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Barefoot walking changed relative timing during the support phase but not ground reaction forces in children when compared to different footwear conditions

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ABSTRACT

Background: There is a paucity of available biomechanical kinetic data comparing shod and barefoot conditions in children.
Research question: Do children wearing footwear have comparable gait velocity, ground reaction forces (GRF), spatiotemporal parameters, propulsive and braking impulses when compared to children walking barefoot?
Methods: Seventy-five children were divided into four groups: Group 1 females aged 4–9 years old (n = 29). Group 2 females aged 3–5 years old (n = 16). Group 3 males aged 6–9 years old (n = 13). Group 4 males aged 4–8 years old (n = 17). Children walked at a self-selected pace over a walkway of force platforms. Each footwear and barefoot represented a separate condition. The order of conditions was randomized. A repeated-measures ANOVA was performed to investigate the effects of the footwear type on gait parameters in each group. Multiple comparisons with Bonferroni corrections were conducted when appropriate.
Results: There were no statistical differences in velocity or in vertical and anteroposterior GRF across conditions for all groups. There was a significant effect of the footwear worn on time to loading response peak ($p = 0.008$), time to midstance force ($p = 0.006$), and time to propulsive peak ($p < 0.001$). For Group 3, there was a significant effect of the footwear worn on time to braking peak ($p < 0.001$) and time to propulsive peak ($p < 0.001$). Regarding impulses for Group 1, there was a significant effect of the footwear worn on the loading response impulse ($p = 0.016$) and terminal stance and pre-swing impulse ($p = 0.001$). For Group 4, there was a significant effect of the footwear worn on the loading response impulse ($p = 0.028$).
Significance: There is no influence of the evaluated children's footwear on gait velocity or GRF.

1. Introduction

To generate the walking gait cycle, the lower extremity muscles are activated in a synchronized fashion to elevate, accelerate, and balance the body on a base of support [1]. Mueller et al. reported that skeletal muscle and tendon forces, as well as the length and size of the feet, increase in the first years of independent walking, resulting in an optimized motor adaptation of gait [2]. Furthermore, the authors emphasize that the study of dynamic gait parameters may provide a larger amount of information when compared to the study of static parameters. The magnitudes of reaction forces imposed on the human body during the gait cycle can be analyzed through force-time curves derived from the measuring of GRF. Several parameters can be represented on these curves. The most frequently studied parameters are forces, time, and impulses during the subphases of the stance phase [15]. Vaverka et al. provide an example of the importance of GRF for human movement in their study about the parameters that characterize human gait. They focused specifically on vertical braking and propulsive forces, impulses, spatiotemporal parameters [15].

The comparison between children's shod and barefoot gait has been the target of several recent studies [3–6]. Chen et al. compared shod and barefoot walking in healthy and flat-footed children. Hollander et al.

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investigated the differences in the foot-strike pattern of children and adolescents that grew up habitually barefoot and those that were habitually shod [5]. In their kinematic study, they have shown that habitually shod children tended to have a predominantly heel-striking gait pattern when reaching adolescence, while the opposite seemed to have occurred in younger children. Lythgo et al. investigated the timing parameters of children in U.S. primary schools and that of young adults walking barefoot and with footwear. Their study found that both double support and stance time lengths of participants in shod condition increased. It is somewhat unclear when or why the popularity of barefoot gait and "minimalist" footwear for children increased. However, the adult footwear industry has reacted to new research claims associated with the barefoot running movement. The footwear produced as a result of this new research intended to mimic the barefoot experience while still providing some protection to the feet [7]; thus, several years ago, we observed the introduction of footwear for adults that offered a different experience [8]. This design trend eventually reached the footwear market for children [9].

Among the claims associated with this barefoot movement was the assumption that barefoot running would lower maximum vertical ground reaction forces (GRF) [10,11]. It was assumed, during that time, that these GRF were well correlated with running injuries. However, Van Gent et al. soon established a dose relationship between time and injuries, instead of GRF. More recently, Metijevich et al. have reported that GRF are not strongly correlated with tibial bone loading, one of the metrics believed to be the cause of tibial stress fractures. In their systematic review on the benefits of running barefoot or in minimalist footwear, Perkins et al. concluded that changes in gait due to different types of footwear can be either beneficial or not, depending on the individual. Since their whole review is based on data originating from adult cohorts, care is needed before extrapolating this finding to children.

How the industry made a connection between adult running gait and children's gait remains a scientific mystery. Nevertheless, "minimalist" footwear is manufactured for children under the same beneficial health claims made for adults. In a systematic review of children's gait, it was concluded that footwear did have a significant impact in children's gait biomechanics when compared to the barefoot condition [16]. However, Wegener et al. did not distinguish between types of footwear. In a more recent review on the impact of footwear flexibility on children's gait biomechanics, the authors also reported no changes in gait parameters due to greater flexibility of the footwear [17]. We can speculate that children are more prone to lower extremities injuries, especially at younger ages, when bones, ligaments, muscles, and tendons are still in development. However, just as with the adult cohorts, the evidence appears to point towards overuse injuries, rather than loading magnitude, at least regarding sports [12,13]. Before we can attempt to resolve the debate surrounding the health benefits of "minimalist" footwear for children, first we need to know if different footwear models have different effects on children's kinetic gait parameters.

