

Original Article

Effect of linear running velocity on the increase on foot pronation

João Otacílio Libardoni dos Santos*, André Luiz Ribeiro Gomes, Ahlan Benezar Lima, Ericles de Paiva Vieira, Ewertton de Souza Bezerra*, Mateus Rossato

Universidade Federal do Amazonas, Faculdade de Educação Física e Fisioterapia, Laboratório de Estudos do Desempenho Humano, Manaus, AM, Brazil



ARTICLE INFO

Keywords:

Foot pronation
Running
Sports medicine

ABSTRACT

The purpose of this study was to investigate the behavior of foot pronation at different percentages of peak velocity in 23 physically active men. An ergospirometric test was carried out with an initial velocity of 9 km h^{-1} and increments of 1 km h^{-1} until exhaustion. 2D kinematic analysis was performed in the posterior frontal plane at all velocities to identify the maximal angle of pronation (MAP) of the right leg. The analyses were performed between the initial periods (0%), 25%, 50%, 75%, and 100% (peak of velocity — PV). All comparisons of the PV phases with the MAP showed an increase in the angle of foot pronation, with the exception of between the start and 25% of PV. Only 4 (~17%) subjects maintained MAP values within a normal range until PV was reached. Control of the volume and intensity of training, as well as the running technique is suggested and strengthening of the muscles responsible for stabilization of the foot pronation.

1. Introduction

The incidence of injuries during running has been extensively studied [1,2]. Van Gent et al. [1] reported an occurrence of up to 79% of injuries in non-elite runners, in different body regions. However, Nigg et al. [2] emphasized that although many studies discuss the prevalence of injuries in running, there is great variability in the results related to frequency, varying between 15% and 85% over the years. This raises a question about the factors that may be involved in this variability, with the aim of defining effective prevention strategies.

Injuries in running can have extrinsic and intrinsic origins, where extrinsic risk factors, or risk factors external to the runner, include training volume, injury history, and training environments [2]. Among the intrinsic risk factors, the two most commonly pointed out in the literature that may be associated with the development of injuries during running are the impact forces during the touch of the heel on the ground and the foot pronation [2,3]. Historically, foot mechanics have been considered to contribute to misalignment and consequent onset of lower extremity pathology through joint coupling with internal rotation of the tibia [4].

However, it is known that foot pronation is a motion of the foot articulations that allows the foot to become more prone to the support surface, thereby increasing the ground contact surface area of the foot [5], which is necessary to attenuate the impact forces between the foot and the ground, since it provides the necessary absorption during the

stance, allowing effective locomotion [6]. Nevertheless, the inability to achieve these end range of joint motions safely when necessary may in its self be an injury mechanism [5,6]. Therefore, it will only be harmful when it reaches excessive values for a long time, added to which, even if pathology is not provoked, a joint moving excessively is a sign that the metabolic efficiency of the motion will be less than optimal [5,6].

Foot pronation has received great attention in scientific studies [4,7] and clinical practice as a potential risk factor for lower extremity overload injuries, particularly when related to increased range of motion (foot hyperpronation). Despite receiving attention in several studies, the existence of a dichotomy in the use of hyperpronation (HP) as a term for normal and abnormal motion helps to perpetuate a state of confusion [5]. However, in this study, foot hyperpronation was understood as a range of motion within the foot that makes the foot more prone to the support surface, which is greater than required by the individual to adjust to morphology or to adapt to the forces placed on the musculoskeletal system by kinetic and kinematic events within gait or another given action [5]. A definition of HP should represent the three states in which HP can occur, these being the amount of pronation; the duration of pronation; and the rate at which forces of pronation are applied to the foot. Each of these situations can cause HP as a single factor or in any combination.

