

Effect of Footwear on Running Impact Loading in the Preschool Years

Jan Plesek (✉ jan.plesek@osu.cz)

University of Ostrava <https://orcid.org/0000-0002-6496-0751>

Joseph Hamill

University of Massachusetts Amherst

Denisa Blaschova

University of Ostrava: Ostravska univerzita

Julia Freedman Silvermail

University of Nevada Las Vegas

Daniel Jandacka

University of Ostrava: Ostravska univerzita

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Abstract

Background

Previous research indicated that running barefoot or in minimalist shoes led to lower impact loading in an adolescent and adult population. Running as fundamental locomotor skill significantly develops during early childhood (preschool age). However, no study has focused on effect of footwear condition on lower limb impact loading during running in this age. Therefore, the purpose of this study was to assess effect of footwear conditions (barefoot, minimalist and standard running shoes) on running impact loading in the preschool years.

Methods

Forty-eight habitually shod preschool children were divided into 4 age groups. Children performed simple running game in 3 different footwear conditions (random counter-balanced order), 3-dimensional biomechanical analysis were carried out during overground running. The key dependent variables included vertical ground reaction force (VGRF) and vertical instantaneous loading rate (VILR). Statistical parametric mapping was performed to reveal possible differences in VGRF and one-way repeated measures ANOVA in VILR.

Results

Three-year-old children displayed significantly lower impact peak of VGRF in barefoot condition compared to minimalist (3-7% stance, $P = 0.012$) and standard running shoes (7-11% stance, $P = 0.009$). Furthermore, in 3-year-old in minimalist shoes had higher loading than in standard running shoes (0-4% stance, $P = 0.007$). There were also differences in VILR, where 3-year-old had lower loading in barefoot than in minimalist ($P = 0.010$, $d = 1.19$) or standard running shoes ($P = 0.045$, $d = 0.98$). No differences were found in older children.

Conclusion

Running in minimalist shoes did not imitate barefoot running and did not lower impact forces compared to standard running shoes in 3-year-old children. On the contrary, increased loading was observed in minimalist shoes in early running developmental stages. Professionals who work with children should consider effect of minimalist shoes on impact loading (running on hard surfaces).

Key Points

- Barefoot running significantly reduced impact loading compared to minimalist and standard running shoes in 3-year-old children, even though footstrike patterns did not differ according to footwear conditions.
- Running in minimalist shoes did not imitate barefoot running and did not lower impact forces compared to standard running shoes in early running developmental stages.
- Professionals who work with children should be careful and consider specificity of minimalist shoes effect on loading when their children are exposed to run on hard surfaces.

Introduction

It has been shown that running is the most common physical activity in preschool age children [1]. Keeping children physically active should be of great interest to parents, particularly within the restrictions of the Covid-19 pandemic [2]. The importance of physical activity has been shown for brain development [3], academic success (achievement, performance) [4], and long-term health benefits (e.g., skeletal, mental, cardio-respiratory, etc.) with physical activity continuing from childhood to adulthood [5]. Moreover, recent studies on mice have shown that mechanical loading during exercise could stimulate lymphopoiesis (generation of immune cells) along with osteogenesis in bone marrow and consequently reduce vulnerability against infections etc [6, 7].

Although running routine leads to highly commendable health benefits, there also remains a high incidence of running-related injuries in youth and adult runners [8, 9]. Therefore, some researchers suggested the importance for focusing research on children [10–13], and potentially elucidate the way children interact with environment during running from a mechanical loading perspective [13, 14].

In the past decade, many researchers have focused on investigating impact loading during running as represented by the magnitude and shape of the ground reaction force [15–21]. In particular, high vertical loading rates have been associated with bony and soft tissue injuries in runners [20]. Previous studies on adults and adolescents showed that the type of footwear and footstrike pattern could affect impact loading of the lower limb during running [16, 17, 19, 22–24]. In addition, running barefoot or running in minimalist shoes with a forefoot strike pattern may lead to lower impact loading and the visual absence of impact peak on the vertical ground reaction force component (VGFR) [16, 21, 24]. Davis and Hollander [19] confirmed that the interaction of footwear and footstrike pattern is an important issue associated with loading in specific musculoskeletal sites. They suggested that, if all children would start to use a minimalist shoe early in their lives, this would likely lead them to adopt forefoot strike running patterns and consequently reduce impact loading. Additionally, Krabak et al. [14] also proposed that perhaps toddlers and young children could start to wear footwear that would promote a forefoot strike pattern during running. These researchers suggested that this would potentially lead to strengthening of the foot and ankle, along with the aforementioned lowering of impact forces with a future possible reduction of running related injuries.