Due to the different methods of gait evaluation, some of the effects of footwear on children's gait parameters are already well understood, however, some controversies remain concerning the effects on the kinetic evaluation of their gait parameters [14]. Morrison et al. provide a review of the current body of knowledge regarding changes to children's gait based on their choice of footwear [14]. The study concluded that there is a lack of data on contemporary footwear and stresses the need to further investigate their biomechanical elements in children. The study of kinetic parameters, e.g. ground reaction forces, timing, and impulses, is of special interest in the field of gait biomechanics as these parameters are essential to movement and may aid in answering important clinical questions in the future, e.g. injury incidence and recovery.

Given the paucity of biomechanical data comparing shod and barefoot conditions in children, there is a need to ascertain if different types of footwear can impose significant kinetic gait changes throughout different developmental stages. The objective of this study was to assess, at least in part, the proposed need for different types of footwear for children, based on anecdotal reports and health-impacting claims by the industry, by comparing the kinetic gait parameters of healthy male and female children, between the ages of 3–9 years, in both shod and barefoot conditions. We have hypothesized that no significant changes would be observed in GRF parameters between the studied footwear types at a self-selected walking speed.

2. Methodology

2.1. Participants

A total of 99 children from local schools, between three and nine years of age, were invited to participate in this research. Twenty-four children dropped out during the study. The reasons for dropout were tiredness, distraction, drowsiness, irritability, and nausea; which did not allow the tests to be performed correctly. A non-probability consecutive sampling method was used [18]. Participants that could not properly follow the testing protocol or with a history of injury, neuromuscular conditions, or neurological/orthopedic surgery in the previous two years were excluded. Participants were divided into four groups based on their age, sex, and footwear model available for their foot size. Group 1 (G1) was composed of females aged 4–9 years ($n = 29$, $M = 6.8$, $SD = 1.3$ y.). Group 2 (G2) was also composed of females, aged 3–5 years ($n = 16$, $M = 3.9$, $SD = 0.6$ y.). Group 3 (G3) was composed of males aged 6–9 years ($n = 13$, $M = 7.3$, $SD = 1.1$ y.). Lastly, group 4 (G4) was composed of males, aged 4–8 years ($n = 17$, $M = 5.5$, $SD = 1.2$ y.). This project was approved by the local research ethics committee (80431317.0.0000.5336). Written informed consent was obtained from parents or guardians. Informed assent was obtained from the children.

2.2. Footwear

The types of footwear were different for all groups included in this study and divided into three main types: sneakers (SN), open toes flat sole (OT), and closed toes flat sole (CS) footwear. The Baby Birk, Miss Bibi, and Classic models are girls' leather sandals with flat soles and open toes. Roller New and Basic Sandals are neoprene boys' sandals with thin and flat EVA (ethylene-vinyl acetate) soles; the Roller New has closed toes, while the Basic Sandals has open toes. The Disco and the Drop New models are sneakers with thick EVA soles. The Renascence and the Anjos Joy are classic ballet flats for girls with thin and flat rubber soles and closed toes, and the Agility model is a type of casual footwear for boys with thick flat soles and closed toes. Group 1 wore models Classic (OT), Disco (SN), and Renascence (CT). Group 2 wore models Anjos Joy (CT), Baby Birk (OT), and Miss Bibi (OT_2). Group 3 wore models Agility (CT), Basic Sandals (OT), and Drop New (SN). Lastly, Group 4 wore models Basic Sandals (OT), Drop New (CT), and Roller New (SN). All participants were also evaluated barefoot (BF).

2.3. Hardware and software

A walkway with 8 embedded force platforms (BTS Bioengineering, Milan, Italy; Fig. 1) was used. In the trials in which they were unable to do so, data were discarded. The GRF sampling rate was 1000 Hz. The force platforms were positioned in a way that anteroposterior vectors were in the y-direction, mediolateral vectors in the x-direction, and vertical vectors in the z-direction. Data were exported in text format containing the triaxial forces and times.