For many years, it was considered that foot pronation, over the thousands of repetitive running cycles, was one of the main factors responsible for the development of overuse injuries [6]. Thus, angular

* Corresponding author at: Laboratório de Estudo do Desempenho Humano (LEDEHU), Faculdade de Educação Física e Fisioterapia, Universidade Federal do Amazonas, Avenida General Rodrigo Octavio Jordão Ramos, nº 3000, Coroado, CEP 69077-000, Manaus, AM, Brazil.

E-mail address: jlibardoni@ufam.edu.br (J.O. Libardoni dos Santos).

<https://doi.org/10.1016/j.foot.2019.09.004>

Received 3 November 2018; Received in revised form 26 August 2019; Accepted 25 September 2019

0958-2592/© 2019 Elsevier Ltd. All rights reserved.

values of foot pronation between 7° and 10° have demonstrated a lower association with the incidence of injury, however, foot hyperpronation (above 10°) has been related with a high prevalence of injuries [2,7,8]. It is believed that this increase in foot pronation may lead to an increase in the magnitude, velocity, and duration of internal rotation of the knee and hip, thus altering the stress imposed on structures of the lower limbs and lumbo-pelvic complex [9].

Therefore, in addition to anatomical factors, the use of orthoses [10], footwear [11], different types of sole [12], and running velocity [7] also seem to exert influence on pronation levels of the hindfoot. Hindfoot hyperpronation can be understood as a range of motion [5]; with regard to running velocity [7], it was observed that increases in velocity lead to significant increases in the maximal pronation angle and maximal pronation velocity. Although the authors evaluated only submaximal intensities (70 and 75% of VO_{2max}), evidence suggests that maintaining high running velocities may alter the heel strategy for the midfoot, and the increase in overload in the first metatarsal could be the explanation for the increase in the angle of pronation of the hindfoot, especially due to the fatigue in the muscles responsible for controlling this movement [13,14]. Most middle-distance and long-distance competitions are performed at submaximal intensities [15], however, during training sessions, maximal and supramaximal velocity stimuli are often required to improve both aerobic capacity and power [16].

Running at high intensities leads to an increase in fatigue, and reduction in neuromuscular control, which may be detrimental to runners [17]. This reduction in neuromuscular control may affect the balance of subtalar complex morphology in the forces imposed on the musculoskeletal system by high intensity running [17,18]. Therefore, foot pronation encountered in moderate intensity running as a natural mechanism of absorption of forces may become foot hyperpronation in high intensity running [19]. This foot hyperpronation induced by fatigue decreases the stiffness of the lower extremity and the energy absorbing capacity results in kinematic, kinetic, and muscle activation compensations to maintain appropriate muscle–joint–complex stiffness and performance [17].

Understanding the responses of this mechanism of absorption of impact (foot pronation) when submitted to non-functional situations by external factors (running intensity), and the consequences on the locomotive apparatus, has aroused the interest of researchers [8,19]. Knowing that several velocities and intensities of running are required in the training sessions and competitions, the objective of the present study was to investigate the behavior of foot pronation at different percentages of peak of velocity. Our hypothesis was that elevation in exercise intensity, by inducing fatigue and reducing neuromuscular control, would lead to increases in foot pronation, which may increase the likelihood of future injuries in running practitioners.

2. Methods

Twenty-three physically active men volunteered to participate in the study (35.51 ± 10.71 years, 69.26 ± 10.25 kg weight, 171.65 ± 8.04 cm height). All participants were submitted to a maximal incremental ergospirometric test on a treadmill with monitoring of cardiorespiratory parameters (heart rate (HR) and volume of oxygen uptake (VO_2)) and kinematic variables (maximal angle of pronation of the hindfoot). The inclusion criteria were: free of heart disease and orthopedic dysfunctions in the upper and lower limbs and physically active with regular aerobic training ($5 \times$ wk) for at least 12 months prior to the start of the study. All procedures performed were approved by the local ethics committee on human research (No. 1,062,842), in accordance with the ethical guidelines of the Declaration of Helsinki (64th WMA General Assembly, Fortaleza, Brazil, October 2013).

