FH) and negative spring (DH) (Down Heel) (forefoot 5 mm higher). Data were analyzed with a repeated- measures ANOVA for significant differences between shoe insoles ($p<0.05$).

Results: Ankle kinematics was systematically altered in response to the inserts (expected) by VO_2 and running economy was not changed. It was shown that not all subject followed the implied changes so when looking at 10 responders a higher activity for Tibialis Anterior (TA) was shown.

Conclusion: It was concluded that heel spring potentially changes energy exchange in the triceps-surae while changes in muscle coordination may compensate for these improvements. RE is related to many factors such as running style and individually properties.

Introduction

Shoes and shoe inserts have been advocated and successfully used for many years for running and other physically intensive activities to alter internal loading (Cavanagh, 1980; Gross et al., 1991; Smith et al., 1986). Footwear has been suggested as a means to influence economical running based on specific design features (Frederick, 1983; Roy & Stefanyshyn, 2006). Although footwear weight is the factor which consistently shows a clear relationship with RE with every 100 g weight adding about 1% extra metabolic cost per foot (Frederick, 1983; Frederick et al., 1983), recent studies have shown that midsoles elasticity or forefoot elastic components may lead to small but significant differences in performance (Roy & Stefanyshyn, 2006; Worobets et al., 2014).

Frederick et al. (1986) have demonstrated that the energy cost of treadmill running could be reduced by more than 2% through an alteration of midsole hardness and wedge composition

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(Frederick et al., 1986). Divert et al. (2008) theorized that the shock-absorbing properties of shoe cushioning might take away energy that might otherwise be stored and reused as elastic energy, causing a net efficiency loss (Divert et al., 2008). Following this track of thought, Nigg and Segesser (1992) suggested that the return of energy is not an appropriate approach to improve performance in sport shoe construction and that focus should be on strategies to minimize energy loss(Nigg & Segesser, 1992). On the other hand, shoes with moderate dorsiflexion can trigger activation of lower limb muscles differently compared with both standard shoes and shoes with large dorsiflexion during submaximal exercises and locomotion (Bourgit et al., 2008). Thus, it appears plausible that altered muscular activation might be triggered by changes to footwear which, as a consequence, would be accompanied by changes in metabolic cost. Moritani and Yoshitake (1998) have shown that the EMG signal integrated over several cycles of a repetitive movement will linearly relate to oxygen consumption. If muscle activity during running would be varied due to changes in footwear of foot movement either during pre-Touch Down (TD) or over the whole running cycle a corresponding change in oxygen consumption should occur (Moritani & Yoshitake, 1998).

Running Economy (RE) has been identified as an important determinant of running performance (Anderson, 1996; Di Prampero et al., 1986; Joyner, 1991). It is determined by measuring the steady state oxygen consumption at submaximal running speed (V˙O_2submax) and it was shown to be a better performance predictor than maximum oxygen consumption (V˙O_2max) (Di Prampero et al., 1986; Scholz et al., 2008). One of the most important hypotheses which have been generally accepted to explain the variation in running economy is storage and reutilization of elastic energy in tendons which substantially reduces energy demands in running (Cavagna et al., 1964). It has been pointed out that substantially more elastic energy can be stored in in the muscle tendon unit (MTU) of the triceps surae (Albracht & Arampatzis, 2006) as compared to the energy return features found in footwear modifications (Moran & Greer, 2013; Stefanyshyn, 2000; Worobets et al., 2014). The amount of energy stored in a tendon depends on the mechanical properties of the tendon (compliance and rest length) and on the force that stretches the tendon (Scholz et al., 2008). Tendon force, elastic energy storage and return are inversely related to the moment arm of the tendon scaling during locomotion (Biewener, 2005).

Factors influencing distance running performance such as different running technique, velocity, footwear, and surface or muscle activity were previously investigated (Joyner, 1991; Lake & Cavanagh, 1996; Scholz et al., 2008). Most studies have shown that runners generally run at or close to their optimum step frequency (Anderson, 1996; Joyner, 1991; Saunders et al., 2004) while a surface of intermediate compliance has been shown to offer potential for improved running economy (RE) through reduced foot contact time and increased step length (Anderson, 1996). The author pointed out that co-activation of the muscles around the knee and ankle joints increased the joint stiffness, which appears to be related to better RE (Anderson, 1996). It has also been indicated that the integration and timing of muscle activity to utilize the storage and release of elastic energy within the body system more effectively may lead to improvements in RE (Anderson, 1996; Saunders et al., 2004). However, increased co-contraction may require more metabolic substrates. It is therefore required to investigate to what extent increased muscle activity and potential benefits to muscle mechanics can be linked to improve RE.

