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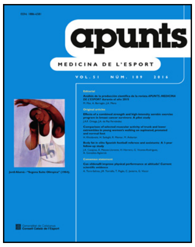

ORIGINAL ARTICLE

Acute effects of barefoot running and running requirement on lower-limb kinematics in habitually shod endurance runners

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KEYWORDS
Long-distance runners;
Lower-limb joint angles;
Running speed;
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Unshod

Abstract The aim of this study was to analyse kinematic variables when running barefoot and when wearing conventional running shoes at comfortable and demanding running speeds. Sixty healthy recreational male runners (age = 35.6 ± 11.7 years old, body mass index = 22.9 ± 2.4 kg/m^2) performed trials in shod/barefoot running conditions on a treadmill at self-selected comfortable and demanding speeds. Photogrammetric techniques (2D) were employed. In barefoot conditions, contact time was shorter ($p < 0.001$) at demanding speed, flight time was shorter at comfortable ($p < 0.05$) and demanding ($p < 0.05$) speeds, and there was greater stride frequency at both speeds ($p < 0.001$). In addition, in barefoot conditions, runners landed with significantly greater knee flexion ($p < 0.05$); lower ankle dorsiflexion ($p < 0.001$); and lower knee flexion in take-off at demanding speed ($p = 0.002$) compared with shod conditions. In conclusion, the current study has provided evidence to suggest that acute changes occur in the temporal variables and kinematics between shod/barefoot conditions at low and high speeds in habitually shod runners. Significant differences were found in spatial–temporal events between shod/barefoot conditions, with shorter times in barefoot conditions with greater knee flexion and ankle dorsiflexion. When speed was increased in barefoot conditions, duration of timing variables decreased significantly both comfortable and demanding speed ($p < 0.001$). Because of this, stride and gait cycle was significantly faster and thus there was a higher stride frequency.

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PALABRAS CLAVE
Corredores de larga distancia;
Ángulos de articulación de las extremidades inferiores;
Velocidad de carrera;
Parámetros espaciotemporales;
Descalzo

Efectos agudos de la carrera sin zapatillas y sus requisitos en la cinemática de las extremidades inferiores en corredores resistentes habitualmente calzados

Resumen El objetivo de este estudio fue analizar las variables cinemáticas en la carrera sin zapatillas y utilizando zapatillas convencionales específicas para carrera, a nivel de velocidad confortable y exigente. Los participantes fueron 60 corredores recreativos sanos (edad, 35,6 ± 11,7 años, índice de masa corporal, 22,9 ± 2,4 kg/m^2), quienes realizaron las pruebas descalzos sobre una cinta a velocidades confortable y exigente, seleccionadas por ellos mismos. Se utilizaron técnicas fotogramétricas (2D). En la carrera sin zapatillas, el tiempo de contacto fue menor ($p < 0{,}001$) a velocidad exigente, el tiempo de vuelo fue más corto a velocidades confortable ($p < 0{,}05$) y exigente ($p < 0{,}05$), y la frecuencia de la zancada fue superior en ambas velocidades ($p < 0{,}001$). Además, en la carrera sin zapatillas los corredores aterrizaron con una flexión de rodillas considerablemente superior ($p < 0{,}05$), menor dorsiflexión de tobillos ($p < 0{,}001$) y menor flexión de rodillas en el despegue, a velocidad exigente ($p = 0{,}002$) en la carrera con zapatillas. En conclusión, el presente estudio ha aportado una evidencia que sugiere que se producen cambios agudos en las variables temporales y cinemáticas en la carrera con/sin zapatillas a baja y alta velocidad, en los corredores que utilizan normalmente zapatillas. Se hallaron diferencias significativas en cuanto a sucesos espaciotemporales en carrera sin zapatillas, con una mayor flexión de rodillas y dorsiflexión de tobillos. Al aumentar la velocidad al correr descalzos, la duración de las variables de tiempo disminuyó considerablemente tanto en velocidad confortable como en exigente ($p < 0{,}001$). Debido a ello, el ciclo de zancada y de marcha fue considerablemente más rápido y, por tanto, se produjo una mayor frecuencia de zancada.