Through the type of footwear selected, parents buying footwear for their preschool children could indirectly affect their movement pattern [12]. Moreover, underlying kinematic and kinetic differences have been observed in the development of running in comparing preschool and older children running [13, 25]. A recent study reported that footstrike patterns change differently in age groups of preschool children [13]. As we know, children are not little adults and we should be very cautious with application of knowledge from research in adult populations and transfer it to children, particularly to the youngest when running skill is still developing.

According to Cranage et al. [26], there is very limited evidence about the effect of footwear on gait parameters in preschool children. To our knowledge, no study has investigated the effect of footwear on impact loading during running in preschool age. Therefore, the aim of the current study was to compare impact loading in different age groups of preschool children in different footwear conditions during running. Based on the research in adult populations, we hypothesized that running barefoot and in minimalist shoes would lead to lower impact forces and loading compared to standard running shoes in all age groups of preschool children [10, 21, 24]. However, as recent research in preschoolers showed that 3- and 4-year-old children did not change their footstrike pattern (remained rearfoot-midfoot strike) according to footwear condition as 5- and 6-year-old who displayed a similar reaction to adults runners (shifted to forefoot strike in barefoot and minimalist) [13]. Therefore, we hypothesized that higher impact loading in barefoot and minimalist shoes compared standard running shoes in younger children, but lower in the older children.

Methods

Study design

This study used a randomized crossover design with 3 randomly counter balanced treatments (3 footwear conditions – barefoot (B), minimalist (M) and standard running shoes (SRS)). This study was approved by the Ethical Board of the University of Ostrava, Faculty of Education (protocol ID: OU-54483/45-2019) and was conducted in accordance with the principles of the Declaration of Helsinki. Before participating in the study, the children's parents or legal guardians granted informed written consent and child's assent was also required before the start of the measurement.

Participants

Healthy, typically developing forty-eight Caucasian preschool children (26 boys and 22 girls aged 3-6 years) participated in this study. This is a further analysis from the data collection of children in the recent study where we reported changes in lower limb kinematics at footstrike in three different footwear conditions [13]. They were habitually shod and came from the Moravian-Silesian region in Czech Republic. The recruitment of preschoolers was carried out via social networks, flyers and subsequently by snowball sampling methods (emails, phone calls, friends, colleagues, etc.). All children attended a pre-primary educational child care

institution or the first grade of primary education. Exclusion criteria for the current study included developmental coordination disorders or any lower limb abnormalities diagnosed by podiatrist, orthopedist or practitioner (e.g., flatfoot, leg length discrepancy, genu varum, and genu valgum). In addition, all participants were tested using the Movement Assessment Battery for Children-Second Edition (MABC-2) to reveal possible developmental coordination disorders. As an inclusion criterion, the limit for this study was set for over the 15th percentile for a certain age according to Czech norms of the MABC-2 (15th percentile is considered as a boundary for typically developing children from motor developmental perspective, for given age) [27, 28]. Eleven children were excluded from this study because they did not meet criteria or did not finish whole procedure (3 children below 15th percentile in MABC-2, 5 children did not complete biomechanical protocol (bad mood or being nervous or shy etc.), 2 children had diagnosed foot or lower limb deformities, 1 child – parent's time constrain). No stratification for sex was required because a recent study showed no differences in footstrike pattern between preschool boys and girls [12]. Nevertheless, both sexes in each age group were included in the current study (Table 1).

Instrumentation

Kinematic and kinetic data were collected by using a 10-camera 3D motion capture system (Oqus, Qualysis, Inc., Göteborg, Sweden) sampling at 240 Hz and recorded synchronously with ground reaction forces from 3 force platforms at 1200 Hz (one large - 90 x 90 cm 9287CCAQ02 and two small - 60 x 40 cm 9286AA, 9281CA, Kistler, Winterthur, Switzerland). Height and body mass of all children were measured using by stadiometer (In Body 370, Biospace, Seoul, South Korea) and body composition analyzer (Inbody 770, Biospace, Seoul, South Korea). Body mass index (BMI) was calculated by dividing body mass (kilograms) by body height² (meters squared) and BMI percentile was evaluated for each child according to Czech norms [29].