Based on previous studies greater MTU elongation would improve energy return as long as muscle activation remains unchanged. Also, the improved energy return of in the triceps surae MTU will lead to reduced overall oxygen consumption. If muscle activity is modulated by variations in running shoes it is likely that this will influence fatigue during longer training sessions. A decreased neuromuscular effort (Moritani et al. 1993) should then accompany lower energy consumption during running possibly leading to a reduced overuse injury risk. Substantial modifications in midsole geometry to vary rearfoot movement were used on trained subjects who performed 12.5 km runs with each shoe modification respectively (Kersting and Newman 2003). Impact forces and rearfoot motion did not follow predicted values from previous studies (Stacoff et al. 1988). However, results showed large, but individually different variations in neuromuscular effort. No current literature has compared subtle changes in rearfoot kinematics to oxygen consumption and muscle activations during running. In this study we tried to recruited trained athletes and control most parameters during training to have real condition.

It was the aim of this study to modulate the energy storage and return mechanism of the triceps surae muscle group by inserts which systematically modify the dynamic elongation of the triceps surae MTU during running. To achieve this goal inserts with different heel heights were used in an otherwise non-supportive running shoe while sagittal plane kinematics and muscle activity were monitored. First, it was hypothesized that greater MTU elongation would improve energy return as long as muscle activation remains unchanged. Second, it was expected that the improved energy return of the triceps surae MTU will lead to reduced overall oxygen consumption.

Method

Subjects

Fifteen healthy well-trained male runners (age 25.5±5.2 yr.; height 176.4±5.1 cm; mass 75.6±6.7 kg) volunteered for the study. All subjects were free from recent lower extremity injury or pain in the six months preceding the study. All participants had been training for, and participating in, regional running competitions for at least 5 years. They were in equal level based on their record in last three competitions, all subjects provided written informed consent before participation and the procedures were approved by the ethics committee of Northern Jutland (N-20130015).

Procedures

After a familiarization run over 5 min on the treadmill, the subjects were asked to perform three times 10-minute running bouts, in a random order using insoles in a non-supportive running shoe (ECCO, biom, Bredebro, Denmark). Shoes without insert had a heel spring of 0 mm and a midsole hardness of 45 Shore A. Three different insoles of similar weight, made out of cork (62 Shore A) were used with the heel higher than the forefoot (Up; 12 mm heel spring), heel and forefoot at the same height (Flat) and the heel below the forefoot (Down; -5 mm heel spring). The choice aimed at minimizing potential energy return by the insole material itself in order to isolate the effect of altering ankle joint kinematics.

Subjects were asked to run on a treadmill at submaximal running speed corresponding to 75 – 80% of their 5000 m best. Heart rate and oxygen consumption were monitored during the experiment to confirm a steady state pace. The tests were performed on a motorized treadmill (Woodway Pro, Foster Court Waukesha, USA). For each participant, running economy was determined as the rate of oxygen consumption (V ̇O_2) per kg body mass when running at the pre-established speed. Pre-established speed was the mean speed of final practice of subject on treadmill, based on their ability in the controlled speed, a light-weight accelerometer (50 g, Biovision, Germany) was attached to the medial aspect of the tibia approximately half way between the knee and ankle joints. The accelerometer was glued to the skin, secured with medical tape and held tightly by an elastic rubber band strapped around the leg (Hennig et al., 1993).

2D kinematics: Sagittal plane kinematics was obtained by a 100 Hz video camera (Basler scout, Winterthur, CH) including a static reference trial for each insole. Which was sufficient for the data analyze in the c-motion software. The camera was mounted 2 m away from the treadmill at a height of 0.2 m above treadmill surface level next to a 500 W halogen light source. Five retro-reflective markers were placed on the metatarsal head 5, lateral calcaneus, lateral malleolus, lateral femoral condyle and greater trochanter of the left leg. Windows were cut into the shoe to enable automatic digitization of the foot markers (Skill Spector, Video4Coach, Denmark). A static reference measurement with the flat insole was used as a reference for each subject and defined as 0 degrees with all other ankle angles expressed in relation to this angle.

