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ORIGINAL ARTICLE

Effect of submaximal running in rocker shoes on gluteal muscle activation under different running conditions

Effet de la course sous-maximale dans des chaussures à bascule sur l'activation des muscles fessiers dans différentes conditions de course

L. Freitag[a,b,*], E. Hohenauer[b,c,d,e], A. Meichtry[a], C.A. Pauli[a], B. Sommer[a], E.S. Graf[a]

[a] *Institute of Physiotherapy, School of Health Professions, Zurich University of Applied Sciences, Winterthur, Switzerland*
[b] *Rehabilitation and Exercise Science Laboratory (RES lab), University of Applied Sciences and Arts of Southern Switzerland Weststrasse 8, 7302, Landquart, Switzerland*
[c] *International University of Applied Sciences THIM, Landquart, Switzerland*
[d] *School of Sport, Health & Exercise Science, University of Portsmouth, Portsmouth, United Kingdom*
[e] *Department of Neurosciences and Movement Sciences, University of Fribourg, Fribourg, Switzerland*

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Gluteal muscle ;
Iliotibialis syndrome ;
Rocker shoes ;
Running ;
Running-related injury

Summary
Objectives. — Iliotibialis syndrome is one of the most common types of running injury of the lateral knee. Earlier studies have mainly focused on the relationship between iliotibialis syndrome and hip muscle forces, since the latter are often the target of intervention during rehabilitation. The results suggest that a curved shoe sole may affect lower limb mechanics during running. The main purpose of this study was to assess the effects of different curves of rocker shoes on activation of the musculus gluteus medius and maximus under various running conditions.
Equipment and methods. — Fifteen recreational runners (1.77 ± 0.44 m height, 74.25 ± 6.68 kg weight, 23.73 ± 1.79 kg/m^2 BMI) were recruited to test three rocker shoes with different forefoot curvatures on a flat laboratory floor and a treadmill at flat, uphill, and downhill gradients. Surface electromyography data were collected for musculus gluteus medius and maximus,

* Corresponding author.
Adresse e-mail : livia.freitag@supsi.ch (L. Freitag).

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resulting in a three-way within-subject design (running condition (4) x shoe (3) x muscle (2)) with 24 measurement combinations for each runner. A linear mixed model was fitted to the data to quantify running condition, shoe curve and muscle effects.
Results. — The main effects of running condition, shoe and muscle were estimated. While running uphill, significant decreases were observed in both peak ($P = 0.021$, log%MVC) and duration ($P = 0.015$, log%MVC) compared to running on a flat laboratory surface. Both average (0.033 log%MVC) and peak muscle activation (0.069 log%MVC) were increased with a smaller radius of shoe curvature.
Conclusion. — In conclusion, the study shows that rocker shoes appear to affect gluteal muscle activation and could potentially assist in stabilising the pelvis during running. This knowledge might be of interest for runners with an increased risk of ITBS and may therefore gain health benefits from wearing rocker shoes.

MOTS CLÉS
Muscle fessier ;
Syndrome iliotibialis ;
Chaussures à bascule ;
Course à pied ;
Blessure liée à la course