2.1. Ergospirometric test

The warm-up for the maximal incremental ergospirometric test (*Movement RT350*®) began at 8 km h^{-1} , with a 5 min duration, preceded by standard stretching exercises for the trunk (spine), and upper (shoulders) and lower limbs (hips, knees, and ankles) consisting of two sets of 15 s, sustained for each exercise. After the warm-up, the experimental protocol started at a velocity of 9 km h^{-1} (start), increasing by 1 km h^{-1} every minute, until maximal voluntary exhaustion (non-sustained total time of the period after the increase) [20]. The participants were encouraged to continue the test until they were no longer able to withstand the stress. After the negative signal expressed by the subject, the velocity was reduced to 4 km h^{-1} , and the 5 min recovery began. Volume of Oxygen consumed (VO_2), Pulmonary Ventilation (VE), and Volume of Carbonic Gas produced (VCO_2) were measured continuously by means of a gas analyzer (*VO2000, Aerosport Medical Graphics, USA*) only as control variables. HR was monitored throughout the test (*Polar RS400*®). The maximum heart rate (HRmax) was determined as the highest value observed throughout the test. Peak velocity (PV) was considered to be the final velocity completed (End).

2.2. Determination of foot pronation

The foot pronation in this study was characterized by maximal angle of pronation of the hindfoot (MAP). The MAP was determined by the difference between the relative angle (α) formed between the segments S1 (D–C) and S2 (A–B) [19], (Fig. 1), obtained in the flat foot phase (Fig. 2d) (highest value observed up to 40% of the support phase from the foot strike) and the angle found at the touch of the heel at the initial contact of the hindfoot (Fig. 2b). To track the points in the software, reflective markers were used, according to previous studies [12,21].

The entire experimental protocol was recorded with a camera (*Panasonic, Lumix FZ 200, 120 Hz*) positioned in the posterior frontal plane, 30 cm above the ground and 1 m from the treadmill. The

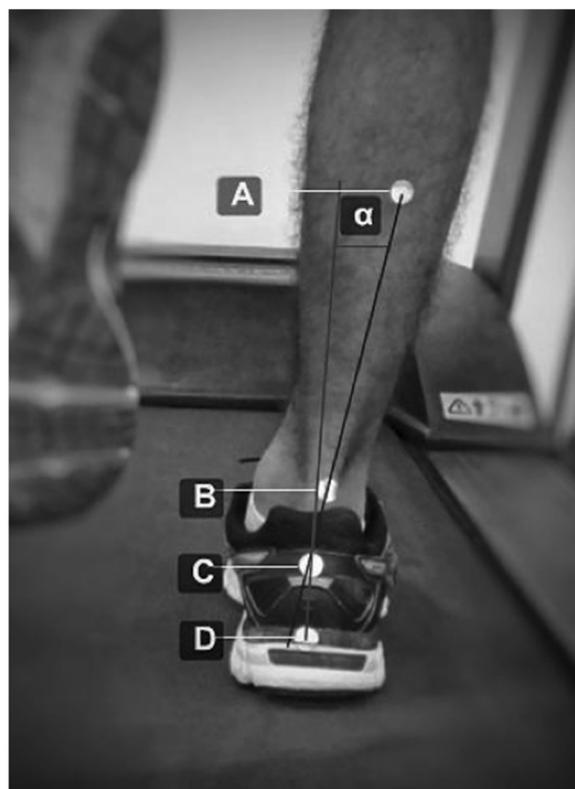


Fig. 1. Four-point mathematical model for calculating the foot pronation angle, posterior frontal plane.