Running Economy: For each participant, running economy was determined as the rate of oxygen consumption (V ̇O_2) per kg body mass when running at the test speed. Oxygen consumption was measured during a 10-min period using a breath-by-breath spirometer. The spirometer (CareFusion version 02, San Diego, USA) was calibrated before each session by means of a two-point calibration using environmental air and a calibration gas mixture. The last 2 min of respiratory measurements were averaged and used for RE calculation (Divert et al., 2008; Scholz et al., 2008).

EMG data: Data from tibia acceleration were low-pass filtered (60 Hz) and running cycles was determined following previously reported methods (Selles et al. 2005). Muscle activity of eight muscles of the thigh and leg were recorded using bipolar surface electromyography (EMG) with a ground electrode on the lower medial tibial aspect.

Skin preparation and electrode (AMBU blue sensor, Denmark) positioning followed SENIAM guidelines (Hennig et al., 1993). Electrodes and miniature amplifiers (Biovision) were secured by tape and tight pants. The respective locations on the legs and thighs of the runners were shaved and wiped with alcohol to provide an optimum adhesion of electrodes and tape. Based on previous studies and the muscle which is active during this kind of tasks the muscles recorded were Tibialis Anterior, (TA), Soleus (SOL), Medial and Lateral Gastrocnemius (GM, GL), Vastus Medialis (VM), Vastus Lateralis (VL), Biceps Femoris (BF) and Rectus Femoris (RF). (Divert et al., 2008; Scholz et al., 2008) The exact placement for muscles was based on SENIAM methodology(http://www.seniam.org/).

EMG measures were taken at minute six and eight for 20 s each. EMG data were band-pass filtered at 20 – 500 Hz with a zero phase-lag 4th order Butterworth filter, full-wave rectified and low pass filtered at 10 Hz. The resulting envelopes were integrated (iEMG) over the whole stride (CYC) (left touch down until subsequent touch down) and over a period of 50 ms prior to TD (PRE). For each muscle, the maximum EMG amplitude from the step with highest EMG amplitude of the Flat insoles was used to normalize EMG curves. (Divert et al., 2008; Scholz et al., 2008). All signal processing was performed in Matlab (Vers. 7.3, The Math Works, USA).

Data Analysis

Statistical analyses were carried out using NCSS (version 5.0) statistical analysis software and data were presented as means and +/- standard deviation (SD). To test for normality for measured variables Shapiro-Wilk statistic test were applied. A repeated measures ANOVA with a Fisher LSD test was employed to study the effects of heel height on oxygen consumption, kinematics and EMG parameters. The level of statistical significance was set to p<0.01 to account for multiple comparisons.

Results

Kinematic results in the static reference trial, at touch-down (TD) as well as maximum angles and velocities during stance are presented in Table 1. From the static angles only the ankle position was significantly affected and showed a change which matches the respective insole geometry. <Note that statistical tests were carried out on raw measures while Table 1 gives the results after subtracting the respective offsets. The static ankle angle of Up was more plantarflexed than for Flat and Down (p<0.001). Matching this static pattern, the maximum ankle angle induced by the three different insoles (Figure1) showed a significant difference between Up versus Down and Flat (p<0.001). On average the whole sample altered the maximum ankle angle (dorsiflexion) during stance systematically showing a 6.5-degree range of changes (p<0.001). There was a change in TD angle (p<0.001) for the dynamic conditions which was on average less than 2 degrees in magnitude indicating that the static alterations do not transfer directly to the running condition. The maximum ankle extension velocity was altered accordingly (p<0.001) with Up showing the lowest value.

Table 1. Descriptive kinematic results.