Résumé
Objectifs. — Le syndrome de l'iliotibialis est l'un des types les plus courants de blessure en course à pied du genou latéral. Les études précédentes se sont principalement concentrées sur la relation entre le syndrome iliotibialis et les forces musculaires de la hanche, puisque ces dernières sont souvent la cible d'interventions lors de la rééducation. Les résultats suggèrent qu'une semelle de chaussure incurvée peut affecter la mécanique des membres inférieurs pendant la course. L'objectif principal de cette étude était d'évaluer les effets de différentes courbes de chaussures à bascule sur l'activation du muscle fessier moyen et du muscle grand fessier dans diverses conditions de course.
Équipement et méthodes. — Quinze coureurs récréatifs (1,77 ± 0,44 m taille, 74,25 ± 6,68 kg poids, 23,73 ± 1,79 kg/m^2 BMI) ont été recrutés pour tester trois chaussures à bascule avec différentes courbures de l'avant-pied sur un sol de laboratoire plat et un tapis roulant à plat, en montée et en descente. Des données d'électromyographie de surface ont été recueillies pour le musculus gluteus medius et le maximus, ce qui a permis d'obtenir une conception à trois voies au sein du sujet (condition de course (4) x chaussure (3) x muscle (2)) avec 24 combinaisons de mesures pour chaque coureur. Un modèle linéaire mixte a été adapté aux données pour quantifier les effets de la condition de course, de la courbe de la chaussure et du muscle.
Résultats. — Les principaux effets de la condition de course, de la chaussure et du muscle ont été estimés. Lors de la course en montée, des diminutions significatives ont été observées tant au niveau du pic ($p = 0{,}021$, log%MVC) que de la durée ($p = 0{,}015$, log%MVC) par rapport à la course sur une surface plane de laboratoire. L'activation musculaire moyenne (0,033 log%MVC) et maximale (0,069 log%MVC) a augmenté avec un rayon de courbure de la chaussure plus petit.
Conclusion. — En conclusion, l'étude montre que les chaussures à bascule semblent affecter l'activation des muscles fessiers et pourraient potentiellement aider à stabiliser le bassin pendant la course. Cette connaissance pourrait être intéressante pour les coureurs présentant un risque accru de SII et qui pourraient donc tirer des avantages pour leur santé du port de chaussures à bascule.

1. Introduction

Endurance running is one of the most common recreational sports in Switzerland. A report in 2014 showed that around 23% of the Swiss population performed regular running exercises over the year [1]. Running is defined as a repeated sequence of gait cycles, which includes two phases: a stance phase, with single limb support and a contact-free swing phase [2]. Both, concentric and eccentric muscle activation of lower limb muscles are needed to evoke locomotion [3]. It is known that the hip abductor muscles play a key role during the stance phase to provide an efficient and controlled running pattern [4]. Not surprising, the hip joint absorbs the main ground reaction forces during uphill and downhill running [5].

Despite the positive effect of running on general health [6], the incidence of running-related injuries (RRI) of the lower extremity is fairly high, varying between 11% and 85% per 1000 hours of running [7]. Several risk factors have been identified that contribute to the occurrence of running-related injuries [8,9]. One main cause is excessive mechanical stress [10], which can lead to patellofemoral pain syndrome, stress fracture, Achilles tendinopathy, and iliotibialis syndrome (ITBS) [8,11]. One of the most common syndromes of the lateral side of the knee in runners is the ITBS [12]. ITBS is characterized by lateral knee pain and swelling at the lateral epicondyle of the femur. Occasionally, the pain radiates proximally towards the hip joint and is further aggravated during running. Untreated ITBS often results in persistent pain after training [13]. So-called ''trigger factors'' that contribute to the development of ITBS include a sudden increase in exercise intensity (mileage/hilltraining/speed work), potentially increased tension of the ITB due to downhill running and wearing old shoes [14]. Furthermore, excessive running on the same side of the cambered road, leg length discrepancy, excessive pronation of the subtalar joint, a tight ITB or weakness of the hip abductor muscles can also lead to ITBS [14]. Activation of the gluteus medius (GMed) and gluteus maximus (GMax) muscles is reported to influence joint excursions and torques at the hip [15]. Furthermore, increased hip adduction and internal rotation angle during running have been shown to increase strain on the ITB during the stance phase and promote ITBS [16]. Consequently, rehabilitation interventions mainly focus on resistance exercises for GMed and GMax, in combination with the usual care [11].

The type of running shoe used (sole material, thickness or hardness) may positively affect muscular activity, ground reaction force and soft tissue vibrations during running [17]. The effects of a curved forefoot shoe form (also designated 'rocker shoes') while running has been investigated only in few studies to date [18—22]. Significantly reduced mechanical work at the ankle joint while running in rocker shoes has been reported [18]. Furthermore, running in rocker shoes led to a marked reduction in plantar flexion moment and ankle power generation during the push-off phase of gait [19], indicating that lower forces are generated by the tricep surae muscles, which may be beneficial for runners with Achilles tendinopathy [20]. One study that analyzed plantar forces of the foot during running revealed significantly smaller forces for rocker shoes [20]. This reduction in force in the forefoot appears to have a protective effect against overuse injuries, such as metatarsal stress fractures [21]. Electromyography (EMG) analysis of muscular activity showed an increase in peak activity of tibialis anterior when walking in rocker shoes [23]. However, the results in the literature are inconsistent [22]. To our knowledge, no study have focused on analyzing gluteal muscle activity with EMG using rocker shoes under different running conditions yet.