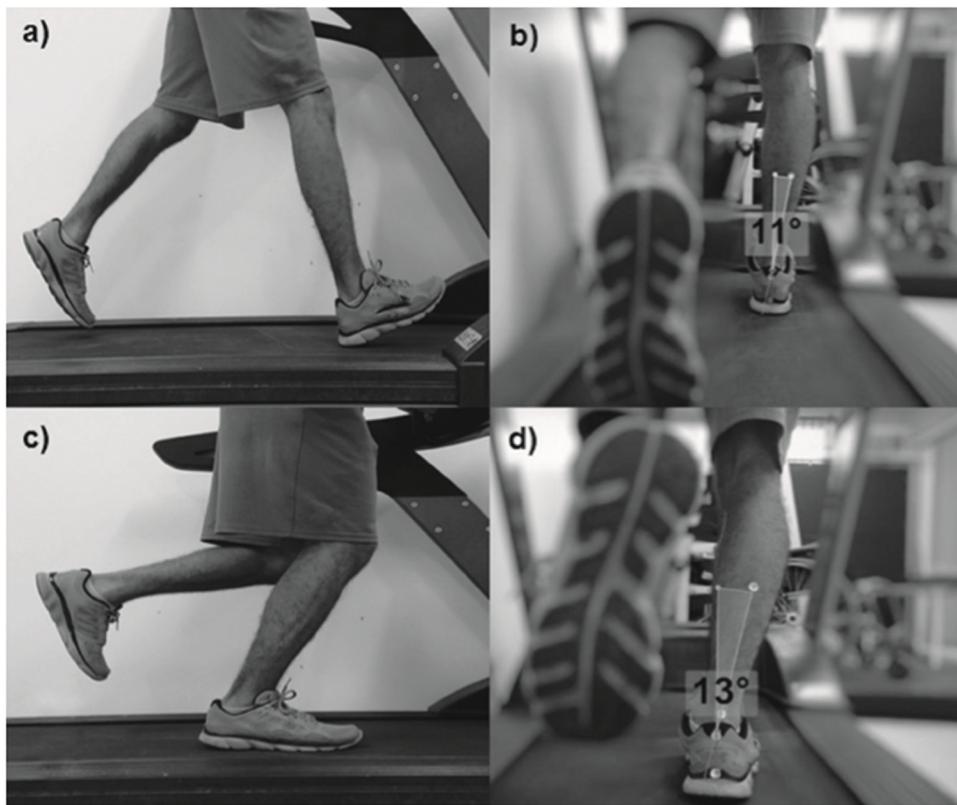


Fig. 2. Initial contact (a), 40% of the support phase (c), and angles in the respective phases (b and d).

sampling rate used in this study was 120 Hz (frames per second). After the test, the MAP of the right lower limb was analyzed through *Kinovea* software (version 0.8.25 Joan Charmant & Contrib) in 5 steps for each velocity [12]. The data were normalized individually. Participants were instructed to perform the test with training shoes suitable for running. For the purpose of analysis, the velocity of 9 km h⁻¹ (start), the PV, and 25, 50, and 75% of the PV (End) were considered.

2.3. Statistical analysis

The effect size (ES) was calculated to compare the MAP in different % of PV. Magnitude-based inference analyses were used to examine practical significances. The magnitude of differences between %PVs was calculated and expressed as standardized mean differences. We adopted the criteria of Cohen for the analysis (0.20: small; 0.50: moderate; and 0.80: large) [22]. The chances of the true (unknown) mean changes being trivial, positive, or negative (i.e., greater than the smallest worthwhile change [0.2 multiplied by the between-subjects' SD]) were determined. Quantitative chances of a positive or negative effect were assessed qualitatively, as follows: < 1% = most unlikely; 1–5% = very unlikely; 5–25% = unlikely; 25–75% = possibly; 75–95% = likely; 95–99% = very likely; and > 99% = most likely. If the chances of positive and negative effects were both 5%, then the true difference was assessed as unclear.

3. Results

The physiological and maximal and submaximal parameters are

Table 1
Maximum physiological parameters and maximal and submaximal performances.