	Up	Flat	Down
	Mean ± SD	**Mean ± SD**	**Mean ± SD**
Ankle angle static (°)	-10.4 ± 4.9 ¤, *§*	0.0 ± 0.0	2.7 ± 2.3
Knee angle static (°)	-0.5 ± 4.3	0.0 ± 0.0	1.4 ± 4.1
Hip angle TD (°)	-24.9 ± 3.9	-25.0 ± 3.3	-24.9 ± 3.8
Max hip angle (°)	9.4 ± 4.5	10.3 ± 5.6	10.5 ± (5.5)
Max knee flexion vel (°/s)	241 ± 53 ¤	260 ± 44	252 ± 49
Max ankle extension vel (°/s)	149 ± 31 ¤, *§*	172 ± 27	184 ± 35

Note: Ankle and Knee angles; during standing reference trial, at touch-down (TD), Maximum (Max) value and velocity (vel) during ground contact. ¤ = significant difference between Up and Flat, § = significant difference between Up and Down.

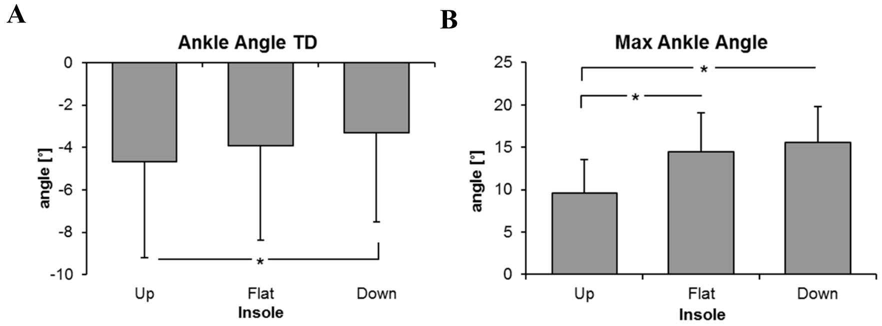

Figure 1. Maximum dorsiflexion angle during stance at TD (A), and Maximum (B). (*: p<0.05).

Knee kinematics was influenced by the intervention. While the knee angle at TD was slightly, increasing with decreasing heel height, showing a significant difference between Up and Down (p=0.002), the knee maximum flexion was significantly less for Down compared to Flat and Up (p<0.001).

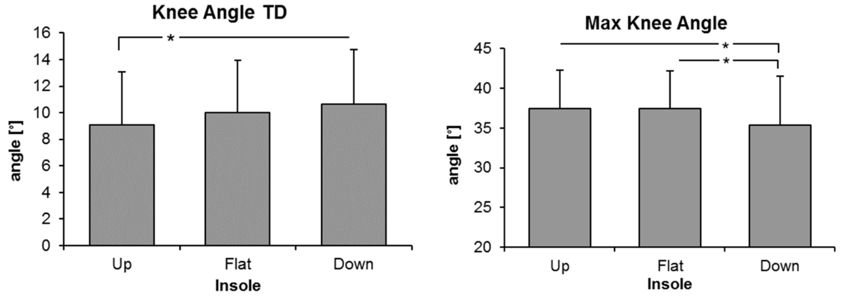

Figure 2. Knee angle degree at TD (A), and Maximum (B). (*: p<0.05).

Results for oxygen consumption (V̇O_2), EMG values for eight lower limb muscles, HR and RPE are summarized for all insoles in Table 2. Steady state oxygen consumption showed considerable variation for individual subjects with the lowest value for Up (~1.3% difference), however no statistically significant changes were found. Similarly, there were no differences for RPE or HR indicating that the intervention did not affect RE.

Table 2. Descriptive metabolic results.

