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The Influence of the Shoe over the Medial Foot Arch and the Lower Limbs Kinematics in Toddlers*

A influência de calçados no arco longitudinal medial do pé e na cinemática dos membros inferiores de crianças no início da fase de aquisição de marcha

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Abstract

Objective To evaluate the biomechanical behavior of the medial longitudinal arch (MLA) of the foot and the kinematic parameters of the lower limbs with biomimetic footwear (BF) and non-biomimetic (NB1, NB2, NB3 and NB4) footwear in children at the beginning of the gait acquisition phase.

Methods Four toddlers were evaluated at the beginning of the gait acquisition phase under the following conditions: walking barefoot, ambulation with BF and NB1, NB2, NB3 and NB4 footwear in hard floor. BF is described as biomimetic because of its property of emulating natural and irregular floors through a dynamic internal insole. The MLA and kinematics of the hip, knee, and ankle during gait were evaluated by three-dimensional motion analysis system. The similarity between the kinematic curves of barefoot and footwear conditions was analyzed by root mean square error (RMSE).

Results The use of BF presented the highest magnitude of MLA and the greatest difference in relation to barefoot condition (higher RMSE). The BF showed less difference in the kinematics of the knee and ankle joints during gait when compared to barefoot condition (lower RMSE). NB2 footwear presented hip kinematics more similar to barefoot condition (lower RMSE).

Keywords
- gait
- child
- biomimetics
- shoes

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Conclusion Biomimetics footwear and NB2 shoes (both with wider forefoot region) generated smaller differences in lower limbs compared to barefoot. In addition, the MLA was higher in the BF, probably because different design from other shoes.

Resumo

Objetivo Avaliar o comportamento do arco longitudinal medial (ALM) do pé e os parâmetros cinemáticos dos membros inferiores durante a deambulação com calçados biomiméticos (CBs) e não biomiméticos (NB1, NB2, NB3 e NB4) em crianças no início da fase de aquisição da marcha.

Métodos Foram avaliadas quatro crianças no início da fase de aquisição da marcha nas seguintes condições: andar descalço, andar com CBs e com calçados NB1, NB2, NB3 e NB4 em solo plano. O CB é descrito como biomimético por emular pisos naturais e irregulares por meio de uma palmilha interna dinâmica. O ALM e a cinemática do quadril, joelho e tornozelo durante a marcha foram avaliados por meio de um sistema de análise do movimento tridimensional. A similaridade entre as curvas cinemáticas das condições descalça e com calçado foi analisada por meio do cálculo de *root mean square error* (RMSE).

Resultados O CB foi o que apresentou maior magnitude do ALM e maior diferença do ALM em relação à condição descalça (maior RMSE). O CB apresentou ainda menor diferença na cinemática das articulações do joelho e tornozelo durante a marcha quando comparado à condição descalça (menor RMSE). O calçado NB2 apresentou a cinemática do quadril mais semelhante à condição descalça (menor RMSE).

Conclusão Os calçados CB e NB2 que apresentam a região do antepé mais larga geraram menores diferenças na cinemática dos membros inferiores. Além disso, o ALM foi maior no CB, provavelmente devido a seu design ser diferente daquele dos demais calçados.

Palavras-chave
- marcha
- criança
- biomimética
- calçados

Introduction

Urban life causes children to be constantly with shoes.[1–3] Shoes are the interface between the body and the ground, in the upright position. During locomotion, footwear directly affects how ground reaction forces are generated and transfer to the entire body.[4,5] Despite the growing interest in the literature on the effect of footwear on locomotion, this effect in toddlers, at gait development phase, has not been extensively explored.[6]

The beginning of the independent gait takes place around 15 months of age.[7,8] The foot has several functions in the gait: i) to accommodate soil irregularity and balance maintenance; ii) weight support and load absorption and iii) generate forward movement, transmitting propulsive forces.[9] Thus, during locomotion, oddlers need to move their body mass forward while balancing on uni and bipodal support, bringing a double challenge of stability and progression.[10]

At the beginning of the acquisition of independent gait, the feet bones have several ossification centers connected by soft tissues[11] The development of bone structures happens until the age of five years old.[12] This process of ossification corroborates the absence of the medial longitudinal arch (MLA) of the foot in toddlers.[9] Thus, it is expected that the gait itself will help to promote the development of the MLA.