A Python 3 (Python Software Foundation; v3.8.1) script was developed to visually inspect and calculate the mean of the peaks of vertical forces and anteroposterior forces and their respective times across all steps. It also calculated the impulses using Simpson's rule to numerically integrate the area under the time-force curve [19]. The script normalized the data to body weight (BW) and then calculated the parameters of interest. The vertical parameters were loading response force peak (F1),

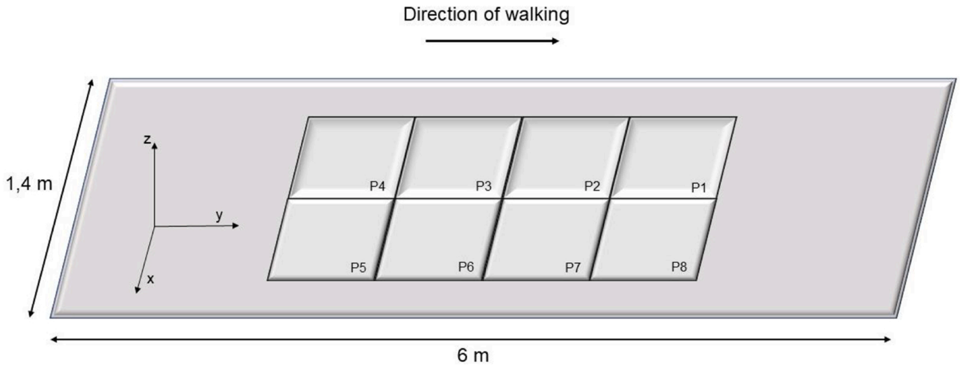
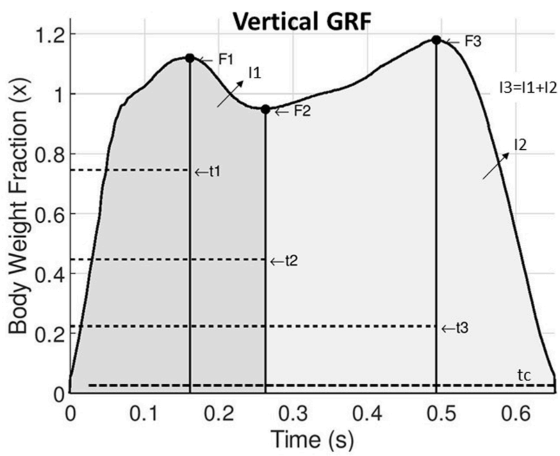


Fig. 1. Representation of the eight force platforms (P1-P8: force platforms 1-8), the walking direction, and the triaxial orientation of force vectors.

midstance force (F2), terminal stance force peak (F3), braking peak (F4), propulsive peak (F5), loading response impulse (I1), terminal stance and pre-swing impulse (I2), total vertical impulse (I3), braking impulse (I4), propulsive impulse (I5), time to F1 (t1), time to F2 (t2), time to F3 (t3), time to F4 (t4), time of braking phase (t5), time to F5 (t6), time of propulsive phase (t7), and time of stance phase (tc). A graphical summary of all measured parameters is shown in Fig. 2. The hardware and software setups are similar to previously published work [20]. The velocity was calculated using the total distance traveled by the child on the platforms, specifically, four platforms, by the variation of the time where the GRF signal was detected.



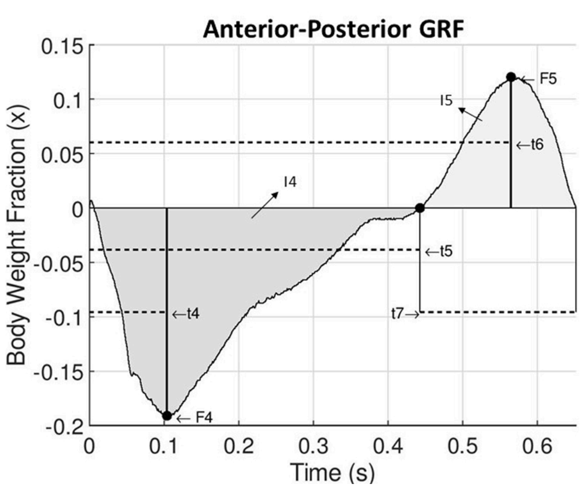


Fig. 2. F1: loading response peak force; F2: midstance force; F3: terminal stance peak force; F4: braking peak; F5: propulsive peak; I1: loading response impulse; I2: terminal stance and pre-swing impulse; I3: total vertical impulse; I4: braking impulse; I5: propulsive impulse; t1: time to F1; t2: time to F2; t3: time to F3; t4: time to F4; t5: time of braking phase; t6: time to F5; t7: time of propulsive phase; tc: time of stance phase.

2.4. Experimental procedures

Each participant was assigned three different models of footwear, according to their age, sex, and footwear size. Each one of the three footwear models, as well as barefoot gait, represented a different condition, for a total of four conditions in each group. The order of conditions was randomized. Each participant completed five trials in each condition, in which they were asked to walk at a self-selected pace across the force platforms. All participants completed all trials in one visit.