		Up	Flat	Down
		Mean ± SD	**Mean ± SD**	**Mean ± SD**
$\dot{VO}_2$ (ml/min/kg)		384.9 (53.8)	387.8 (49.2)	386 (43.4)
RPE		4.7 ± 2.8	4.1 ± 2.7 *	5.2 ± 2.5
HR (1/min)		175 ± 13.4	172 ± 15.9	171 ± 17.3
EMG Values PRE (%)	**TA**	84.9 ± 27.2	70.6 ± 9.9	68.3 ±17.1
	SOL	59.7 ± 14.7	68.2 ± 9.1	68.1 ± 17.3
	GM	57.3 ± 19.2*	66.1 ± 12.2	74.3 ± 20.3
	GL	64.6 ± 19.5	65.9 ± 6.4	63.3 ± 21.9
	VL	74.6 ± 21.7	71.6 ± 10.2	69.2 ± 19.0
	VM	74.6 ± 21.7	71.6 ± 10.1	69.2± 20.1
	RF	75.1± 29.8	72.9 ± 8.8	67.2 ± 22.00
	BF	56.3 ± 20.2	59.3 ± 11.8	50.0 ± 20.00
	PL	78.3 ± 31.2	70.2 ± 9.1	62.1 ± 12.50
EMG Values CYC (%)	**TA**	78.9 ± 14.3	86.8 ± 3.5	86.4 ± 13.60
	SOL	83.7 ± 14.1	87.0 ± 5.6	83.2 ± 11.1
	GM	74.6 ± 12.2	85.2 ± 5.6	78.3 ± 20.3
	GL	72.7 ± 17.3	84.1 ± 6.2	73.0 ± 24.0
	VL	82.9 ± 11.0	82.2 ± 8.1	76.0 ± 14.7
	VM	79.4 ± 21.5	84.5 ± 3.7	70.5 ± 23.2
	RF	88.6 ± 18.7	83.5 ± 5.6	84.3 ± 21.3
	BF	71.8 ± 14.1 ¤	83.8 ± 6.2	74.6 ± 12.6
	PL	75.0 ± 20.6	86.1 ± 4.7	75.7 ± 22.0

Note: VO_2 = Oxygen consumption (ml/min/kg). EMG values for nine lower limb muscles, HR = heart rate (1/min), RPE = rate of perceived exertion. * = significant difference between Up and Flat.

Subjects exhibited a significantly (p=0.01) lower muscle activity during pre-activation for GM for the Up condition in contrast to the Flat insole (Table 2). Further, BF muscle activity in the thigh was statistically significantly lower for Up compared to the Flat insole (p=0.005).

Discussion and Conclusion

The aim of this study was to investigate how insoles with different heel spring affect ankle kinematics during ground contact in running. Further, it was aimed at relating the resultant kinematic changes to muscular activity in the lower extremity and metabolic energy requirements during steady state running. It was confirmed that shoe insoles affected the maximum ankle angle and range of motion during stance which potentially allows for altered energy storage and release in the triceps surae muscle. However, there were no systematic variations of RE while individual subjects showed considerable differences between insoles. A reduced plantar flexor pre-activity was shown for the Up insole, with a similar change for the Biceps Femoris muscle over the whole stride cycle.

Several studies can be cited in which shoe modifications were introduced to improve energy return in running shoes. It appears that midsole hardness or the relation of its elastic and viscous properties are factors which have repeatedly been investigated, however, with inconsistent outcomes. Rubin et al. (2009) could not ascertain any effects on RE when comparing a motion control shoe to a standard running shoe while no material properties of the respective midsoles were reported in their paper. In a study by Hardin et al. (2003), no shoe effect on oxygen consumption occurred while some significant changes to ankle kinematics were shown when running on surfaces with different hardness. It was argued that the intrinsic dampening of impact forces may counteract the potential energy return of a harder midsole. This reasoning may be consistent with findings provided by Frederick and co-workers who argued that if the shoe provides inadequate shock absorption the runner has to react with greater muscular effort to compensate for this lack of cushioning (Frederick, 1983; Frederick et al., 1983). However, Perl et al. (Perl et al., 2012) could show a slightly better economy when running with minimal shoes compared to standard shoes. The authors discussed that a substantial interaction with foot strike pattern was demonstrated with distinct individual changes in strategy. Based on Worobets et al. (2014), a softer but more elastic midsole may be advantageous, which is only consistent with some of the previous studies varying midsole material alone (Bosco & RUSKO, 1983; Frederick et al., 1986; Nigg et al., 2003). The observed inconsistencies may partly be explained by differences in testing protocols, types of footwear and subject groups used. Common to these studies appears to be a simple mechanical model which entails that the energy return mechanism lies purely in the midsole material's mechanical properties.