More than protect the feet, the size, shape, and design of footwear can interfere the structural development and its function, impacting on the musculoskeletal system over the time.[3] Studies indicate the use of footwear in early childhood can lead to morphological changes, compared to people who do not wear shoes.[13,14] These changes in the shape of the foot can reduce the ability to mitigate the impact of forces by podal structures, and may change the way we walk. Studies highlighted the importance of walking barefoot for the function and complete foot development.[13,14] Walking barefoot provides muscle strength, foot mobility, prevents static deformities and affects the height of the MLA.[2,13,14] Walking in natural and different types of terrain has the potential to affect the mechanics and energy of locomotion,[15] allowing feet generating constant adjustments to maintain stability.[16] Footwear worn by children during the gait development phase may play an important role in the development of the musculoskeletal system.

The design of nature-inspired products has been called biomimetics.[17] Considering walking barefoot provides good experiences because the contact of natural terrain, biomimetic footwear could impact over MLA of toddlers. Specially in the gait development phase and over kinematics of the lower limb joints during this movement. The aim of this study was to evaluate the biomechanical behavior of MLA and kinematic parameters of the lower limbs of toddlers during gait using biomimetic and non-biomimetic footwear, comparing with walking barefoot.

Methods

A case study[18] was conducted with four oddlers aged between 13 and 17 months (15.50 ± 1.73 months), with body mass from 10 to 12 kg (11.20 ± 0.74 kg), and height from 78 to 90 cm (82 ± 5 cm), with typical motor development. All ddlers had between 2 and 3 months of experience of walking without support. The present study was approved by the research ethics committee of the institution (number 2,083,328), and all parents signed the free and informed consent form before any procedure was performed.

The toddlers performed independent gait on hard floor and were evaluated in six randomized conditions 1) Barefoot; 2) biomimetic footwear (BF); 3) Non-biomimetic footwear 1 (NB1); 4) Non-biomimetic footwear 2 (NB2); 5) Non-biomimetic footwear 3 (NB3); 6) Non-biomimetic footwear 4 (NB4). ►**Table 1** shows the characteristics, and ►**Figure 1** shows the images of the shoes tested.

Gait evaluation was performed by three-dimensional motion analysis system (Qualisys Medical AB, Gothenburg, Sweden). Pelvis, thigh, leg, and foot were tracked during gait by 22 retro reflective markers (►**Figure 2**). Anatomical markers were used for static calibration to define body segments and their coordinate systems.

The data were analyzed in visual 3D software (C-Motion Inc., Rockville, MD, USA). All data were low pass filtered with butterworth, fourth order at 6Hz cutoff frequency. Joint centers were estimated according to the literature.[19] The hip, knee and ankle angles in the sagittal plane were extracted. The MLA of the foot was determined by the angle between a vector connecting calcaneus and navicular markers and a vector connecting the navicular and the first metatarsal head markerers.[20] Thus, the smaller the angle, the greater the MLA of the foot. In addition, the lower limbs were classified as support and advance foot.[10] In this classification, the lower limb with the longest stride length is classified as the advance foot, and the contralateral as the support.[10]

The toddlers walked independently, at self-selected speed. Verbal, visual, and playful stimuli were used to facilitate the task performance. At least 10 complete strides were analyzed for each lower limb.

The RootMean Square Error (RMSE) index was calculated to estimate the similarity between the curves of the angular variation over time with each shoe and the barefoot walk. This RMSE index is always positive and measures the magnitude of the difference between kinematic curves.[20] In other words, this score measures the difference between the kinematic curve data of each condition (BF, NB1, NB2, NB3, NB4) in relation to the mean of a reference standard, which, in this study, was the barefoot condition. Thus, the higher the RMSE value, the greater the difference between the curves obtained with the shoes analyzed in relation to walking barefoot.