Protocol and Setting

All children accompanied by their parents or family members visited the Human Motion Diagnostic Centre Biomechanics Laboratory at University of Ostrava. The detailed protocol including a diagram of laboratory and game settings was described in the study by Plešek et al. [13].

Prior to biomechanical measurements, parents returned a 6-item Barefoot Questionnaire (BFQ) evaluating how frequently their children wore shoes in 2 different weather conditions (cold, warm) and three environments (educational institution, sports, in and around the house). Scoring in the BFQ was based on a three-point Likert scale (very barely = 1 point, often = 2 points, always = 3 points). Total score could range from minimal 6 points (almost always barefoot) to maximal 18 points (almost always shod). Children were considered as habitually shod if they scored at least 4 points per condition (e. g. 3 points in warm or cold condition = habitually barefoot) [30]. This BFQ was modified for preschoolers and used in the previous study.[13].

Briefly, parents chose the right shoe size for their child before the data collection began (sizes ranged from 24 to 35 UK; from 8K to 3.5 US). The intervention shoes consisted of true minimalist shoes (Leguanito, Leguano, Buchholz, Germany; with minimalist index 96%) and standard running shoes (FortaRun CF I and K, Adidas, Herzogenaurach, Germany; with minimalist index 30%). Both types of shoes were commercially available in all children sizes. The minimalist index score ranges from 0% (least minimalist) to 100% (most minimalist) [31]. The following step included marker placement on each child carried out by an experienced researcher in 3D movement analysis. Retroreflective markers (6.4-mm diameter) were placed on each child's landmarks (18 right limb, 4 on pelvis, 1 on the left greater trochanter and 1 left heel).[32]

Participants performed a very simple running game (back and forth submaximal self-selected speed running between 2 posts). The game based on shuttle running locomotion was presented to the children in a random counterbalanced order due to 3 different footwear conditions. The distance between the 2 ends of the runway (hard, flat, and non-slippery surface) increased progressively by 1 meter according to age of participants (3-yr = 10 m, 4-yr = 11 m, 5-yr = 12 m and 6-yr-old = 13 m). One running game consisted of 8 running trials and was accomplished 2 times in each footwear condition (with at least 3 minutes long break between games). There was also an approximately 10-15 minutes break between footwear conditions due to removing and placing a new set of markers on the child's foot or intact shoe that was followed by a standing calibration. Separate calibrations were recorded before each running footwear condition. Before each game in the new footwear condition, each child started by 4 non-recorded running trials which served for familiarization and habituation to the footwear. In total, each child ran 60 times back and forth including 12 running trials for familiarization. The duration of the whole protocol did not exceed 1 hour. Sixteen recorded running trials/footwear condition/participant were collected for the 3D biomechanical analysis.

Data Processing

We compared the key variables in this study (maximal vertical instantaneous loading rate (VILR), vertical ground reaction force (VGRF)) among 3 footwear conditions (B, M and SRS) in 4 age groups of preschool children (3-, 4-, 5- and 6-year-old). The primary reason for this analysis of the effect of footwear in each year separately is that running skill substantially develops during preschool age [25] and footstrike pattern is affected by footwear differently at these ages [13]. To avoid the effects of running speed on the aforementioned dependent variables, we calculated a dimensionless speed as control variable based on pelvic horizontal velocity and lower extremity length [33]. Frequency analysis of impact peak occurrence and nominally classified footstrike patterns based on strike index (rearfoot strike/midfoot strike/forefoot strike) were secondary outcomes [34]. In our previous study, we showed a main effect of footwear on strike index in the cohort of 48 preschool children (aged 3-6 years), although there was a significant interaction with ankle angle which indicated that footstrike pattern is affected by footwear [13]. Moreover, Wei et al. [35] analyzed loading rate and footstrike pattern between preschool children and adults (10 preschoolers, aged 3-6 years and 10 adults, aged 18-27 years). They mentioned as main limitations uncontrolled footwear conditions and impossibility to divide preschoolers into age subgroups (due to small sample of participants) and consequently investigate the impact of time length of wearing the shoes and running experience. Therefore, we also included strike index as secondary outcome variable in the current study which was analyzed by one-way repeated measures ANOVA in each preschool year separately.