Aiming at using other constructional features of running shoes, Roy and Stefanyshyn (2006) assessed the effect of a change in midsole bending stiffness to improve running economy and found that an optimum bending stiffness may exist at which energy consumption is minimal (Roy & Stefanyshyn, 2006). Forefoot lugs have been used in the study by Moran and Greer (2013), where positive but small overall improvements were shown. Based on their study, a more elastic midsole material in the forefoot improved RE by about 1% on average. While both these studies assume an energy return mechanism resulting from the material properties of the midsole, several of the abovementioned studies (Moran & Greer, 2013; Nigg et al., 2003; Perl et al., 2012)discuss the individuality of the responses. This implies that depending on the footfall pattern or individual anatomical factors the energy return within each individual's musculoskeletal system may be influenced differently by different shoes which would make it difficult to make any predictions.

In the current study, the cushioning properties choice aimed at minimizing potential energy return by the material between foot and ground in order to isolate the effect of altering ankle joint kinematics and with that triceps surae mechanics. This intervention was successful in the standing condition (Table 1) and the maximum ankle dorsiflexion during stance being systematically altered (Figure 1). While there was a significant difference between the Up versus Flat and Down conditions there were also changes in ankle angle and foot orientation at TD which make the range of ankle movement during stance significantly different and systematic between all insole conditions of this study (results not shown). As stride rate remained similar between conditions it can be excluded that any other major change in strike pattern or running style occurred and that the intended alteration of triceps surae stretch was achieved. It has to be noted, however, that knee joint kinematics showed simultaneous alterations.

For the Down condition knee flexion at TD was increased while the maximum flexion was decreased (Figure 2). Thus, it can be stated that ankle range of motion and knee range of motion changed alternatingly, possibly in an attempt to compensate for the changed movement related deceleration of the lower extremity.

Several studies have looked at the energetic demand of running barefoot versus shod or running in minimal shoes compared to conventional shoes. One observation in which these studies agree is that running in shoes is biomechanically distinct from barefoot running, leading to alterations in step length and frequency (Bonacci et al., 2013; Perl et al., 2012). While the resulting biomechanical differences can have energetic consequences it is in general difficult to account for weight effects in combination with the described alterations in landing technique and kinematic changes (Divert et al., 2008; Frederick, 1983; Hanson et al., 2011; Squadrone & Gallozzi, 2009). Based on the observed systematic kinematic changes observed at the ankle and knee joints with no other significant changes in movement pattern it is reasonable to conclude that the insole intervention used in this study was successful in isolating ankle joint alterations and accompanied by changes at the knee. These changes have to be viewed in conjunction with the EMG differences, which were only small. The GM was higher activated prior to TD for the Up condition which reflects the situation in a conventional running shoe with a heel spring of 12 mm. Vice versa, it means that the GM pre-activation was higher for Flat and Down which could be in anticipation of a higher forefoot loading as intended by these modifications. While no force or in-shoe pressure measurements were included in this study the TD ankle angles confirm that subjects were heel strikers. The only change in muscle activity of muscles crossing the knee joint was for the BF over a whole cycle. The BF has been shown to be active during stance and, at a higher intensity, during late swing (Gross et al., 1991). The higher EMG activity during Down could therefore be interpreted as an attempt to stiffen the knee joint in compensation for a higher ankle joint ROM. According to these changes in muscle activity, being reduced for two muscles for the Down condition, RE should be improved for the Up insole.

Scholz et al. (2008) hypothesized that a change in economy might be due to increased energy storage in the Achilles tendon. Based on their theory (Scholz et al., 2008) it was expected that a smaller moment arm of the Achilles tendon should be associated with superior running economy and lower rates of metabolic energy consumption as it was confirmed in their data. While it is experimentally not possible to alter the moment arm in a specific subject, a greater Achilles tendon stretch was produced in the Down insole compared to the Up insole. According to Scholz et al.'s argumentation, a shorter moment arm of the tendon would require a stronger contraction of the triceps surae to generate similar propulsion, i.e., force under the forefoot. This stronger contraction would generate a greater stretch of the Achilles tendon and therefore an increased energy storage. Accordingly, the intervention used in the present experiment should enable to increase the stretch in the Achilles tendon which, at a similar contraction level, would also improve the energy storage in the tendon. However, the metabolic results do not support this reasoning as there are no systematic changes observed (Table 2). This may, in parts, be explained by the changes in electromyography activity following the observations of Moritani and Yoshitake (1998). I may however be difficult to estimate the summed effect of the observed alterations in muscle activity in this study (Table 2). At the ankle joint the pre-activity of the gastrocnemius is highest for the Flat condition while TA remains unchanged. If muscle changes would be restricted to just muscles acting across the ankle this would mean that the activity, and with that the metabolic cost, is increased for the flat insole while this would potentially increase the force generated in the tendon, leading to a higher storage of elastic energy. At the same time the activity of knee flexors is increased which would further increase the metabolic cost, resulting in a negligible overall effect.