Results

All participants presented longer stride length on the right side (0.399 ± 0.08 m) than on the left side (0.393 ± 0.08 m), classified as advance and support foot, respectively.

The MLA's mean curves at each conditions are presented in ►**Figure 3**, and the RMSE values are represented in ►**Figure 4.** ►**Figures 3a** and **3b** present the MLA mean curve during the stance phase of the gait cycle in the barefoot condition. In these curves, it is possible to observe that the MLA angle is small in the initial gait contact, and it gradually increases, with the peak of this angle occurring around 80% of the support phase, probably contributing to the body impulsion during gait. Still considering barefoot condition, it is clear the difference between advance and support foot. The advance foot (►**Figure 3b**) presented greater MLA angle than support foot (►**Figure 3a**). ►**Figures 3c** and **3d** show the MLA curves in barefoot (red line), used as a reference, and different shoes investigated. We observed the effect of footwear is different depending on the function of the foot: support (►**Figure 3c**) or advance (►**Figure 3d**). Biomimetic Footwear (turquoise blue line) presented the highest MLA (i.e., smallest angle) on both feet. This finding corroborates to the highest RMSE (►**Figure 4**). At this way, BF presented the MLA most different from the barefoot condition.

The average angles curves of hip, knee, and ankle in each condition are presented in ►**Figure 5.** The greatest differences between the conditions are at the end of the support phase (approximately between 50 and 70% of the gait cycle) at ankle joint. The RMSE differences between the barefoot and with the shoes investigated are shown in ►**Figure 6**. The shoes that presented lower RMSE (i.e., greater similarity with

Table 1 Measurements of the footwear used

Footwear	Length (cm)	Mass (g)	External width forefoot (cm)	Internal width forefoot (cm)	Insole	Distance from foot to ground (cm)
Biomimetic (BF)	13.6	517.0	7.3	6.7	Dynamics	1.0
Non-Biomimetic 1 (NB1)	14.6	291.0	6.9	6.0	Static	2.0
Non-Biomimetic 2 (NB2)	14.2	195.5	6.9	6.4	Static	2.0
Non-Biomimetic 3 (NB3)	14.1	429.5	6.5	5.6	Static	1.5
Non-Biomimetic 4 (NB4)	13.9	561.5	6.8	5.6	Static	1.3

Source: elaborated by the authors (2021)

Fig. 1 Images of the toddlers' shoes evaluated. (A) BF: biomimetic footwear; (B) NB1: non-biomimetic footwear 1; (C) NB2: non-biomimetic footwear 2; (D) NB3: non-biomimetic footwear 3, (E) NB4: non-biomimetic footwear 4. Source: elaborated by the authors (2021).

barefoot gait) were BF (turquoise column) and NB2 (green column) (►Figure 6).

Discussion

This study showed graphical differences between shod and unshod conditions. This finding suggests footwear may affect the movement pattern of children. In addition, the findings indicated walking with BF was, in general, more similar to barefoot at lower limb (i.e., lower RMSE) and more different at MLA angle (i.e., higher RMSE). Considering this, the footwear design seems to influence the lower limb kinematic variables in toddlers. This study suggests that design that considers biomimetism may impacts MLA of toddlers, and preserves joint movements of lower limbs more similar to barefoot.

There is a growing interest in children's footwear, especially in the last 10 years.[5] However, just few studies consider the impact of footwear on toddlers. Some authors[3,21] claim that footwear can have a long-term effect on foot function. Footwear with a biomimetic and anatomical design can protect the foot and may maintain natural flexibility, forefoot width, and sustain foot MLA.