Biomechanical data were processed by using Qualisys Track Manager (QTM, Qualisys, Göteborg, Sweden) and Visual 3D software (C-motion, Germantown, MD, USA). The threshold for the ground reaction forces (resultant) was set at 15 Newtons. Six successful trials were selected and analyzed based on pelvis velocity (the closest 6 trials to the median). A successful running trial was determined when the entire right foot of the child contacted the force plate. A low-pass Butterworth filter using a cut-off frequency of 10 Hz was applied for kinematics and 50 Hz for ground reaction force data.

Strike index was analyzed based on location of the center of pressure at the initial foot-ground contact. For this parameter, three zones were determined: 1) rearfoot strike (RFS) 0-33.3%; 2) midfoot strike (MFS) 33.4-66.6% and 3) forefoot strike (FFS) 66.7-100% of the shoe/foot length measured from the heel [34]. VGRF and VILR were normalized to the body mass of each participant. The VILR was determined by calculating as first derivative of the corresponding VGRF with respect to time. The maximum (peak) of VILR value was obtained from first 27 % of stance as a local maximum using the same approach as in Rice et al. [24]. Moreover, for a one dimensional statistical parametric mapping analysis, the VGRF curve was normalized into 101 points (0-100% stance phase) [36, 37]. Presence of vertical impact peak was defined as a local maximum in VGRF that occurred before the overall maximum peak of VGRF [34].

Statistical Methods and Study Size

An a priori sample size estimation was performed for running footstrike patterns and footwear (barefoot, minimalist, standard running shoes) in different age groups of preschool children analysis in the previous study by Plesek et al. [13] In the aforementioned study, a statistical power analysis software program (G*Power 3.1.9.7, Düsseldorf, Germany) suggested having 12 children per age group. A one way within-subject repeated measures ANOVA with 12 participants in 3 different footwear would be sensitive to effects of partial eta squared $\eta^2 \geq 0.33$ with minimal statistical 80% power (alpha level = 0.05).

A one-way ANOVA or Kruskal-Wallis test for non-normally distributed data was used to compare characteristics (age, height, leg length, weight, BMI, BFQ, MABC-2) of participants among the age groups.

The vertical ground reaction force component was analyzed in Matlab (MATLAB R2017a, Mathworks, Inc., Natick, MA, USA) and an open-source statistical parametric mapping (SPM) software was used to carry out the statistical analysis of the VGRF during entire stance phase [36]. To test the effect of footwear conditions on the VGRF, SPM for a one-way repeated measures analyses of variance was performed for an initial analysis. The critical threshold for statistical significance in the initial analysis was set at $p=0.05$. When significant effects were found in a certain age group, then a post hoc analysis (pairwise comparisons) was carried out by 2 tailed paired t-tests using SPM between each footwear condition separately, with adjusted alpha level of significance with a Bonferroni correction ($P = 0.017$). In the SPM analysis, all aforementioned statistical tests were performed for each point of the VGRF curve during stance phase [37].

All zero-dimensional scale data (VILR, strike index, dimensionless speed) were screened for normality by the Kolmogorov-Smirnov test. Non-normally distributed data were analyzed by the non-parametric Friedman test which is recommended for testing related samples with a Wilcoxon signed rank test *post hoc* tests where necessary. If a normal distribution of the data was assumed, then we used one-way repeated measures ANOVA with Bonferroni correction for all pairwise comparison in *post hoc* analysis. In addition, if sphericity was violated ($P < 0.05$) and $\epsilon \geq 0.75$, then a Huynh-Feldt correction was used. Practical significance (Effect Size) for the main effect in the one-way repeated measures ANOVA was assessed using η^2 (small 0.01–0.06), medium 0.07–0.14, and large >0.14) and Cohen's d (small 0.2–0.5, medium 0.5–0.8, and large >0.8) in pairwise comparison of footwear conditions. [38] An alpha level of significance was set at 0.05 for all tests. All analyses were performed in SPSS 24 (IBM, Armonk, NY, USA).

A Chi-square goodness of fit test was used to assess frequencies of impact peak occurrence and frequencies of the categorized footstrike pattern (RFS/MFS/FFS), between the 3 footwear condition in each age group separately (72 trials/footwear condition/age group). Alpha level was set at 0.05. Pairwise comparison between B-M, B-SRS and M-SRS were performed with Bonferroni correction of the significance level ($P = 0.017$).