The evaluation of the specific muscle activity of the gluteal muscles during running in rocker shoes will improve the understanding of muscle function. Further comparison with symptomatic groups will allow, development of targeted rehabilitation programs will reconsider and preventative strategies for RRI will develop. Consequently, the aim of the current study was to compare the effects of a commercially available heel and forefoot rocker shoe (Scott Palani®) versus two customised pronounced forefoot rocker shoes on muscular activity of the pelvic abductors GMax and GMed in recreational runners under four different conditions (running on flat ground in the laboratory and on a treadmill with gradients of 0%, 24% uphill and 24% downhill). It was hypothesised that (a) the two customised pronounced forefoot rocker shoes generate more muscular activity in GMax and GMed than the commercially available heel and forefoot rocker shoe. We further hypothesised (b) an increase in activation during running on a treadmill with a downhill gradient and (c) greater muscular activity of the GMax than on the GMed.

Table 1 Descriptive characteristics of male participants.

Characteristics	Mean (SD)
Age (years)	38.47 (10.86)
Mass (kg)	74.25 (6.68)
Height (m)	1.77 (0.44)
Body Mass Index (kg/m^2)	23.73 (1.79)
Running experience (years)	23.92 (13.91)
Running speed (min/km)	7.07 (1.17)
Running circumference (km/week)	39.50 (22.05)
Running trainings (number/week)	3.97 (1.32)
Running distance per training (km)	16.59 (5.86)
Running contests (number/year)	7.17 (5.36)
Running distance per contests (km)	27.99 (10.50)

SD: standard deviation.

2. Materials and methods

2.1. Participants

Fifteen recreational male runners volunteered for this study (Table 1) based on an a priori sample size calculation (G*Power, version 3.1.9.3; Franz Faul University of Kiel, Germany = power, 0.8; alpha error, 0.05; correlation, 0.8; significance level, 0.05; total sample size, 12). Participants were included if they had run at least 10 km per week over the past year, were experienced in treadmill running, and had a standard shoe size of US male 9. All participants were free of acute or chronic diseases and lower extremity injuries within the ten months preceding the study period and provided informed written consent. The procedures of this monocentric, cross-sectional study were conducted in accordance with the Declaration of Helsinki and Good Clinical Practice guidelines and approved by the Swiss Ethical Committee of Zurich (BASEC-No. 2018-00310).

2.2. Shoe Characteristics

Three types (A, B and C) of heel and forefoot rocker running Scott Palani® shoes (Scott Sports SA, Switzerland) as a base model with different forefoot curvatures were examined (Fig. 1). Only the forefoot curvature was modelled by inserting a custom-made carbon plate into the shoe. In shoe A, the carbon plate corresponded to the original curvature. In shoes B and C, carbon plates with different curvatures

Figure 1 Scott Palani® running shoe.

Table 2 Characteristics of shoes used in this study (size male US 9).

		Rocker shoe A	Rocker shoe B	Rocker shoe C
Toe spring	(a; mm)	33	50	60
Toe sole diameter	(b; mm)	15	15	15
Heel sole diameter	(c; mm)	26	26	26
Shoe mass	(kg)	0.71	0.71	0.69

mm: millimeter; kg: kilogram.

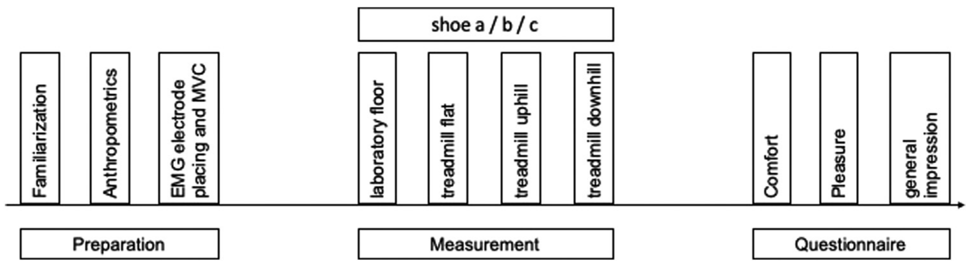

Figure 2 Experimental protocol. EM: Gelectromyography; MVC: maximum voluntary contraction.

in the forefoot region were inserted, resulting in distinct characteristics (Table 2).