2.5. Data reduction

Python 3 was used to visually inspect and detect force signals and their timing in each gait cycle. The clinical gait analysis software SMART-ANALYZER (BTS Bioengineering Corp., Quincy, MA, USA) was used to select one out of the five trials according to the following criteria: (i) support phase corresponding to 60 % of the gait cycle, and swing phase corresponding to 40 % of the gait cycle [21], (ii) no dragging of the toes while walking, and (iii) with symmetrical weight distribution on both feet. The software filtered the raw data using a 4th order low-pass Butterworth zero-lag filter with a cut-off frequency of 20 Hz before it calculated all relevant parameters: F1, F2, F3, F4, F5, tc, t1, t2, t3, t4, t5, t6, t7, I1, I2, I3, I4, and I5 for each step and exported the data to a spreadsheet file. Steps presenting force curves in which it was not possible to identify the two peaks and the valley that are characteristic of walking gait were manually removed from the analysis. The means of the relevant parameters were calculated by averaging their values across the number of remaining valid steps. The time data were normalized to the length of the support phase (%tc). Force data were normalized by the participants' body weight (BW), and the impulse data were calculated using the normalized force (BW*s).

2.6. Statistical analyses

A repeated-measures ANOVA was performed to investigate the effects of the footwear type on gait parameters in each group. Mauchly's test of sphericity was conducted to assess the assumption of homogeneity of variance. When sphericity was violated, the degrees of freedom of the omnibus *F*-test were corrected using Greenhouse-Geisser estimates of sphericity (ε). Multiple comparisons with Bonferroni corrections were conducted when the omnibus *F*-test was significant. Statistical analyses were performed in SPSS v25.0 (IBM, Armonk, NY, USA). The level of significance was set *a priori* at $\alpha = .05$ for all tests.

3. Results

After the data processing, six individuals were excluded from the study, resulting in 69 participants selected for further analysis ($N = 69$, 28 males). The reasons for exclusions were missing data due to errors during data collection and/or excessive noise artifacts. Descriptive statistics for all groups and conditions are summarized in Supplemental Table 1 and graphically presented in Figs. 3–5. Statistically significant results of the pairwise comparisons with a Bonferroni adjustment are graphically presented also in Figs. 3–5. Overall, there were no statistical differences in velocity or forces (F1-5) across conditions for all groups. These results are summarized in Supplemental Table 2 and Fig. 3. Data were missing for one participant in G1, three participants in G2, and two participants in G4.

For G1, Mauchly's test of sphericity was significant for the time to propulsive peak, $\chi^2(5) = 12.09$, $p = 0.034$, $\varepsilon = 0.70$. There was a statistically significant effect of the footwear worn on time to loading response peak (%t1), $F(3, 42) = 4.45$, $p = 0.008$, $\eta_p^2 = .241$, time to midstance force (%t2), $F(3, 42) = 4.83$, $p = 0.006$, $\eta_p^2 = .257$ and time to propulsive peak (%t6), $F(2.11, 29.54) = 27.47$, $p < 0.001$, $\eta_p^2 = .662$. The OT condition had lower time to loading response peak ($M = 20.69$, $SD = 1.82$) than Barefoot ($M = 22.15$, $SD = 2.01$), $p < 0.05$. The CT condition had greater time to loading response peak ($M = 21.97$, $SD = 1.71$) than the OT condition ($M = 20.69$, $SD = 1.82$), $p < 0.05$. The OT condition had lower time to midstance force ($M = 42.67$, $SD = 3.88$) than Barefoot ($M = 46.61$, $SD = 5.00$), $p < 0.05$, while the CT condition had greater time to midstance force ($M = 45.10$, $SD = 3.83$) than the OT condition ($M = 42.67$, $SD = 3.88$), $p < 0.05$, and the SN condition had greater time to midstance force ($M = 46.06$, $SD = 5.54$) than the OT condition ($M = 42.67$, $SD = 3.88$), $p < 0.05$. The OT ($M = 87.69$, $SD = 1.22$), SN ($M = 88.54$, $SD = 0.88$) and CT ($M = 88.23$, $SD = 1.14$) conditions had lower time to propulsive peak than Barefoot ($M = 90.16$, $SD = 0.98$), all $p < 0.001$.

For G3, there was a statistically significant effect of the footwear worn on time to braking peak (%t4), $F(3, 15) = 12.35$, $p < 0.001$, $\eta_p^2 = .712$ and time to propulsive peak (%t6), $F(3, 15) = 93.37$, $p < 0.001$, $\eta_p^2 = .949$. The SN condition had greater time to braking peak ($M = 19.56$, $SD = 1.80$) than the Barefoot ($M = 13.45$, $SD = 2.44$), $p < 0.05$, CT ($M = 15.35$, $SD = 2.61$), $p < 0.05$, and OT ($M = 14.18$, $SD = 2.09$), $p < 0.001$ conditions. In the anteroposterior direction, the Barefoot condition had a greater time to propulsive peak ($M = 90.00$, $SD = 0.92$) when compared to the CT ($M = 86.57$, $SD = 0.55$), $p < 0.001$, OT ($M = 89.03$, $SD = 0.77$), $p < 0.01$, and SN ($M = 87.96$, $SD = 0.44$), $p < 0.01$. Conversely, the CT condition had smaller time to propulsive peak ($M = 86.57$, $SD = 0.55$) when compared to the OT ($M = 89.03$, $SD = 0.77$), $p < 0.001$, and SN ($M = 87.96$, $SD = 0.44$), $p < 0.01$, conditions. There were no statistical differences of gait cycle timing across all conditions for G2 and G4.