Introduction

Barefoot running has become very popular in recent years and remains a hotly debated topic by runners, coaches and researchers. The effect of barefoot foot-strike patterns and its relationship with footwear on the economy, performance and injury rates in endurance runners has been discussed in the literature.[1–3] It has been suggested that the model of running shoes could be a key risk factor leading to injury.[4] Possible causes of injury may include abrupt collision force[5,6] limited proprioception[7] and excessive foot pronation at heel strike.[8,9] Some authors suggest that habitual barefoot running could prevent impact-related injuries.[6,10]

Several studies have focused on the foot-strike patterns of runners and on how changes in running speed and performance can change the way that athletes strike the floor when running.[2,11] Larson et al.[2] concluded that between 87.8% and 93.0% of marathon runners were rearfoot strikers, yet among the fastest runners, midfoot strikes were the most common strike pattern. Hasegawa et al.[11] reported that the percentage of rearfoot strikes increases with decreasing speed, and midfoot strike increases as the speed increases. Thus, it seems that running speed is related to strike pattern.

In order to reduce the risk of injury, the runner's body produces changes in lower-limb kinematics. Reducing stride length is an example of an alteration in running to reduce tibial stress fracture or bone strain.[12] Other previous studies about barefoot running[1,3,13,14] obtained kinematic data, such as shorter step length or increased stride frequency. In addition, barefoot running reduces flight time and causes a lower peak force and higher pre-activation of the sural triceps than shod running.[15] In addition, Squadrone and Gallozzi[3] found differences in contact time between shod and barefoot conditions.

Bosco and Rusko[16] observed a significant change in time parameters when using soft shoes compared to normal running shoes. Previous studies of barefoot running[1,3,13,14] obtained kinematic data of shorter step length or stride frequency.

Some authors, such as Lohman et al.[17] have described kinematic changes that occur in the lower extremities on the barefoot condition. The relationship of the kinematics variables was also studied in a treadmill at 8.0 mph in barefoot condition[13] but does not offer the level of demand involved for the participants because competitive level of each was huge different. Other authors, such as Youngren,[18] have tested the kinematic differences in shod runners' self-selected speed. However, this has not produced a detailed study that combines all joint conditions of the studies described above, the comparison of the spatiotemporal variables in shod/barefoot conditions studied at different self-selected comfortable or demanding speed paces.

Some studies about barefoot running consistently show increased flexion of the knee at initial contact with the ground[1,3,19] and the knee extension starts relatively earlier.[20,21] Edwards et al.[12] used a computer model to indicate that the risk of stress fracture might decrease with decreased stride length and so might reduce the risk of

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tibial stress fracture or bone strain. Other alterations like greater knee flexion might be biomechanics adaptations to self-protect and decrease the excessive impact forces, so landing with greater foot plantar flexion and knee flexion might reduce vertical impact peaks and loading rates in habitually barefoot runners.[3,6]

Considering the above information, more research is needed to determine the kinematic changes in habitually shod endurance runners when running barefoot and how different running speeds – *i.e.* when athletes run at a comfortable speed (CS) or a demanding speed (DS) – can affect these variables.

Material and methods

Subjects

This observational study was done in collaboration with sixty healthy habitual shod runners from three Spanish athletic clubs volunteered (age = 35.6 ± 11.7 years old; height = 168.7 ± 25.9 m; weight = 66.3 ± 10.5 kg).

Each participant signed an informed consent to participate in this study. The study was conducted in adherence to the standards of the Declaration of Helsinki (2008 version) and followed the European Community's guidelines for Good Clinical Practice (111/3976/88 of July 1990), as well as the Spanish legal framework for clinical research on humans (Royal Decree 561/1993 on clinical trials). The Bioethics Committee of the University of Jaén (Spain) approved the informed consent and the study.

The inclusion criteria were: (i) all participants were habitually shod runners with no experience in barefoot running; (ii) none of them had suffered any significant injury or pain in the 3 months prior to the study; (iii) all of them possessed a minimum verifiable performance level (*i.e.* all of them had participated in regional or national athletics championships); (iv) had been training for at least 4 years, five or six times a week, with at least 40 km completed each week. Additionally, participants were excluded from the study if they had any history of foot orthotics. More information about characteristics of the participants and their training background are presented in Table 1.

Table 1 Demographic characteristics and training background of the participants.