Results

There were significant differences in age, height, leg length and mass among age groups. No significant differences were found in BMI, BMI percentile (CZ norms), MABC-2 (CZ norms) and BFQ (Table 1).

Insert Table 1 here

In the statistical parametric mapping analysis of the VGRF, differences among footwear conditions in each year of preschool age (Figs. 1 and 2) were observed. Further post-hoc analyses with Bonferroni corrections for pairwise comparisons revealed significant differences in 3-year-old children between barefoot and both shod conditions during impact peak (B < M 3-7% stance, $P = 0.012$; B < SRS 7-11% stance, $P = 0.009$) and also in 5-years-old children between barefoot and standard running shoes (B < SRS 10-14%, $P = 0.006$). In addition, 3-year-olds were found to have higher values of VGRF in minimalist shoes compared to standard running shoes during 0-4% of stance phase ($P = 0.007$) (Fig. 2). No differences were found between footwear conditions in VGRF curve in 4- and 6-years-old children during 0-50% of stance phase.

Insert Fig. 1 here

Insert Fig. 2 here

Significant differences in VILR were observed among footwear conditions in 3-year-old children ($P = 0.005$, $\eta^2 = 0.386$). Further pairwise comparison indicated that 3-year-olds had a significantly lower VILR in barefoot condition than in minimalist or standard running shoes ($P = 0.010$, $d = 1.19$; $P = 0.045$, $d = 0.98$), respectively. There were no footwear condition differences in VILR in the older age groups (4-, 5- and 6-yr-old children; $P > 0.05$) (Fig. 3).

Insert Fig. 3 here

There were found significant main effect of footwear on strike index in 4-, 5- and 6-years-old children ($P = 0.007$; $P = 0.002$; $P = 0.002$), but no differences in 3-years-old children ($P = 0.196$). Further post hoc analysis showed significant differences only between barefoot and standard running shoes, where children displayed more forefoot strike in barefoot (4-yr-old, $P = 0.008$, $d = 1.33$; 5-yr-old, $P = 0.017$, $d = 1.42$, 6-yr-old, $P = 0.023$, $d = 1.03$).

No differences were found among footwear conditions in dimensionless speed ($P > 0.05$), analyzed by one-way repeated measures ANOVA in each age group separately.

The results obtained from the frequency analysis of three types of footstrike patterns (RFS, MFS and FFS) and impact peak are shown in the Table 2. We found significant differences in frequencies of RFS trials when comparing B with SRS conditions in 4-year-old (SRS > B, $P = 0.005$) and 5-year-old children (SRS > B, $P = 0.008$). Moreover, there were differences in number of FFS when comparing B with SRS and M with SRS, in 4-year-olds (B > SRS, $P = 0.001$; M > SRS, $P = 0.012$), 5-year-olds (B > SRS, $P = 0.001$; M > SRS, $P = 0.001$), 6-year-olds (B > SRS, $P = 0.001$; M > SRS, $P = 0.001$), respectively. No differences were found in frequencies of any

footstrike pattern between footwear conditions in 3-year-old children. In addition, no differences were found in the frequencies of impact peak occurrence regarding footwear condition in all (each) age group.

Insert Table 2 here

Discussion

The aim of this study was to compare impact loading during running with regards to different footwear in preschool children. We hypothesized that running barefoot and in minimalistic shoes would increase impact loading compared to standard running shoes in 3- and 4-year-old children because in these footwear conditions they displayed a rearfoot-midfoot footstrike with a significantly less plantar flexed ankle compared to 5- and 6-year-olds [13]. The results of this study showed contrary findings than we hypothesized. However, the minimalist shoes displayed the highest impact loading in 3-year-old children.

In 3-year-old children, barefoot running reduced impact loading compared to both shod conditions.

This study showed that vertical impact loading (VILR) was significantly lower in the barefoot condition compared to minimalist or standard running shoes in 3-year-old children. This evidence is in the agreement with results of statistical parametric mapping of the VGRF whereas impact peaks (3-11% stance phase) reach significantly higher values in the minimalist and standard running shoes than in the barefoot condition. Barefoot running may be a painful physical activity and it has been shown that only 35% adult runners maintain rearfoot strike on hard surface compared to 80% on a soft surface [39]. We also observed this in our study in the 3-year-old preschoolers (31% RFS, 47% MFS, 22% FFS), even though a previous study suggested insufficiency to forefoot strike landing in such a young children based on less plantar flexed ankle at footstrike [13].