Regarding impulses for G1, there was a statistically significant effect of the footwear worn on the loading response impulse (I1), $F(3, 42) = 3.82$, $p = 0.016$, $\eta_p^2 = .215$ and terminal stance and pre-swing impulse (I2), $F(3, 42) = 6.28$, $p = 0.001$, $\eta_p^2 = .310$. More specifically, the CT condition had greater loading response impulse ($M = 0.18$, $SD = 0.05$) than OT ($M = 0.12$, $SD = 0.06$), $p < 0.05$. Conversely, the CT condition had lower terminal stance and pre-swing impulse ($M = 0.28$, $SD = 0.06$) when compared to the OT ($M = 0.34$, $SD = 0.09$), $p < 0.05$.

For G3, Mauchly's test of sphericity was significant for the total vertical impulse, $\chi^2(5) = 19.15$, $p = 0.003$, $\varepsilon = 0.36$. There was a statistically significant effect of the footwear worn on the total vertical impulse (I3), $F(1.10, 5.53) = 7.25$, $p = 0.037$, $\eta_p^2 = .592$. Multiple comparisons showed that OT had greater total vertical impulse ($M = 0.47$, $SD = 0.03$) when compared to Barefoot ($M = 0.41$, $SD = 0.04$), $p < 0.01$. The omnibus F-test did not reveal a significant effect of the footwear worn on the propulsive impulse (I5), $F(3, 15) = 2.65$, $p = 0.086$, $\eta_p^2 = .347$. However, the multiple comparisons showed that the SN condition had greater propulsive impulse ($M = 0.022$, $SD = 0.003$) when compared to Barefoot ($M = 0.026$, $SD = 0.005$), $p < 0.05$.

For G4, Mauchly's test of sphericity was significant for the loading response impulse, $\chi^2(5) = 13.03$, $p = 0.028$, $\varepsilon = 0.44$. There was a statistically significant effect of the footwear worn on the loading response impulse (I1), $F(1.33, 6.66) = 13.80$, $p = 0.006$, $\eta_p^2 = .734$ and terminal stance and pre-swing impulse (I2), $F(3, 15) = 10.37$, $p = 0.001$, $\eta_p^2 = .675$. The OT had lower loading response impulse ($M = 0.05$, $SD = 0.02$) than the SN ($M = 0.15$, $SD = 0.03$), $p < 0.01$, and the CT ($M = 0.20$, $SD = 0.02$), $p < 0.001$. Similarly, the OT had greater terminal stance and pre-swing impulse ($M = 0.41$, $SD = 0.03$) than the SN ($M = 0.33$, $SD = 0.06$),