	Mean (SD) $N = 60$
Age (years)	35.64 ± 11.67
Height	168.7 ± 25.9
Weigh	66.3 ± 10.5
BMI (kg/m^2)	22.93 ± 2.43
Km per week	60.18 ± 20.41
Sessions per week	5.47 ± 1.29
Competitions per year	13.08 ± 10.50

BMI, body mass index; SD, standard deviation.

Procedures

Videos were recorded from a lateral view using two camcorders with a rate of 240 Hz (Casio Exilim EXZR-10, Dover, NJ, USA). Two cameras were placed 2 m away from the runner, perpendicular and at each side of the treadmill at ground level, with no degree of inclination. Exactly where the cameras were placed was marked.

In this experiment, the participants were asked to run consistently with their own running shoes at a comfortable speed and a demanding speed chosen by themselves, which has been shown to improve the repeatability in kinematic variables.[22] Before recording, markers were placed in the first metatarsal head, the medial trochanter point, the patella medial point and the external malleolus of the ankle. Then, subjects had 8 min to warm up and habituate to the treadmill (Salter E-Line PT-320, Salter International, Barcelona, Spain) and then by progressively increasing the treadmill speed, they reached their self-selected CS or DS pace. A period of 8 min was chosen because previous studies on human locomotion have shown that major changes for accommodation to a new condition occur within this time period.[15,23] After the 8 min of warm up, 1 min was recorded for collecting data. Four steps were analysed in each runner at all conditions (shod/barefoot; CS/DS). Participants were instructed to run (without stopping) at a stable speed in each condition. Once the participants had confirmed their running speed, the researcher recorded the treadmill speed displayed on the screen. Once the running was recorded, the treadmill stopped and the participant changed to a shod or barefoot condition, depending on what the runner had already done. Then the protocol started again, this time with the other condition. The order of conditions was randomised so that sometimes the athletes began with the shod tests and other times with the barefoot tests, thus resulting in the same number of shod and barefoot starts.

Video data were observed using a video editor (VideoSpeed v. 1.38, ErgoSport, Granada, Spain). Photogrammetric techniques (2D) were employed. Anatomic points selected with the markers for the study were manually tracked in the 2D program.

Based on previous studies[1,3] variables tested were: (1) foot plantar flexion, as the angle formed by the sole of the foot (the fifth metatarsal head and heel point of support) and the horizontal plane; (2) knee flexion (the angle formed by the medial trochanter point, the patella medial point and the external malleolus of the ankle) at first contact of the foot with the ground in the loading phase and at last contact of the foot with the ground in the take-off phase (Fig. 1); (3) total contact time (time the foot is in contact with the ground) divided into three different moments (landing phase, stance phase and take-off phase); (4) flight time (time where there is no contact with the ground); (5) stride duration (total time of the movement of the lower limbs including flight phase and contact phase); (6) step time (total time of only one lower limb, including flight phase and contact phase); (7) cadence (number of strides in a minute).

Data analysis

The data were tested for normality before statistical analysis (Kolmogorov–Smirnov test). Descriptive statistics

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Figure 1 Kinematic variables.

are represented as mean, standard deviation, frequency and percentage. To analyse the differences between the shod/barefoot conditions and the effect of running speed, the Student's *t*-test and Wilcoxon test were used. Pearson correlations between variables were performed. The average of both feet (left and right steps) was used for the analysis. The level of significance was $p < 0.05$. Data analysis was performed using SPSS (version 21, SPSS Inc., Chicago, IL, USA).

Results

Temporal variables

The results are shown in Table 2. At CS and DS, in shod conditions, runners take longer in the landing phase ($p < 0.001$). In the stance phase, significant differences between shod and barefoot conditions at DS ($p < 0.01$) were found in the contact time, which was longer in shod conditions. Referring the total contact time higher values were found in shod condition at DS running ($p < 0.001$). In barefoot conditions, athletes had lower flight time than in shod conditions ($p < 0.05$) at CS and DS, and therefore, stride duration and step time were lower ($p < 0.001$). Finally, the stride frequency was also affected, with more strides in the barefoot conditions ($p < 0.001$) during both CS and DS. Significant differences were found for the rest of the variables tested (contact time = $p < 0.001$, flight phase = $p < 0.001$, stride duration = $p < 0.001$) when comparing CS and DS in both shod and barefoot conditions ($p < 0.001$). In addition, the three phases of total contact time tested (landing phase barefoot $p = 0.021$, landing phase shod $p = 0.006$, stance phase $p < 0.001$ and take-off phase $p < 0.001$) were significant at both paces and conditions.