	VO _{2max} (ml kg ⁻¹ min ⁻¹)	HR _{Ma} (bpm)	PV (km h ⁻¹)	Vel. v _{T1} (km h ⁻¹)	Vel. v _{T2} (km h ⁻¹)
n = 23	43.25 ± 8.90	178 ± 1	18.91 ± 2.83	10.43 ± 1.47	13.17 ± 2.06

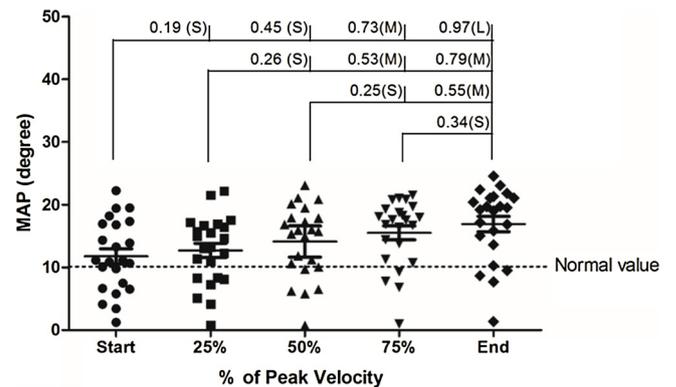


Fig. 3. Effect size of the running intensities on the maximum angle of pronation.

described in Table 1.

Fig. 3 presents the values of MAP at the different percentages of the peak velocity (Start, 25, 50, 75%, and End), as well as their respective ES. Considering the ES values, a gradual increase in MAP was observed as the intensity rose. These increases are barely perceptible (ES = S-small) when compared to the higher intensity (Start to 25%: ES = 0.19; 25%–50%: ES = 0.26; 50%–75%: ES = 0.25; 75% to End: ES = 0.34). It was also observed that at 9 km/h (Start), 9 subjects (~39%) presented MAP values considered adequate (< 12°). The number of subjects who maintained MAP values within a normal range decreased to 4

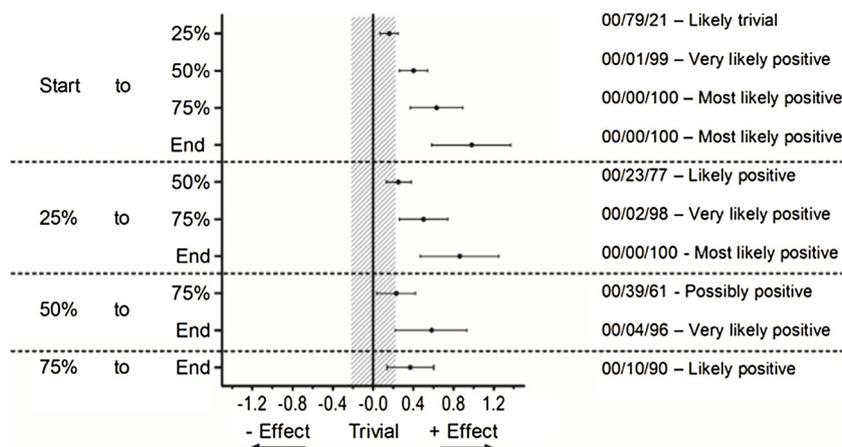


Fig. 4. Magnitude of the effect comparing different running intensities.

(~17%) at peak velocity (End).

The qualitative analyses of the MAP at the different intensities are presented in Fig. 4. With the exception of the comparison between Start and 25% (Likely trivial) all other comparisons presented positive effects of intensity on the increase in MAP. Comparisons with peak velocity (End) indicated “Most likely positive” effects for the conditions Start and 25%, “Very likely positive” effects for the intensity of 50%, and “Likely positive” for the intensity of 75%. These results reinforce the findings of Fig. 3, where the increase in the intensity of the effort raises the odds of foot hyperpronation.

4. Discussion

The main objective of the present study was to investigate the behavior of foot pronation at different percentages of peak of velocity. Our data confirmed the hypothesis that an increase in intensity leads to increases in MAP both at submaximal and maximal intensities. In addition, we observed that some subjects, who presented MAP values considered to be normal (< 10°) at submaximal running intensities, presented higher MAP values with increased intensity of the effort. These results reinforce the need for MAP assessments at different intensities, including the PV.