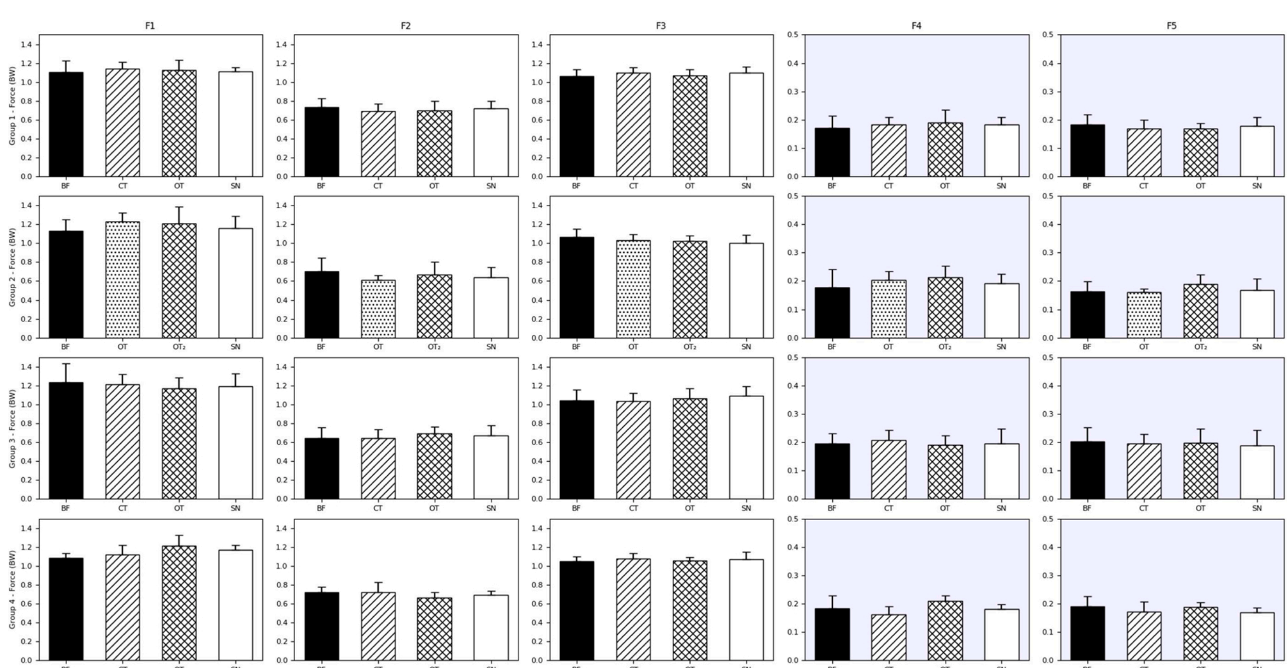


Fig. 3. Bars are means and whiskers are standard deviation; F1: loading response force peak; F2: midstance force; F3: terminal stance force peak; F4: braking peak; F5: propulsive peak; BF: barefoot; CT: closed toes; OT: open toes; SN: sneakers; OT_2: second open toes (Miss Bibi, for G2.

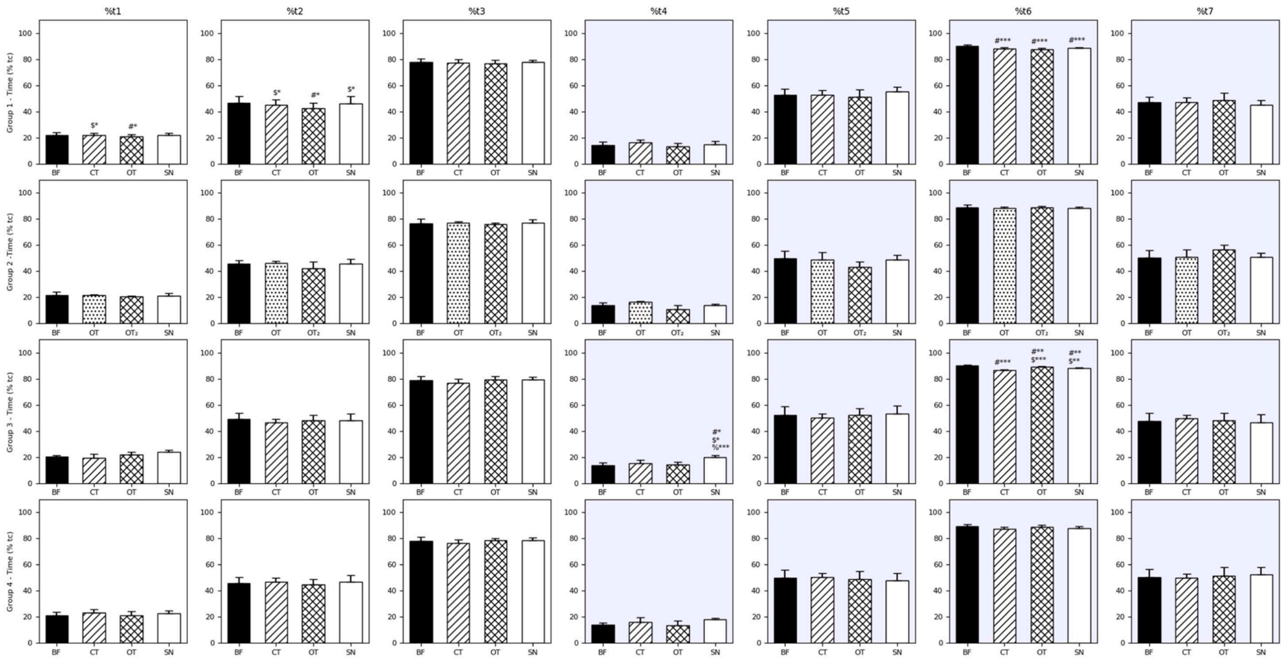


Fig. 4. Bars are means and whiskers are standard deviation; %t1: t1 normalized by tc; %t2: t2 normalized by tc; %t3: t3 normalized by tc; %t4: t4 normalized by tc; %t5: t5 normalized by tc; %t6: t6 normalized by tc; %t7: t7 normalized by tc. BF: barefoot; CT: closed toes; OT: open toes; SN: sneakers; OT_2: second open toes (Miss Bibi, for G2 only). #: significantly different than barefoot; $: significantly different than the first condition; %: significantly different than the second condition; *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