2.3. Experimental procedures

Prior to measurements, the participants' anthropometric data, including age, mass and height, were assessed. Subsequently, participants were instructed to run in four different settings: treadmill on a level setting (ergo_run medical α24, daum electronic gmbh, Fürth, Germany), treadmill at a 24% uphill gradient, treadmill at a 24% downhill gradient, and 10 m on a flat surface in the laboratory, without warming-up exercises (see Fig. 2). A randomization of the running tasks was waived, to ensure that all participants were experienced the same muscular demands at the same measuring time. Within three pilot tests, the running pace was maintained at a constant speed of 3.3 m/s, except for the uphill treadmill setting, since the trial with the same speed was impossible to complete. In order to generate a similar effort and thus ensure comparability, the pace for uphill treadmill running was set at 2.0 m/s. All running paces were chosen to induce a medium intensity load to the participants. Three pilot tests were conducted to increase the reliability of measurement procedures prior to the experiment. For running conditions on the flat laboratory surface, ten complete gait cycles were recorded. For measurements under treadmill conditions, the last 15 seconds from a total running time of one minute were recorded. After each running performance, a rest period was allowed of five minutes, where the participants changed the shoes and had time for a short habituation. The order of shoe usage was determined using a computer-controlled randomization program (Excel, Microsoft Windows, Washington, USA).

2.4. Instrumentation and data collection

Skeletal muscle activity was measured at 1000 Hz using surface electromyography (EMG, Myon, Switzerland). Skin was initially prepared by shaving and cleaning with alcohol. Electrodes were placed on the right GMax and GMed muscles according to Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) recommendations [24]. This steps were always conducted from the same researcher (LF). Two maximum voluntary contractions (MVC) trials (with 10 seconds break between trials) of five seconds for both muscles were performed with verbal encouragement according to standardized guidelines to obtain information on signal intensity at maximal contraction for each muscle prior to the gait trials [25].

2.5. Data treatment

Following data collection, raw EMG data were filtered and rectified using a 2nd order Butterworth bandpass filter with a high-pass frequency cut-off at 20 Hz and low-pass frequency cut-off at 300 Hz [26,27]. To determine the threshold for the onset of muscle activity, 5% of the maximum value of the respective muscles measured during the MVC trial was considered [28]. The zero-phase digital filtering function was used to prevent time-shifts. Processing was performed with Matlab R2018a® (Mathworks, Natick, USA). Variables of interest were as follows: duration of muscle on, peak amplitude of muscle activity, and average amplitude of muscle activity. EMG amplitude was determined as mean and standard deviation (SD) for each participant, followed by logarithmic transformation to generate a normal distribution.

2.6. Statistical analysis

Subject characteristics (Table 1) are expressed as mean values and SD. Nominal scale data were determined as absolute (n) and relative frequency (%).

For this three-way within-subject design, a linear mixed model (LMM) was fitted to the data. The primary outcome were the comparison between shoe A and B as well as between shoe A and C. Rocker shoes (S (a, b and c), running