The MLA is dependent on passive and active anatomical structures. Plantar aponeurosis is considered important structure during the support phase, along with ligaments, while leg and intrinsics foot muscles act as an active support.[22] ►Figure 3 shows average feet MLA curves during gait of four toddlers in the barefoot condition. Graphically, the behavior of the curves is very similar to the curves of the MLA of adults in the barefoot condition.[22,23] The differences described by the RMSE related to MLA, especially BF compared to walking barefoot, can be explained by two conjectures. The first would be through a mechanical effect of the insole of biomimetic footwear. During the gait stance phase, a higher pressure is applied to the lateral part of the foot. The biomimetic footwear has a dynamic insole that contains material similar to grains of sand. The insole material probably accumulates under the region with lower pressure (i.e., the medial region of the foot), favoring the increase of MLA. The second conjecture is the dynamic insole of biomimetic footwear may have stimulated the activity of

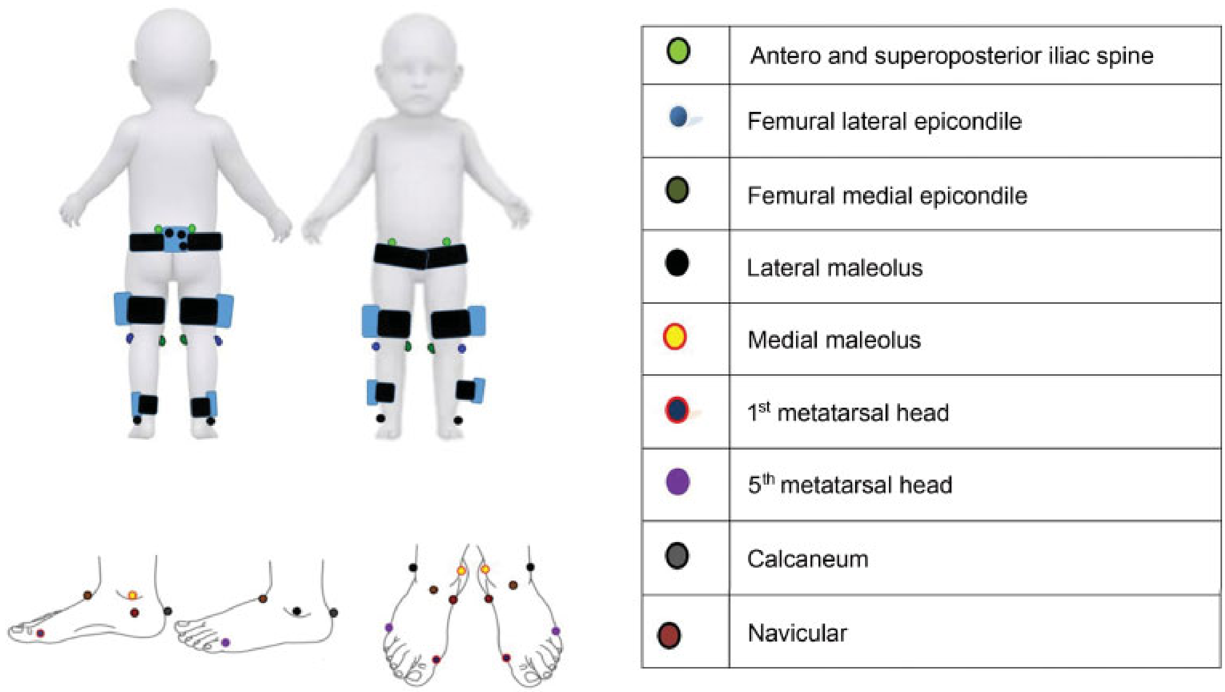

Fig. 2 Squematic design illustrating the positioning of retroreflective markers used over toddlers' bodies. The bottom image illustrates in more detail the position of the feet markers. Source: elaborated by the authors (2021).