An elevation in running velocity has been pointed out as a potential modifying factor of the magnitude of biomechanical variables during locomotion [23]. The hypothesis that the increase in running velocity could affect the MAP was first confirmed by Tartaruga et al. [7]. The authors observed that when running velocity ranged from 11 to 13 km h⁻¹, the MAP increased from 5.87 ± 4.66° to 9.44 ± 5.15° in women, while in men, when the velocity increased from 14 km h⁻¹ to 16 km h⁻¹ the MAP increment was from 6.79 ± 4.01° to 9.69 ± 3.14°. Subsequently, Oliveira et al. [8] also investigated the effects of the slope gradient (+ 1%, + 5%, + 10%, + 15%) on MAP in submaximal running and did not observe significant changes. Our data confirm the hypothesis raised by Tartaruga et al. [7], since we observed increases of 8.7% (start to 25%), 12.6% (25–50%), 11.8% (50–75%), and 10.2% (75% to End), especially when approaching exhaustion. It is believed this change demonstrates subtle compensations in running patterns as runners approach exhaustion and that some individuals are more sensitive to the effects of fatigue, as evidenced by extreme compensations in running pattern [24]. Van Gheluwa et al. [25] concluded that running at high speed to voluntary exhaustion significantly increases rearfoot motion, as represented by maximal heel eversion and subtalar pronation, and the pattern of heel eversion and subtalar pronation is similarly affected by exhaustion, and, furthermore, the rearfoot movement is directly affected by fatigue and not by a fatigue-induced increase in step length.

It is also worth noting that the subjects who presented MAP within

normality (MAP < 10°) at submaximal intensities, no longer presented normal levels as the intensity of effort rose. An example of this is that at the rate of 9 km h⁻¹ (Start), 8 subjects presented MAP values below 10°, while at the end (End) only 4 subjects maintained this normality. Thus, elevation of the angular values of MAP and the fact that subjects at intensities near maximal present values higher than those considered normal, leads to concern. This is due to the increase in the range of motion in this joint, which alters the stresses imposed on the structures of the lower limbs and the lumbo-pelvic complex, which may cause damage to the musculoskeletal system [26]. Furthermore, there is strong evidence that foot hyperpronation is a risk factor for the development of medial tibial stress syndrome and possibly a risk factor for the development of patellofemoral pain [3].

It is known that high intensities affect many parameters of running [24], and these changes can be explained by the increased fatigue, with a consequent decrease in neuromuscular system control [17]. This reduction makes it difficult to maintain the compensations necessary in the muscle–joint–complex, and consequently, the stiffness of the joint and performance during running [17].

Thus, understanding that the mechanics of the feet contribute to the misalignment and pathology of the lower extremities by means of joint coupling with the internal rotation of the tibia [4], and that amplitudes greater than those considered physiological characterize foot hyperpronation and cause greater joint overload and may be associated with the onset of injuries [3], the importance of minimizing these alterations during running practice should be emphasized. In addition, it was found that an increase in the running intensity exposed the majority of the individuals to foot pronation beyond that considered normal. It is believed that strict control of factors related to the training regime (training volume, intensity, and rest periods), training environment (including soil rigidity, incline, decline, and traction), and variables such as body composition, aerobic fitness, muscle strength, balance, and movement technique may contribute to reducing these alterations while preserving the integrity of the lower limbs.

In addition, the importance of strengthening the anterior tibial muscle, one of the muscles responsible for the neuromuscular control of this joint during foot-strike, is also highlighted. Previous studies have shown that fatigue of this muscle promotes imbalance between dorsiflexors and ankle flexors and a consequent increase in the acceleration of tibial impact [17,18]. This fact alerts athletes to the aspects to which they are subjected, since immediate care, such as strengthening the specific muscles responsible for controlling this movement, especially at higher training intensities, could be an important ally in the prediction of injuries.