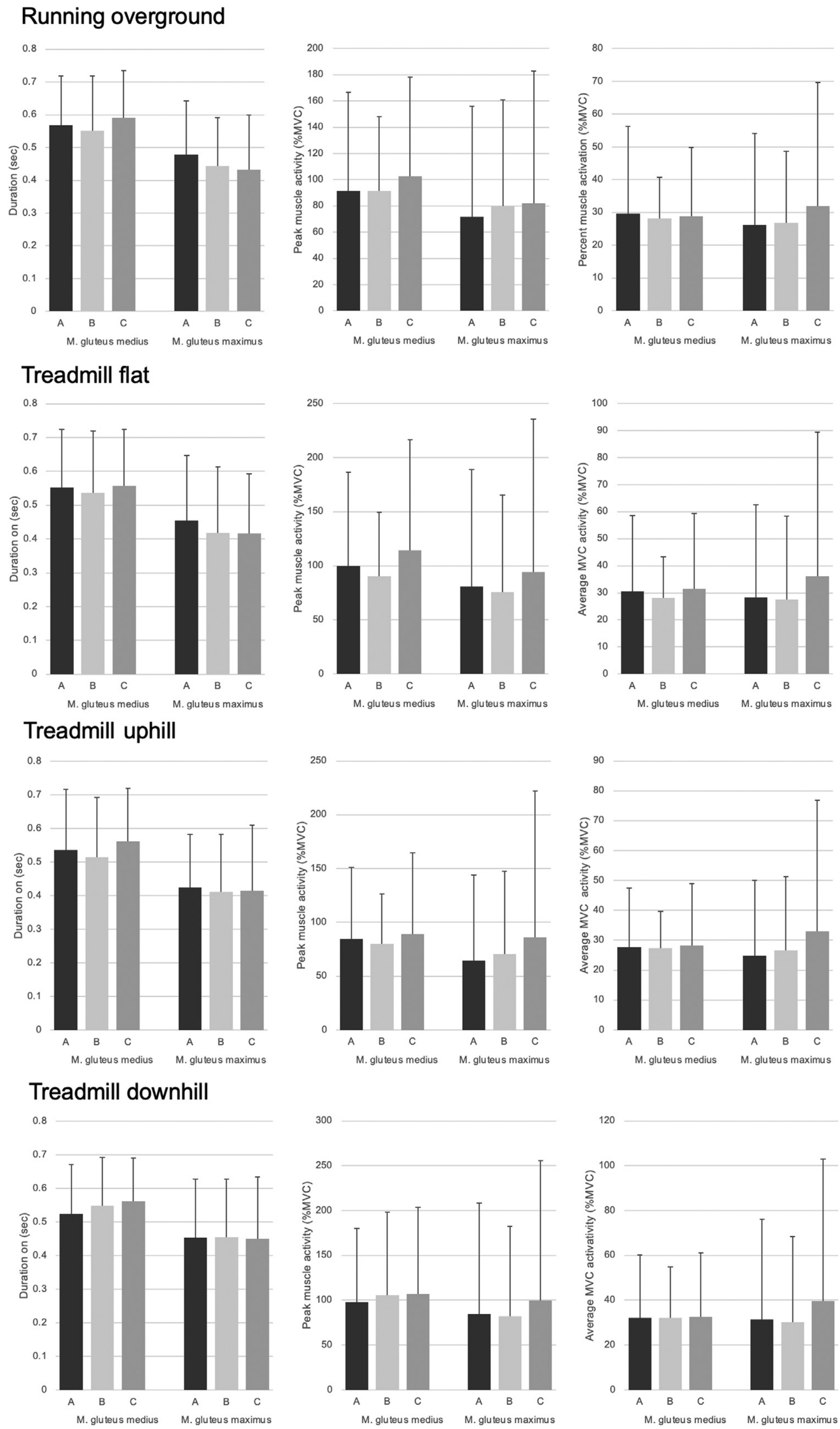

Figure 3 EMG Results.

conditions (C) (flat laboratory surface and treadmill flat, uphill gradient or downhill gradient) and muscle group (M) (GMed and GMax) were used as fixed effects. Intrasubject correlation structure was modeled by adding random effects for person (P) and interactions with C,M and S respectively, leading to the following model: $Y_{ijkl} = \mu + C_i + M_j + S_k + CM_{ij} + CS_{ik} + MS_{jk} + CMS_{ijk} + P_l + PC_{li} + PM_{lj} + PS_{lk} + \varepsilon_{ijkl}$

Intraclass correlation (ICC) estimates for repeated measurements were calculated based on generalizability theory (G-theory) [29]: $G_{global} = \frac{\sigma_P^2}{\sigma_P^2+\sigma_{PC}^2+\sigma_{PM}^2+\sigma_{res}^2}$

Intraclass correlation coefficients were additionally computed for inter-condition, inter-shoe and inter-muscle reliability. Values >0.90, 0.75—0.9, 0.5—0.75, and <0.5 represent excellent, good, moderate, and poor reliability, respectively [30].

The level of significance was set at $P \leq 0.05$ All analyses were performed using statistical software R version 3.6.3 (The R Foundation, Vienna, Austria). Results were verified using the STROBE Statement for observational studies in epidemiology [31].