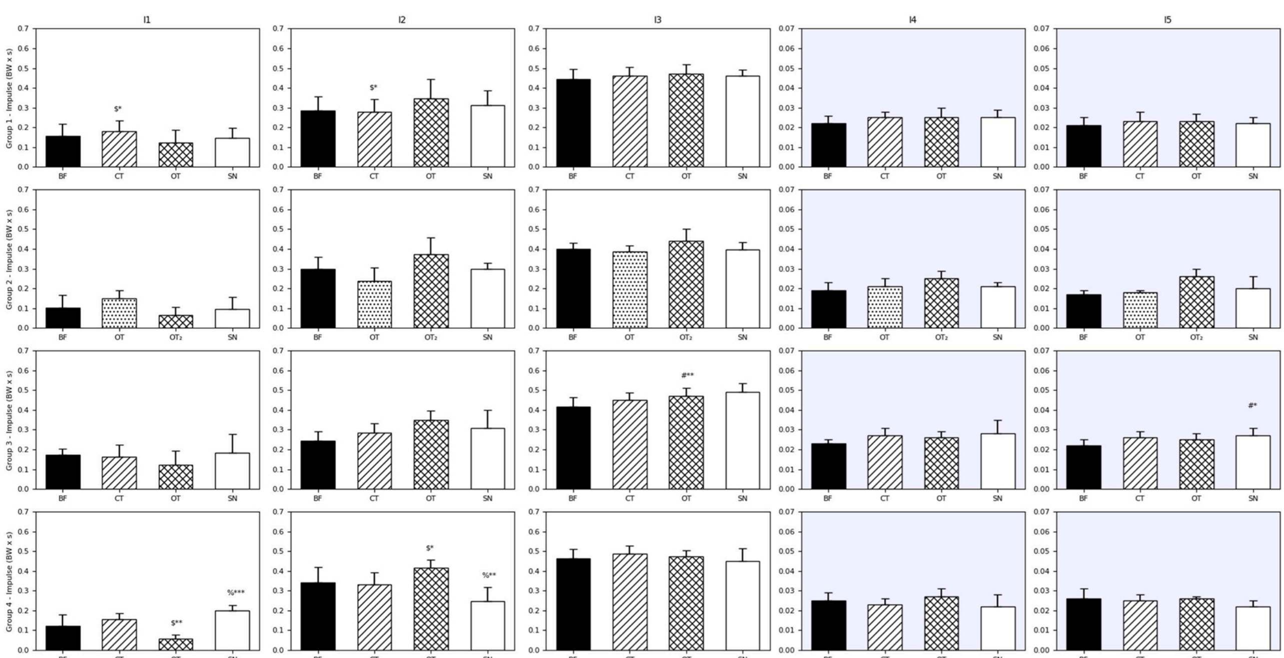


Fig. 5. Bars are means and whiskers are standard deviation; I1: loading response impulse; I2: terminal stance and pre-swing impulse; I3: total vertical impulse; I4: braking impulse; I5: propulsive impulse; BF: barefoot; CT: closed toes; OT: open toes; SN: sneakers; OT_2: second open toes (Miss Bibi, for G2 only). #: significantly different than barefoot; $: significantly different than the first condition; %: significantly different than the second condition; *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$.

$p < 0.05$, and the CT ($M = 0.24$, $SD = 0.06$), $p < 0.01$, conditions.

4. Discussion

We aimed to compare the GRF of healthy male and female children, aged 3–9 years while walking in both shod and barefoot conditions. The absence of data comparing the kinetic parameters of children in shod and barefoot conditions presents a challenge for this discussion. The main finding of this study was that no significant changes were observed in GRF parameters at a self-selected walking speed and wearing the footwear chosen for this study. We believe that this finding may equip clinicians to better choose/recommend children’s footwear for regular daily-living activities, more specifically walking. It may also help guide parents in the selection of footwear for their children, independent of the industry's recommendations.

Jafarnezhadgero et al. reported that GRF loading response and terminal stance peaks during gait at a self-selected pace have a magnitude of approximately 1.07 % BW [23]. Similar to their findings, our results for the loading response and terminal stance corresponded to approximately 1.00–1.20 % BW for all conditions. In a systematic review of 11 studies on the effects of children's footwear on gait, only 2 articles related to force parameters could be found [16]. Overall, Wegener et al. reported that no significant differences were found in kinetic walking parameters. However, a higher vertical GRF for shod walking was reported by one of the reviewed studies [24]. Unlike the findings of Kristen et al., we found no differences in force parameters for any of the groups, across all conditions.

In a systematic review, Fukuchi et al. reported that children tended to exhibit lower vertical GRF, both at the loading response and terminal stance phases when they walked with lower speed [25]. Regarding the walking velocity, Xu et al. demonstrated that participants tended to decrease their walking speed when transitioning from regular athletic footwear to "minimalist" footwear [22]. This was not the case in our study, as we have found that children did not substantially change their walking speed, regardless of footwear, sex, or age. These results support our initial hypothesis that GRF would not change when children wore different types of footwear while walking at a self-selected pace.