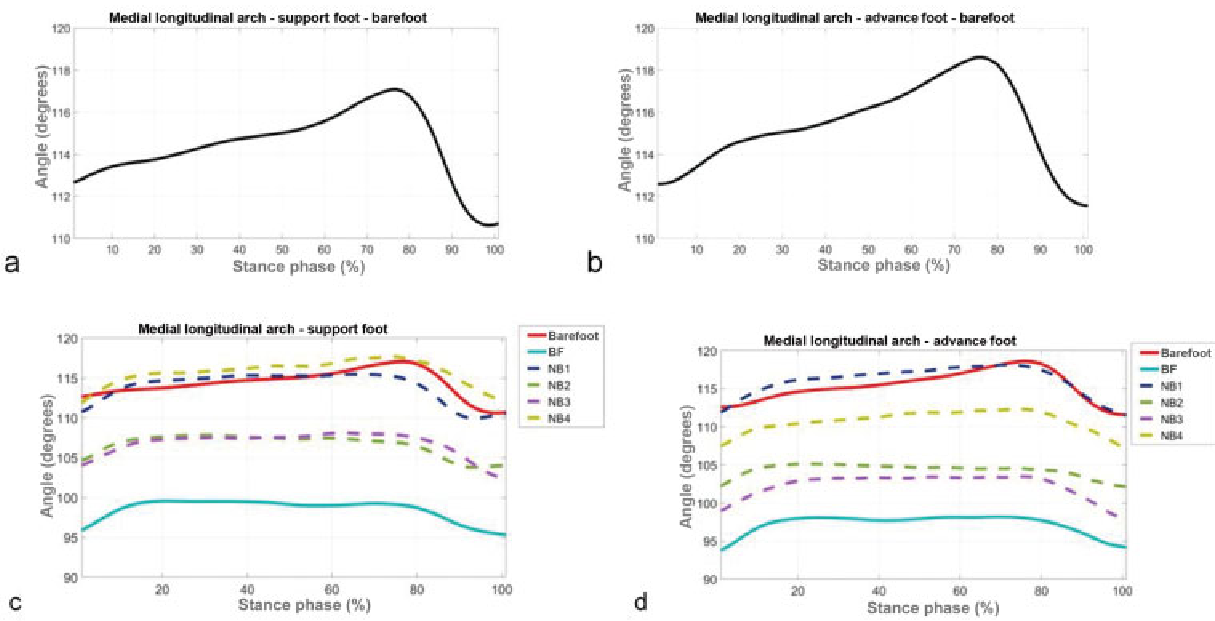

Fig. 3 Graphics of the mean medial longitudinal arch (MLA) curves of the foot during the gait of four toddlers in all conditions evaluated. (**A**) Barefoot support foot; (**B**) Barefoot advance foot; (**C**) Support foot: BF (biomimetic footwear), NB1 (non-biomimetic footwear 1), NB2 (non-biomimetic footwear 2), NB3 (non-biomimetic footwear 3), NB4 (non-biomimetic footwear 4) and, (**D**) Advancefoot: BF (biomimetic footwear), NB1 (non-biomimetic footwear 1), NB2 n-biomimetic footwear 2), NB3 (non-biomimetic footwear 3), NB4 (non-biomimetic footwear 4). Source: elaborated by the authors (2021).

the muscles of the plantar region of the foot. In this perspective, muscle contraction may contribute to the formation of MLA. This second possibility corroborates the observations of Kung et al.,[1] who stated that walking barefoot would increase muscle strength in the ankle and foot region, specifically plantar flexors, inverters, and ankle adductors. RMSE showed MLA higher difference between BF and barefoot. This difference and the biomechanical behavior of MLA when toddler is using BF suggest an increase of the stiffness of the midfoot. This effect corroborates the role of the foot in acting as a rigid lever at the end of the stance phase to impulse the body ahead during gait.[24] However the literature