3. Results

The approximate normal distributions of residuals can be found in the Supplementary files (Figs. 4-6) (Figs. 4-6). Visual inspection revealed no obvious deviations from homoscedasticity or normality. The results of the EMG analyses are shown in Fig. 3.

In general, duration of muscular activation of GMed and GMax while running on a treadmill was shorter than that during flat laboratory surface running. Analysis of the fixed-effects model revealed that uphill running on the treadmill resulted in a shorter duration of muscle activation compared to flat surface running in the laboratory by 0.034 sec. (P = 0.015; 95% CI −0.060, −0.008). In terms of the different shoe types examined, longer (P = 0.831; 95% CI −0.044, 0.055) duration of muscle activation (0.005 sec) was only observed for shoe ‘C’ with a smaller radius of curvature vs shoe A and B. Regarding the fixed effects on gluteal muscles, significantly shorter duration of activation was observed for GMax compared to GMed (difference of 0.108 sec; P = 0.021; 95% CI −0.193, −0.024).

A significant decrease in peak activity was observed while running on an uphill gradient (0.139 log%MVC) compared to flat laboratory surface running (P = 0.021; 95%CI −0.252, −0.027) using shoe A. Additionally, muscle activation of GMed (− 0.391 log%MVC) was significantly higher relative to GMax (P = 0.041, 95% CI −0.743, −0.040) using shoe A.

LMM analysis revealed no significant differences in average muscle activation (average MVC) among the different running conditions, shoe or muscle types. Running on a flat laboratory surface resulted in higher muscle activation compared to treadmill running (0.029, 0.036, 0.006 log%MVC). Smaller radius of rocker shoe curvature was associated with increased muscle activation (0.044, 0.033 log%MVC) as well as variable peak (P = 0.569, 0.671). Average muscule activation tended to be lower for GMax than GMed (P = 0.181).

All reliability data are presented in Table 3. Inter-measurement reliability was interpreted as ‘poor’, with the exception of variable average MVC (Global = 0.510), for which the level was classified as ‘good’. The intraclass correlation of the running conditions (ICCcondition = 0.920, 0.902, 0.842) was interpreted as ‘excellent’ or ‘good’ for all variables. The results of the correlation calculations for the different shoes were also classified as ‘moderate’ to ‘good’ (ICCshoe = 0.711, 0.810, 0.853). GMax and GMed values (ICCmuscle = 0.414, 0.578, 0.629) showed the lowest intraclass correlations.

Table 3 Intraclass correlation coefficient.

	G_{global}	$ICC_{condition}$	ICC_{shoe}	ICC_{muscle}
Duration on	0.234	0.842	0.711	0.414
Peak	0.428	0.902	0.810	0.578
Average MVC	0.510	0.920	0.853	0.629

G: Generalization reliability; ICC: intraclass correlation coefficient.

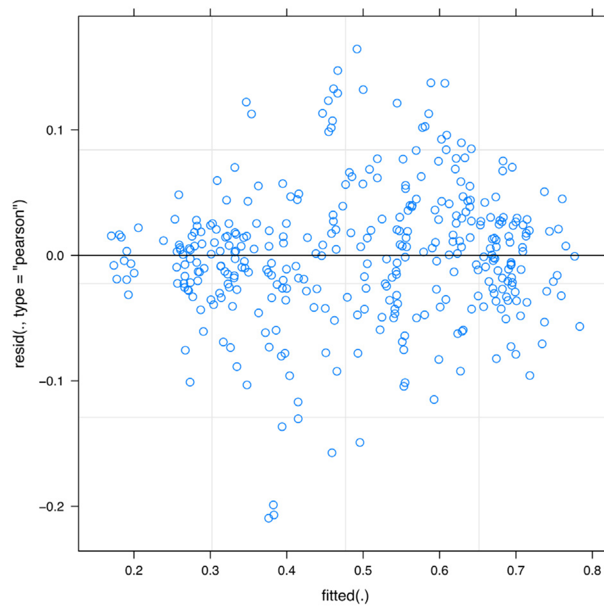

Figure 4 Residuals versus fitted values (duration_on).