There is evidence suggesting that children tend to reduce their walking speed while wearing footwear with reduced heel-to-toe drop [22]. In their systematic review, Fukuchi et al. also report that when children reduce their walking speed, they do so by decreasing their step length and stride rate, while increasing their stance duration. Wegener et al. [16], on the other hand, concluded that children walked faster when wearing footwear. They argue that since the walking cadence was found to decrease, there is an increase in stride length, and try to explain the longer stride in shod conditions by an increase in the leg length. These findings seem to be inconclusive and dependent on the footwear model. However, our results contribute to further confounding of the evidence, as we have observed no differences in the self-selected walking speed in any condition and studied group.

However, while forces remained mostly unchanged, the timing of each gait subphase is an important variable that needs to be discussed because it determines the rate with which reaction forces are applied to the body. In G1, 4–9 year-old girls, all shod conditions had lower time to propulsive peak than the barefoot condition. Moreover, the OT condition had lower time to loading response peak and midstance force than the barefoot condition. This may be related to the fact that the Classic model is a leather sandal with flat soles for girls. Robbins et al. suggested that footwear can filter peripheral sensory-motor information from receptors to the central nervous system. It has been previously hypothesized that this reduction in proprioceptive feedback may lead to gait modifications to maintain stability [26].

Hamill et al. have found evidence that runners tend to change their foot strike mechanics when alternating between shod and barefoot conditions. Similarly, Hatala et al. have suggested that foot strike patterns are chosen based on several factors, among which are the running speed, training level, and the mechanical properties of the substrate [27]. Unfortunately, comparisons of children's walking gait are difficult due to the scarcity of data. Moreover, to the best of our knowledge, there are no studies that have investigated differences in footfall patterns during walking in healthy adults or children. One parallel can be drawn with the work of Hollander et al., in which they used kinematics to demonstrate that habitually barefoot children do change their gait strategy when wearing footwear. In another work, Hollander et al. also showed that preadolescent running biomechanics are influenced by footwear, especially by cushioned running footwear [9].

We have observed differences in impulses for certain footwear models in G1, G3, and G4. Those may be related to the characteristics of the footwear. Decreased impulse during the pre-swing phase of gait is associated with a shorter step length to increase ankle compliance when barefoot [10]. A thicker sole width is a feature of the shod conditions that may increase the base of support [16]. Consequently, this can be a cause for a different time to the braking peak. Conversely, Addison & Lieberman have reported an increase in the loading response impulses during walking with decreased footwear stiffness in young adults. Their findings are somewhat aligned with our results, for some of the footwear tested. The authors have also shown an inverse relationship between peak impulse and loading rate of the loading repose GRF. Regarding footwear vs. barefoot conditions in adults, Zhang et al. showed a smaller loading rate, i.e. greater impulse, in shod condition compared to barefoot. This phenomenon was not observed in our results. To the best of our knowledge, there are no data of impulses during the stance phase from a children cohort available for comparison and discussion.

The present study has some limitations. It was solely focused on using kinetic parameters data to compare the influence of footwear on children's walking. Since only GRF data were analyzed, assumptions about additional mechanisms that might be involved in the force and impulse generation should be made with care. Future studies may want to consider the simultaneous analysis of full-body kinematic and electromyographic data to investigate in greater depth the influence of shod and barefoot walking in children. Moreover, our study has evaluated children from 3 to 9 years; for children outside this age range, extrapolation of these results must be done carefully.

5. Conclusion

The results of this study suggest that there is no influence of the evaluated children's footwear on vertical and anteroposterior forces. Gait velocity was not different for any of the groups, regardless of condition. We have found that, for some types of children's footwear, shod walking is only different from barefoot in vertical and propulsive impulses, as well as in time to propulsive and braking peak, time to loading response peak, and midstance force. When compared to barefoot, for the group of 4–9 years old girls, flat sole with open toes footwear slightly reduced the time to loading response peak and the time to midstance force, while sneakers and flat sole with closed toes footwear reduced the time to propulsive peak. For the group of 6–9 years old boys, sneakers have slightly increased time to braking peak, while both flat sole (with open and closed toes) footwear and sneakers have slightly reduced the time to propulsive peak. Furthermore, for this group, sandals and sneakers have respectively minimally increased the total vertical impulse and the anteroposterior propulsive impulse.

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Author's contributions

Rafael Reimann Baptista has conceived, designed, and coordinated the project, reviewed the paper, and wrote parts of the introduction, methods, and most of the discussion and conclusion. Gustavo Sandri Heidner has analyzed the data, performed the statistical analysis of the data, and wrote most of this paper. Rodrigo Nascimento contributed to the writing of the Introduction and Methodology sections of this paper. Andreia Gomes Aires analyzed the data and wrote parts of the paper.

Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.gaitpost.2020.10.034.

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