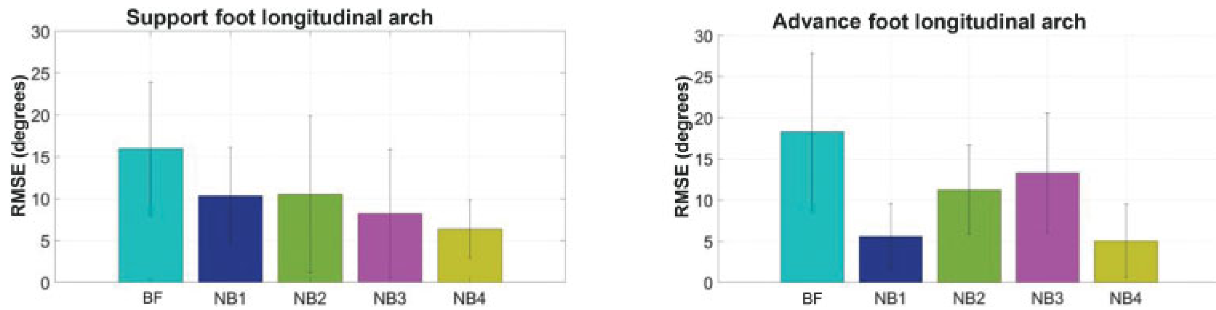

Fig. 4 Graphs of the means of the differences of the curves of the longitudinal arch of the foot (RMSE) during the gait of four children with different shoes, compared with barefoot condition. BF (biomimetic footwear), NB1 (non-biomimetic footwear 1), NB2 (non-biomimetic footwear 2), NB3 (non- biomimetic footwear 3), NB4 (non- biomimetic footwear 4). Source: Prepared by the authors (2021).