Following this line of thought, the Up-condition lead to a reduced contraction of the thigh and leg muscles while the stretch of the gastrocnemius MTU was the lowest with unchanged triceps surae activity. These differences did not alter metabolic cost of running significantly. A possible explanation may be that a stretch of a complete MTU does not exclusively affect the series elastic element. At the same time the parallel elastic structures are stretched with their stiffness being dependent on contraction level (Selles et al., 2005). The dynamic behavior of the whole muscle tendon unit is dependent on its training and adaptational status and will therefore be highly individual (Hermens et al., 1999). Further, there will be an interaction of muscles spanning the ankle and knee and, potentially, the hip which require a well-tuned muscular coordination to function energetically efficiently. It is therefore possible that, even with the intended kinematic change induced by the current footwear intervention, combined adaptations in kinematics and muscular activity make it impossible to make predictions for a whole group or individual (Perl et al., 2012).

This interpretation would then allow to explain the previously discussed individuality in responses in studies comparing different types of footwear (Gruber et al. 2011, Perl et al., 2012). The human musculoskeletal system is capable of adapting on all different levels. While all runners have to act within the constraints dictated by our individual anatomy (Scholz et al., 2008), we can immediately as well as over an extended adaptational period alter skeletal alignment and muscular activity in timing and magnitude. To what extent we use these capacities will depend on habituation (Perl et al., 2012), mechanical properties of the passive components of our musculoskeletal system (Albracht & Arampatzis, 2006; Griffin et al., 2015) neuromuscular adaptations (insert one of the plyometric training studies from the review paper, where these adaptations are discussed). It might be assumed that any individual will aim at finding the optimum solution within these constraints for any given type of footwear, however, at our current state of knowledge on these mechanisms it appears close to impossible to make predictions which may benefit a given individual or a group of individuals who are similar in regard to mechanical, anatomical and neurophysiological parameters.

In continuation to the preceding paragraph there are several limitations to this study. While all runners tested were ambitious athletes, they were not equally trained. We did not select runners based on footfall pattern while the kinematic measurements indicated that all were rearfoot or midfoot strikers. However, a separation into two groups did not provide more conclusive patterns and was not presented here as the statistical power would have been compromised. Kinematic parameters were obtained from skin markers on the foot while in many other studies markers on the shoe were used which may bear some problems (Stefanyshyn, 2000). The chosen method of assessment of 'true' skeletal movement was necessary but there are potential effects on frontal plane movements which may interact with measures. However, these effects were expected to be much less in regard to Achilles' tendon stretch. Further, there are deformations of the arch (Perl et al., 2012), the windlass mechanism (Griffin et al., 2015) which have been proposed to contribute to energy storage and release but were neglected in this experiment.

In the present study the effect of different shoe insoles on kinematics, lower limb muscular activity and oxygen consumption during running on a treadmill were investigated. It was shown that ankle joint kinematics can be altered which potentially affects energy return within the musculoskeletal system. While this kinematic effect was systematic within this experiment no related physiological responses could be identified. It seems that a whole set of individual anatomical and training adaptational factors needs to be taken into account when optimizing footwear for running economy. Future research should aim at studying footwear mechanics by including the anatomical and neurophysiological mechanisms in relation to each other. This might only be possible with more invasive studies as well as using advanced modeling techniques which include more anatomical details and muscle mechanics.

Acknowledgments

We thank ECCO for provision of the shoes and Iben Andersen from Sahva Aalborg for manufacturing the insoles. We have to express our thanks to the Iranian Ministry of Science (Grant No. 151338-1392/07/01) for support of this PhD project.

Conflict of interests

All authors of this paper declare that they have no conflict of interest.

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