4.1. Brief summary

- Intensity of running is a determining factor on the other variables that could influence the maximum angle of foot pronation.
- Emphasis is placed on the importance of care in training control, as well as on the running technique and strengthening of the muscles responsible for stabilization of the foot pronation.
- The originality of MAP testing at maximal aerobic velocities (PV).
- Use of a simple method to identify MAP, which could be used by professionals such as running technicians and physiotherapists.

Conflict of interest

We wish to confirm that there are no known conflicts of interest.

References

- [1] van Gent RN, Siem D, van Middelkoop M, van Os AG, Bierma-Zeinstra SMA, Koes BW. Incidence and determinants of lower extremity running injuries in long distance runners: a systematic review. *Br J Sports Med* 2007;41:469–80. <https://doi.org/10.1136/bjism.2006.033548>. discussion 480.
- [2] Nigg BM, Baltich J, Hoerzer S, Enders H. Running shoes and running injuries: mythbusting and a proposal for two new paradigms: “preferred movement path” and “comfort filter”. *Br J Sports Med* 2015;49:1290–4. <https://doi.org/10.1136/bjsports-2015-095054>.
- [3] Neal BS, Griffiths IB, Dowling GJ, Murley GS, Munteanu SE, Franettovich Smith MM, et al. Foot posture as a risk factor for lower limb overuse injury: a systematic review and meta-analysis. *J Foot Ankle Res* 2014;7. <https://doi.org/10.1186/s13047-014-0055-4>.
- [4] Tiberio D. The effect of excessive subtalar joint pronation on patellofemoral mechanics: a theoretical model. *J Orthop Sports Phys Ther* 1987;9:160–5. doi:1911 [pii].
- [5] Horwood AM, Chockalingam N. Defining excessive, over, or hyper-pronation: a quandary. *Foot* 2017;31:49–55. <https://doi.org/10.1016/j.foot.2017.03.001>.
- [6] Jimenez-Perez I, Gil-Calvo M, Priego Quesada JI, Aparicio I, Sanchis-Sanchis R, Pérez-Soriano P. Foot orthosis in running. *Mater Sport Equip* 2019;451–85. <https://doi.org/10.1016/B978-0-08-102582-6.00016-2>.
- [7] Tartaruga LAP, Tartaruga MP, Black GL, Coertjens M, Ribas LR, Krueel LFM. Comparação do ângulo da articulação subtalar durante velocidades submáximas de corrida. *Acta Ortopédica Bras* 2005;13:57–60. <https://doi.org/10.1590/S1413-78522005000200001>.
- [8] Oliveira VM, Detoni GC, Ferreira C, Portela BS, Queiroga MR, Tartaruga MP. Influência do gradiente de inclinação na pronação subtalar em corrida submáxima. *Acta Ortop Bras* 2013;21:163–6. <https://doi.org/10.1590/S1413-78522013000300007>.
- [9] T.R. Souza, R.Z. Pinto, R.G. Trede, R.N. Kirkwood, A.E. Pertence, S.T. Fonseca, Late rearfoot eversion and lower-limb internal rotation caused by changes in the interaction between forefoot and support surface, *J Am Podiatr Med Assoc*, n.d., 99: 503–511.
- [10] McCulloch MU, Brunt D, Vander Linden D. The effect of foot orthotics and gait velocity on lower limb kinematics and temporal events of stance. *J Orthop Sports Phys Ther* 1993;17:2–10. <https://doi.org/10.2519/jospt.1993.17.1.2>.
- [11] Zhang X, Delabastita T, Lissens J, De Beenhouwer F, Vanwanseele B. The morphology of foot soft tissues is associated with running shoe type in healthy recreational runners. *J Sci Med Sport* 2018;21:686–90. <https://doi.org/10.1016/j.jsams.2017.11.008>.