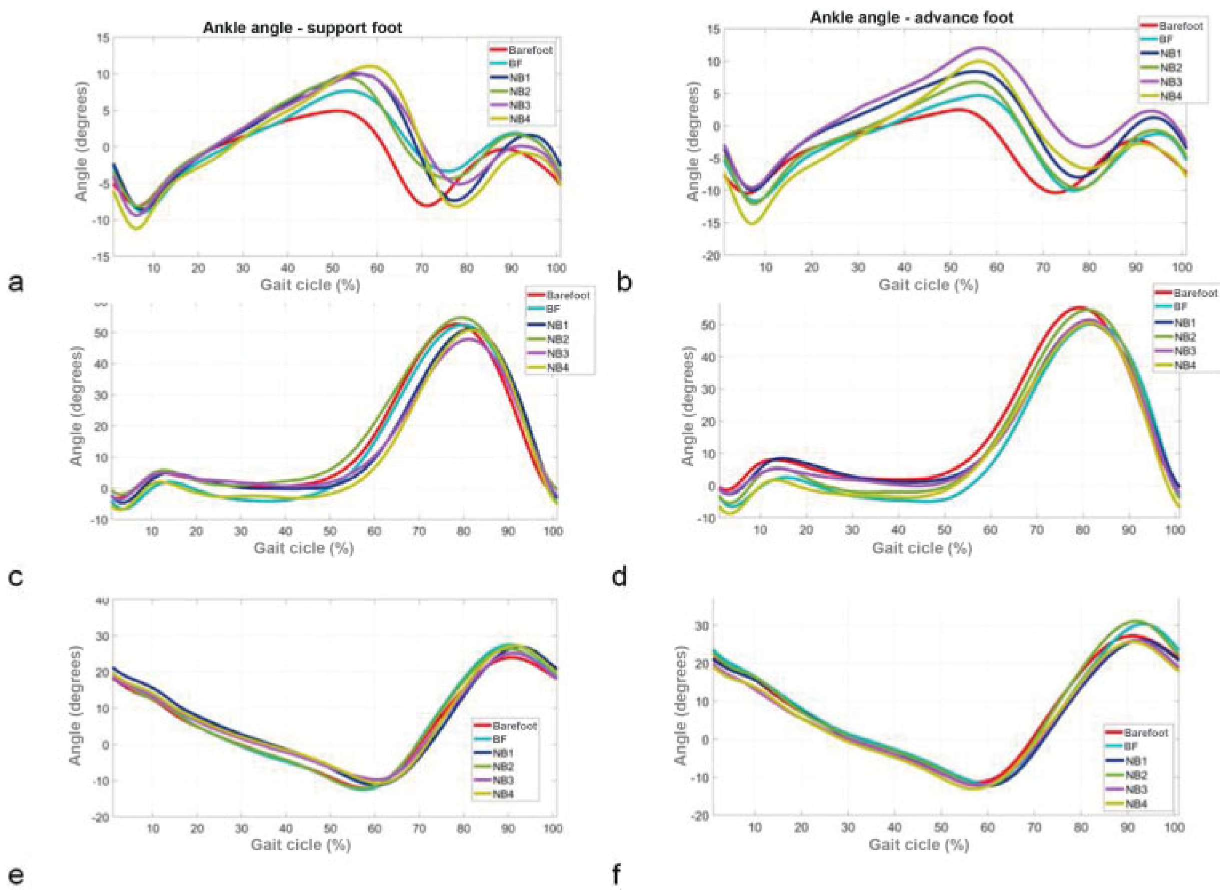

Fig. 5 Graphs of the mean of the angular curves of the ankle (a and b), knee (c and d) and hip (e and f) during the gait of four toddlers in all conditions evaluated: Barefoot, BF (biomimetic footwear), NB1 (non-biomimetic footwear 1), NB2 (non-biomimetic footwear 2), NB3 (non-biomimetic footwear 3), NB4 (non-biomimetic footwear 4). Dorsiflexion and flexion: positive values in the graphs. Source: elaborated by the authors (2021).

indicates MLA is not influenced only by local factors. Its development is dependent on several factors, such as body weight, physical activity, ethnicity, and age.[12,25]

The morphology and anatomy of the to foot at the beginning of gait acquisition has been associated with the body dimensions of the child.[26] Body weight more than doubles from birth to the first year of life. In addition, the length of the lower limb increases around 50% from birth to 18 months old, and 50% of the adult foot length is reached around 12 to 18 months old.[26] Studies[27] indicates that motor development depends not only on neuromuscular maturation, but also the influence of external factors, such as posture (gravity and positioning), physical growth (mass, length, and proportions), muscle strength, and upright balance development. Between two and five years old is considered an important period where the independent gait starts significantly impact directly on the development of the foot.[26] Shoes that mimics the irregularity of surfaces such as walking in the sand, can provide an safe variation for toddlers. Urban children are generally exposed to hard, regular surfaces in