Kinematic variables

Table 3 shows the results of kinematic variables. The ankle dorsiflexion at both paces in the loading phase was significantly lower in barefoot conditions (CS, $p < 0.05$; DS, $p < 0.001$), and only in barefoot conditions, ankle dorsiflexion was higher in CS compared to DS ($p < 0.001$). In addition, there were significant differences in the knee flexion at foot initial contact between shod and barefoot conditions at DS ($p = 0.036$) being higher in barefoot conditions. Moreover, the knee flexion was increased at CS and DS in both conditions ($p < 0.001$). In the take-off phase, knee flexion was lower in barefoot conditions than shod conditions ($p = 0.002$) at DS. Additionally, it was found decreased knee flexion ($p < 0.001$) in CS compared to DS in shod conditions.

Ankle dorsiflexion was positively related to the knee flexion in the take-off phase at CS in barefoot conditions ($r = 0.254$, $p < 0.05$) and shod conditions ($r = 0.267$, $p < 0.05$), and DS in barefoot conditions ($r = 0.430$, $p < 0.01$) and shod conditions ($r = 0.355$, $p < 0.01$). Moreover, ankle dorsiflexion was positively related to contact time at DS ($r = 0.265$, $p < 0.05$) in shod/barefoot conditions.

Discussion

Temporal variables and kinematics at CS or DS were studied in order to gain a better understanding of changes in the lower limbs between shod and barefoot running. As hypothesised, significant differences were found between shod and barefoot conditions at CS and DS in the sagittal plane, which shows that acute changes may be observed in lower-limb kinematics in habitually shod runners not accustomed to barefoot running. When running barefoot, stride duration, flight time, contact time (at DS) and step time were significantly shorter, and stride frequency was significantly higher than in shod conditions. In addition, flexion of the knee during initial contact and take-off phase was significantly lower than in the shod conditions at DS, as well as ankle dorsiflexion at CS and DS.

Flight time was shorter in barefoot conditions at both CS and DS. An increased flight time in the shod conditions might be attributable to the shoe sole providing high propulsion at toe-off, increasing the flight phase of the stride.[3] On the other hand, the contact time was shorter in barefoot conditions at DS. In addition, McCallion et al.[24] showed lower contact times in barefoot conditions compared with

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Table 2 Temporal variables results at different paces in both barefoot and shod conditions.

	CS Mean (SD)	DS Mean (SD)	*p*-value
Landing phase (s)			
Barefoot	0.035 (0.011)	0.032 (0.009)	0.021
Shod	0.044 (0.011)	0.040 (0.009)	0.006
p-value	<0.001	<0.001	
Stance phase (s)			
Barefoot	0.105 (0.018)	0.080 (0.014)	<0.001
Shod	0.104 (0.021)	0.085 (0.015)	<0.001
p-value	0.891	0.010	
Take-off phase (s)			
Barefoot	0.132 (0.019)	0.106 (0.013)	<0.001
Shod	0.127 (0.016)	0.105 (0.012)	<0.001
p-value	0.063	0.612	
Contact time (s)			
Barefoot	0.271 (0.028)	0.218 (0.019)	<0.001
Shod	0.275 (0.027)	0.230 (0.022)	<0.001
p-value	0.253	<0.001	
Flight time (s)			
Barefoot	0.078 (0.031)	0.100 (0.026)	<0.001
Shod	0.083 (0.028)	0.106 (0.026)	<0.001
p-value	0.042	0.022	
Stride duration (s)			
Barefoot	0.696 (0.037)	0.640 (0.043)	<0.001
Shod	0.717 (0.043)	0.674 (0.037)	<0.001
p-value	<0.001	<0.001	
Step time (s)			
Barefoot	0.348 (0.018)	0.320 (0.021)	<0.001
Shod	0.359 (0.021)	0.337 (0.018)	<0.001
p-value	<0.001	<0.001	
Stride frequency (strides min^{-1})			
Barefoot	86.46 (4.89)	94.14 (6.27)	<0.001
Shod	84.93(5.30)	89.33 (5.10)	<0.001
p-value	<0.001	<0.001	

CS, comfortable speed; DS, demanding speed; SD, standard deviation.