4. Discussion

To our knowledge, this is the first study that investigated the effects of rocker shoes on gluteal muscle activation while running on a treadmill and the first study to have compared three variously curved rocker shoes. Both peak and average muscle activation were clearly increased in association with a smaller radius of curvature. This could be due to smaller supporting surface which generated an increase in joint instability and therefore requires a compensatory higher lower limb muscle activation. It is generally known that instable and/or smaller surfaces lead to increased postural control activation to maintain dynamic stability [32]. Furthermore, running downhill did not increase muscle activation of GMed and GMax in comparison with running on a flat surface in the laboratory. Running uphill on a treadmill induced the weakest and shortest duration of muscle activation among the treadmill conditions examined relative to overground running. Moreover, all treadmill conditions

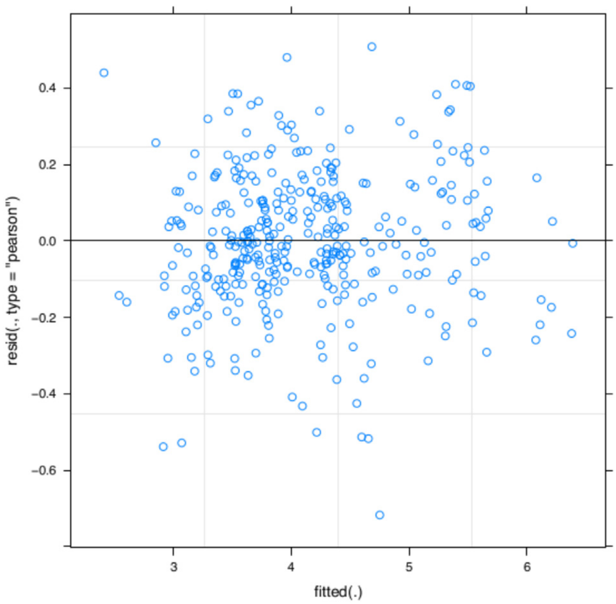

Figure 5 Residuals versus fitted values (peak).

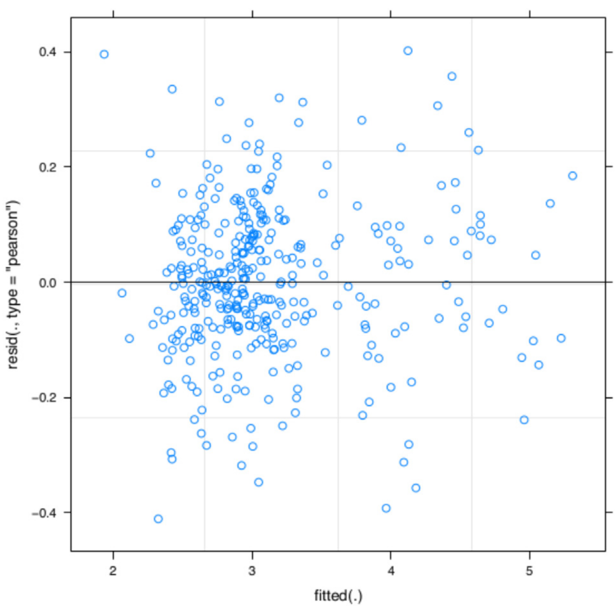

Figure 6 Residuals versus fitted values (average MVC).

required lower muscle activity relative to overground running. It seems legitimate to ask whether the acquisition of the surface (hard, overground running; soft, treadmill running) has an impact on joint stability, which in turn influences muscle activation as mentioned above. Indeed, stiffness, mass and damping properties of the surface have been shown to have a significant impact on muscle activity [33]. Maximum and average activation as well as duration of activation were generally higher for GMed than GMax.

According to the literature, pre-activation of leg muscles is necessary to ensure an optimal effect on soft tissue vibrations [34]. A previously published study has reported that increased pre-activation of musculus tibialis anterior and musculus gastrocnemius lateralis during the stance phase in more economical runners could reduce the risk of running-related injuries [35]. Pre-activation and soft tissue vibration analyses during running using rocker shoes have rarely been documented in the literature. An earlier study noted no significant influence of rocker shoes on soft tissue vibrations recorded with tri-axial accelerometers or pre-activation changes of the gastrocnemius medialis and vastus lateralis [22]. The issue of whether pre-activation of GMax and GMed muscles affects running economy when wearing rocker shoes is yet to be established.