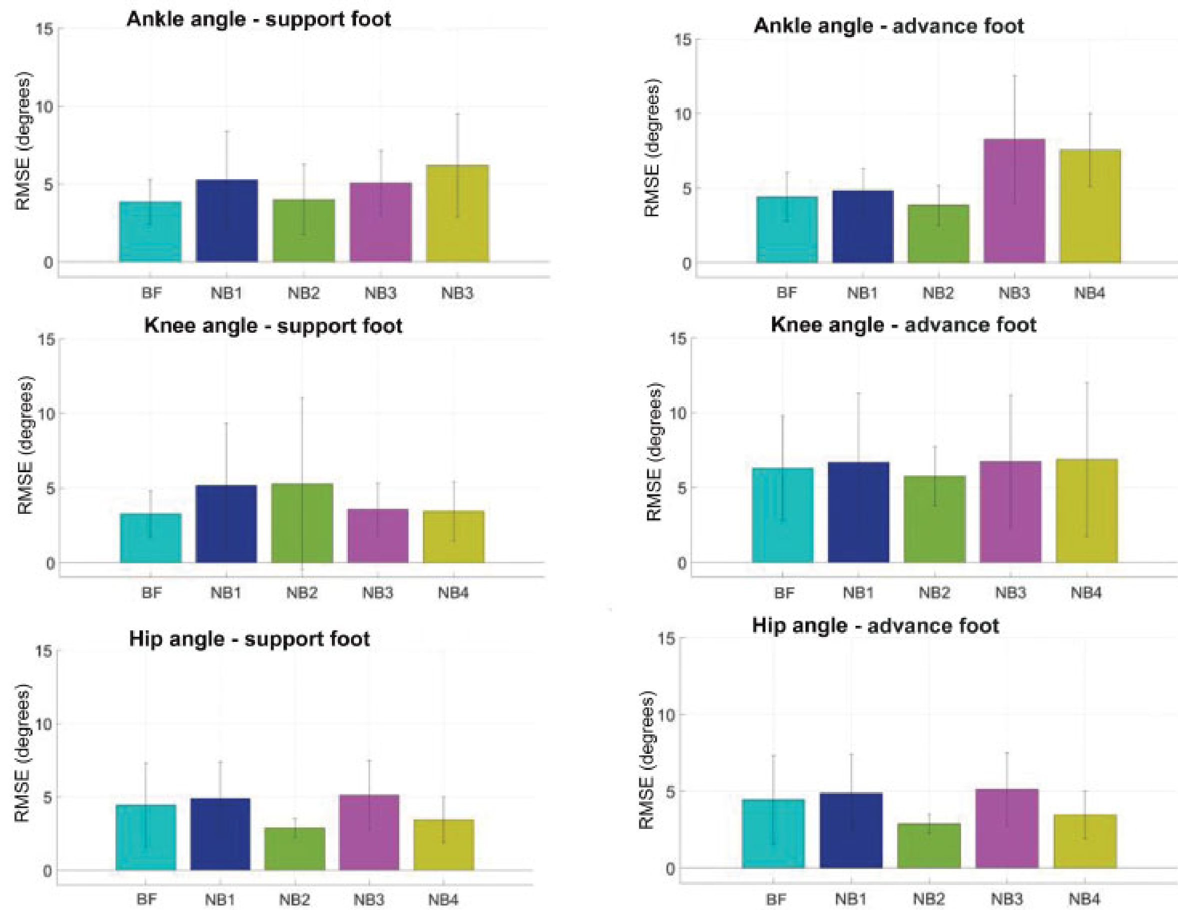

Fig. 6 Graphics illustrating the average differences of the curves of the angular variations of the ankle, knee, and hip joints (RMSE) during the gait of four toddlers with different shoes compared to barefoot condition. BF (biomimetic footwear), NB1 (non- biomimetic footwear 1), NB2 (non- biomimetic footwear 2), NB3 (non- biomimetic footwear 3), NB4 (non- biomimetic footwear 4). Source: elaborated by the authors (2021).

their day-to-day lives. At this way, shoes that mimic a natural environment, such as BF, can offer different stimuli that may help the proper development of the musculoskeletal system in a safe way for urban life. However, this is a cross-sectional study, and, we cannot conclude about the medium and long-term effects. Further studies are needed to investigate the impacts on musculoskeletal development of the use of footwear that mimics irregular terrains.

All shoes used in this study presented some difference described by RMSE with the barefoot condition. The shoes that presented, in general, the smallest RMSE (at joint angles) were BF and NB2. These shoes are similar in the internal design. Both have larger forefoot width (►**Table 1**). Probably, these shoes do not restrict (or restrict less) the increase in the width of the forefoot expected during weight acceptance.[28] During weight acceptance, the foot pronation is expected to help load absorption and allow the foot to adapt to the ground.[29] Specifically, during pronation, it is expected adduction of talus in relation to the calcaneus, moving it anteriorly (i.e., plantar flexion of the talus in relation to the calcaneus).[29] This movement happens at sime time by anterior and inferior displacement of the navicular and cuneiforms, together with an anterior displacement of the three foot medial rays (i.e., metatarsus and their respective phalanges) of the forefoot in relation to the other two lateral rays of the forefoot.[29] This movement is reversed during the supination of the foot, in which the foot becomes a rigid lever to favor the propulsion of the body.[29] A study demonstrates that foot movements are coupled to knee and hip movements in the sagittal plane.[30] Thus, footwear that minimally restricts the movement of the forefoot are more similar to walking barefoot. The impact of the width of the footwear on the forefoot was indicated by Franklin et al.,[28] who indicated that the use of footwear throughout life has resulted in functional and anatomical alterations, mainly in relation to a reduced forefoot width.

The generalization of the findings of this study is limited, since this is a descriptive study based on four toddlers. In addition, the effects described in this study were immediate, that is, toddlers had no previous experience with any of the models of the shoes evaluated. The findings described in this case study may contribute to the planning of future studies to evaluate the acute and chronic effects of footwear use with different designs.

Conclusion

The present study suggests that gait with footwear differs from walking barefoot in the MLA kinematic curves of the foot, ankle, knee, and hip. This difference can be of greater or lesser magnitude depending on the type of footwear. The toddlers showed the greatest difference in MLA with BF. In addition, the smallest differences in ankle, knee, and hip kinematics were observed when the toddlers wore shoes with a wider design in the forefoot region.

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Conflict of Interests
Dr. Liria Akie Okai-Nóbrega and Dr. Ana Paula Lage work with research at Anamê Ciência e Tecnologia em Saúde Infantil Ltda.

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