Table 3 Kinematic variables results at different paces in both barefoot and shod conditions.

	CS Mean (SD)	DS Mean (SD)	*p*-value
Ankle dorsiflexion (°)			
Barefoot	10.51 (10.45)	5.56 (9.05)	<0.001
Shod	13.40 (11.13)	14.00 (8.66)	0.458
p-value	0.007	<0.001	
Knee flexion, first strike (°)			
Barefoot	167.40 (3.71)	162.84(4.02)	<0.001
Shod	166.53 (4.37)	164.18 (4.75)	<0.001
p-value	0.101	0.036	
Knee flexion, take off (°)			
Barefoot	164.41 (8.12)	165.17 (5.99)	0.465
Shod	163.57 (7.55)	166.77 (5.09)	<0.001
p-value	0.278	0.002	

CS, comfortable speed; DS, demanding speed; SD, standard deviation.

shod and minimalist conditions at both CS and DS. Similar results were shown by Schutte et al.[25] The overall results at both CS and DS in contact time were similar to the results of Squadrone and Gallozzi[3] in shod/barefoot conditions. A significant effect of running speed on contact time was detected, with significantly longer contact times noted at CS compared to DS in shod/barefoot conditions. These results are according with the study of McCallion et al.[24]

Stride duration in shod conditions was significantly greater than in barefoot conditions at CS and DS, which is similar to the results found by McCallion et al.[24] In addition, there was a significant effect of running speed on stride duration at CS, which was significantly greater than DS in both shod/barefoot conditions. Stride frequency was greater in barefoot conditions at CS and DS, in accordance with the results of De Wit et al.[1] Likewise, McCallion et al.[24] found greater stride frequency in barefoot conditions compared with minimalist and shod conditions at CS and DS; the results obtained in stride frequency in barefoot conditions were similar to those of this study in CS. Thompson et al.[26] found that barefoot running produced a decrease in stride length, which could cause lower ground reaction forces and sagittal plane joint moments. In addition, stride length was associated with barefoot running and is considered as a tool to reduce the risk of injury.

In relation to the ankle dorsiflexion in the landing phase, significant differences were found in shod/barefoot conditions at CS and DS. However, a significant ankle dorsiflexion is produced in barefoot conditions (2.89–8.77° less than shod). Similar results were shown by Lieberman et al.[6] who showed dorsiflexing reductions of approximately 7–10° in habitually shod runners who grew up wearing shoes when they moved from shod to barefoot conditions. Similar results were shown by Schutte et al.[25] With an increase in speed (CS to DS), a significant reduction in ankle dorsiflexing in barefoot conditions occurs, close to midfoot strike. This trend towards a midfoot strike in barefoot running reduces flight time and causes a lower peak force and higher pre-activation of the sural triceps than shod running.[15] The midfoot strike is thought to be a potential way to decrease impact.[27] Squadrone and Gallozzi[3] highlight this same finding, which causes a reduction of impact forces, lower contact time and increased stride frequency, similar to findings in this study. In a recent review, Hall et al.[28] indicate moderate evidence that barefoot running is associated with reduced peak ground reaction force, increased ankle plantar flexion and increased knee flexion at ground contact compared with running in a neutral shoe.

Most analyses of barefoot and shod running have reported increased ankle plantar flexion at initial contact when barefoot, which may be due to changes in foot strike

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patterns.[1,3,19,29] Lieberman et al.[6] investigated habitually shod and habitually barefoot athletes and theorised that barefoot runners adopted a flatter foot placement at initial contact. De Wit et al.[1] reported that this flatter foot placement was brought about by significantly larger plantar flexion and a significantly more vertical position of the shank at initial contact; the latter effect being brought about by increased knee flexion. Some researchers suggest that the changes in ankle dorsiflexion are a function of the heel height of the modern cushioned shoe[25]; however, Hamill et al.[30] compared the impact characteristics of running footwear of different midsole thicknesses to a barefoot condition and concluded that the change in the impact characteristics is a result of changing footfall pattern rather than midsole thickness.