In accordance to previous results, EMG amplitude was higher during flat laboratory surface running than treadmill running [36]. Altered movement patterns may underlie these differences in muscle activation. Earlier reports have documented shorter step length and increased step frequency in subjects running on a treadmill [37]. Furthermore, a smaller degree of vertical oscillation in the center of mass and more pronounced forward leaning of the upper body during treadmill running were observed compared to flat surface running. In terms of movement patterns of actual running, limited conclusions of a systematic review could be drawn from treadmill data [37]. Muscle activation was significantly lower during uphill treadmill running compared to all other treadmill tasks, possibly since uphill running was performed at a lower velocity relative to other running conditions. Lower sprinting velocity is associated with lower step rate [38]. A previous published study have also documented reduced gluteal muscle activation with lower step rate [4].

Our results demonstrated significantly shorter and less intense activation of GMax compared to the GMed and are consistent with earlier findings, that GMed muscles produce the largest peak muscle force of all hip muscles during running [39,40]. Adequate muscle fiber recruitment is fundamental for the generation of torque necessary to absorb ground reaction forces and support coronal plane pelvic alignment during running [4]. Multiple studies have also disclosed delayed onset and shorter duration of gluteal muscle activation manifesting as enlarged hip adduction and hip internal rotation, which increase the risk of RRI [15,39], supporting the utility of treatments intended to modify GMed and GMax activation. In contrast, another study showed, that muscle activation is not responsible for ITBS, but rather decreased resistance to fatigue [41]. This may be the reason that increased activation of the musculus tensor fasciae latae is observed and neuromuscular factors of the hip muscles contribute to increased knee adduction in runners [40]. To examine this hypothesis, further investigations, including EMG analyses of the musculus tensor fasciae latae and including a fatigue analysis of the signal, are necessary.

A limitation of the current study is the 'poor' global ICC, which reflects variations across investigators, measurements, and errors, including the components involving investigators and measurements. This issue highlights the expected variations, when collecting data on running with surface EMG. So far, there is no consensus on the best way to analyze EMG data during running conditions [42]. Thus, interpretation and comparative analyses of EMG data in the literature are limited. In addition, the low intraclass correlations comparing GMed with GMax indicated a decreased reliability of measurement. However, the 'moderate' to 'excellent' inter-ICC's for running conditions and shoes suggested that this test protocol was appropriate for use in observational studies [43].

Several limitations may have impacted the findings of this study. Rearfoot and forefoot strikers were analyzed together in one group, which could have influenced the results. A previous study on muscle activity and kinematics between rearfoot and forefoot strikers revealed earlier and longer relative activation time of plantar flexor muscles [44]. These differences may also affect activation of the gluteal muscles. Furthermore, the results could only be generalized to male recreational runners and not other running populations. A longer period of adaptation to running with rocker shoes may also generate different results (time-dependent bias). Notably, MVC trials show vulnerability because of the different determinations of the threshold for onset of muscle activity. However, three participants had a continous threshold of ±5% and it is known, that muscle activation can be detected normally at this value [28]. Values below 5% can lead to missinterpretations of the EMG signal [28]. Consequently, different threshold of 20% for one, a 10% threshold for both mucles for the second, and a threshold of 10% for GMed for the third participant had to be selected to detect for on-/off-phases of muscle activation. We assumed that differences between subjects are dependent on technique, strength and skinfold thickness [45]. The present study does not represent a general recommendation for running shoe selection based on different anthropometric, running speed, level of training or performance goal measurements of the runner.

5. Conclusion

In this study, a quantitative analysis of gluteal muscle activation was performed of different curves of rocker shoes under various running conditions. In conclusion, the current study suggests that rocker shoes influence muscular activation of GMed and GMax. These factors could potentially assist with assessment of the integrity of the lateral hip stability mechanism in healthy athletes. Thus, the observed changes in gluteal muscle activation may have some clinical merit, as the results showed that these muscles were differentially activated during the performed running conditions. Further research is warranted to determine the implications of these findings for injured athletes and using validated protocols to investigate the potential therapeutical effects of rocker shoes, the optimal radius of curvature, whether and at what point reverse effects might occur, how much gluteal activation is necessary, and how the occurrence of ITBS is potentially affected.

Disclosure of interest

The authors declare that they have no competing interests.

Contributorship

Authors order was alphabetical determined.

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