- [12] De Wit B, De Clercq D, Lenoir M. The effect of varying midsole hardness on impact forces and foot motion during foot contact in running. *J Appl Biomech* 1995;11:395–406. <https://doi.org/10.1123/jab.11.4.395>.
- [13] Willson JD, Kernozek TW. Plantar loading and cadence alterations with fatigue. *Med Sci Sports Exerc* 1999;31:1828–33.
- [14] Headlee DL, Leonard JL, Hart JM, Ingersoll CD, Hertel J. Fatigue of the plantar intrinsic foot muscles increases navicular drop. *J Electromyogr Kinesiol* 2008;18:420–5. <https://doi.org/10.1016/j.jelekin.2006.11.004>.
- [15] De Souza KM, De Lucas RD, Grossl T, Costa VP, Guilherme L, Guglielmo A. Performance prediction of endurance runners through laboratory and track tests. *Rev Bras Cineantropometria e Desempenho Hum* 2014;465–74. <https://doi.org/10.5007/1980-0037.2014v16n4p465>.
- [16] Cicioni-Kolsky D, Lorenzen C, Williams MD, Kemp JG. Endurance and sprint benefits of high-intensity and supramaximal interval training. *Eur J Sport Sci* 2013;13:304–11. <https://doi.org/10.1080/17461391.2011.606844>.
- [17] Dutto DJ, Smith GA. Changes in spring-mass characteristics during treadmill running to exhaustion. *Changements des caractéristiques de raideur des jambes lors d’une course d’effort sur tapis roulant. Med Sci Sport Exerc* 2002;34:1324–31.
- [18] Mizrahi J, Verbitsky O, Isakov E. Fatigue-related loading imbalance on the shank in running: a possible factor in stress fractures. *Ann Biomed Eng* 2000;28:463–9. <https://doi.org/10.1114/1.284>.
- [19] do Santos JOL, Manfio EF, Carpes FP, de Souza Bezerra E, Palhano R, Otavio Vargas Avila A. Change of pronation angle of the subtalar joint has influence on plantar pressure distribution. *Rev Bras Cineantropom Hum* 2017;316–22. <https://doi.org/10.5007/1980-0037.2017v19n3p316>.
- [20] Eduardo A, De Silva Liveira FR. Estimativa dos limiares ventilatórios através da velocidade máxima em teste incremental. *Motriz Rev Educ Fis* 2004;10:37–44.
- [21] Tartaruga MP, Cadore EL, Alberton CL, Nabinger E, Peyré-Tartaruga LA, Ávila AOV, et al. Comparação de protocolos para determinação do ângulo de pronação subtalar. *Acta Ortopédica Bras* 2010;18:122–6. <https://doi.org/10.1590/S1413-78522010000300001>.
- [22] Cohen J. Hillsdale NJ, editor. *Statistical power analysis for the behavioral sciences*. 2nd ed. Lawrence Erlbaum Associates; 1988.
- [23] Nummela A, Keränen T, Mikkelsen L. Factors related to top running speed and economy. *Int J Sports Med* 2007;28:655–61. <https://doi.org/10.1055/s-2007-964896>.
- [24] Siler WL, Martin PE. Changes in running pattern during a treadmill run to volitional exhaustion: fast versus slower runners. *Int J Sport Biomech* 1991;7:12–28. <https://doi.org/10.1123/ijsb.7.1.12>.
- [25] Van Gheluwe B, Madsen C. Frontal rearfoot kinematics in running prior to volitional exhaustion. *J Appl Biomech* 1997;13:66–75. <https://doi.org/10.1123/jab.13.1.66>.
- [26] de Souza TR, de A Pinto RZ, Trede RG, de Araújo PA, Fonseca HL, da Fonseca ST. Pronação excessiva e varismos de pé e perna: relação com o desenvolvimento de patologias músculo-esqueléticas - revisão de literatura. *Fisioter e Pesqui* 2011;18:92–100. <https://doi.org/10.1590/S1809-29502011000100016>.