Knee flexion on landing at CS in the shod conditions showed significantly higher flexion, which was reversed in the barefoot conditions at DS. De Wit et al.[1] observed lower knee extension in the barefoot conditions at three different speeds, showing the effect of speed in knee extension reduction at landing in shod/barefoot conditions, similar to this study. Similarly, Schutte et al.[25] showed greater knee flexion on landing in barefoot conditions. Squadrone and Gallozzi[3] highlight a decreased knee extension at landing in barefoot conditions compared with minimalist footwear and shod conditions, although this was not statistically significant ($p \geq 0.05$). Accordingly, landing with less ankle dorsiflexion and greater knee flexion causes decreased vertical impact peaks and loading rates in barefoot runners.[3,6] As previously mentioned, Squadrone and Gallozzi[3] showed an increase in stride frequency, lower contact time, lower flight time, higher knee flexion and lower ankle dorsiflexion on landing in barefoot conditions. This kinematic condition was related to a lower peak vertical force on landing. Increased impact characteristics are often cited as a cause of running injuries,[27,30,31] and kinematic results of this study could be interesting in the analysis of injury prevention. Sinclair[32] showed that barefoot and barefoot-inspired footwear was associated with significant reductions in patella femoral kinetic parameters. However, the ankle kinetics indicates that barefoot and barefoot-inspired footwear were associated with significant increases in Achilles tendon force compared to conventional shoes. Therefore, barefoot and barefoot-inspired footwear may serve to reduce the incidence of knee injuries in runners, although corresponding increases in Achilles tendon loading may induce an injury risk at this tendon.

Because humans evolved to run barefoot, a barefoot running style that minimises impact peaks and provides increased proprioception and foot strength is hypothesised to help avoid injury, regardless of whether or not shoes are worn.[31] However, in a recent review, Tam et al.[33] indicate that an unexplored area of the theory of barefoot running is the process in which biomechanical adaptations occur and if these are universally learned.

Acute changes produced running can be trainable and require an adaptation to those changes in lower leg neuromuscular activation in order to ease plantar flexion before the strike. For instance, it is produced higher activation of sural triceps, and this can contribute to a reduction in impact forces and later reduction in mechanical stress during running.[15] Mechanical adaptations can also contribute to improve the storage and retrieval of ankle elastic energy when running unshod. Flexor muscles hold up the tension more time and are less efficient, thereby increasing the possibility of fatigue. Furthermore, barefoot running produces a higher knee flexion at foot strike, the thigh muscle activity can be also higher.

Therefore, during the transition to barefoot running, athletes can be in a higher risk of suffering muscle injuries because stress or fatigue. This is useful to stabilise from a dynamic way, the lower limb joints. For this reason, to avoid possible adverse effects in the transition from shod to unshod running like metatarsal stress fractures,[34] it is recommended a gradual period of transition. Robbins and Hanna[35] suggested that ataptation to running barefoot require a reasonable time of several weeks in order to improve own musculature required to minimise the injury risks, to modify the especific muscular activation and new kinematics patterns.

A limitation of the study was the issue of accuracy in using 2D video analysis to determine analysed variables, while strengths lie in the large number of subjects participating and the analysis of spatiotemporal variables at two different running speeds in shod/barefoot conditions. Thus, this study provides new insight into the already open debate between supporters and detractors of barefoot running. Therefore, this study will help to have a better knowledge about this growing trend.

Conclusions

In order to gain a better understanding of changes in lower-limb kinematics between shod and barefoot conditions, the current study reinforces the statement that acute changes occur in the temporal and kinematic variables between shod and barefoot conditions in habitually shod runners. When barefoot running, stride duration, flight time, contact time and step time were significantly lower and shorter, and stride frequency significantly higher, than the shod conditions. When speed was increased in barefoot condition, timing variables decrease significantly at both comfortable and demanding speeds. Because of this, stride and gait cycle were significantly faster and thus led to the highest stride frequency. More research is needed to clarify the effectiveness of barefoot training programs on temporal variables and kinematics of lower limbs in endurance runners.

Conflict of interest

Authors declare that they don't have any conflict of interest.

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