In terms of footstrike and mechanical loading, a recent study by Zeiniger et al. [40] reported that 3-year-old children who adapted a heel strike pattern during barefoot walking had lower impact forces and calcaneal loading compared with flatfoot initial contact early walkers (high loading on anterior part of calcaneus). It seems to contradict the findings of the current study. However, we should take into account the fact that running is a different mode of locomotion than walking imposing higher external forces on body tissues. Also a flatfoot/midfoot strike in adult runners exposes the body to lower loading rates compared to rearfoot strikers [41]. Our previous study showed that in a cohort of 48 preschoolers (aged 3-6 years) [13], there was a significant main effect of footwear on strike index. However, this effect disappeared when only the 3-year-old group was considered for the analysis in this study (One-way repeated measures ANOVA). Indeed, 3-years-old children showed mostly a midfoot strike pattern, particularly in barefoot condition. A midfoot strike and higher nociceptive stimulation of lower limb flexion reflex could consequently reduce an abrupt impact loading in short period of time after initial contact [42–44]. On the other hand, from the perspective of cutaneous nociceptive stimulation, it seems that 3-year-olds in minimalist shoes with a rearfoot-midfoot strike immediately after foot contact are not able to react due to lower sensitivity of the location of stimulus (heel has higher pain threshold than rest of the foot) [44]. In addition, the VGRF curve in the current study increased immediately after foot contact (0-4% of stance phase) in minimalistic shoes and reached higher values than in standard running shoe. An explanation could be that the peak of VILR usually occurred earlier in minimalist shoes and its magnitude is relatively very high in the youngest children. An absence of a cushioning sole probably could lead to a higher mechanical loading immediately after foot contact. In previous studies, there have been reported several occult fractures of calcaneus in toddlers without any history of significant acute injury [45, 46]. Some researchers suggested that it could indicate some possible overuse of calcaneal bone from locomotion [40]. From this perspective, one should be careful and reconsider using of minimalist shoes and excessive exposure to running activities on hard surfaces in 3-yr-old children because this could be possible contributing risk factor of calcaneal injuries in such a young children.

In 4-6 year-old children footwear did not affect impact loading as did in 3-year-olds

There is only one previous study, published by Hollander et al. [10] that investigated the effect of footwear on running biomechanics in children (aged 6-9 years). This aforementioned study reported significantly lower magnitude of impact peaks in barefoot running and in minimalistic shoes compared to standard running shoes during treadmill running (fixed velocity at the level of 10 km/h which is close to running pace in the current study based on dimensionless speed). In the current study, we showed that from age 4 to 6, children demonstrated more forefoot strike patterns only during barefoot running compared to standard running shoes. Surprisingly, a forefoot strike pattern in 5-year-old children led to lower impact forces when comparing barefoot and

standard running shoes. It seems that, from impact loading perspective, 4 to 6-year-old children are not as sensitive to changing footwear or could possibly adjust their movement patterns via a lower joint limb re-alignment (e.g. more plantar flexed ankle and more eccentric capacity) [13, 47] when they are not fatigued. However, children in the present study (4 to 6-year-olds) in minimalist shoes had the highest loading rate despite a midfoot-forefoot strike. Previously in adult runners, different results regarding to loading rate with respect to footwear and footstrike have been observed. For instance, Rice et al. [24] found significantly lower loading when runners used minimalist shoes and a forefoot pattern compared to rearfoot and forefoot strikers running in SRS. Moreover, Hollander et al. [17] demonstrated that adult runners had significantly lower impact loading during an acute response to barefoot running compared to running in SRS. This was not seen in the 4-year-old and 6-year-old children in the current study. Nevertheless, the differences in VGRF impact peak between barefoot and SRS would be confirmed in all preschool years (3, 4, 5 and 6-year-olds) if the least significance difference technique of the *post hoc* analysis was used as previously recommended by several researchers [48, 49].

Due to a lack of studies investigating impact loading in children during running, it is difficult to compare loading rates values with previous research. However, Wei et al. [35] compared shod running biomechanics (including VILR) between preschool children (3-6 years, mean age = 4.2 years, SD = 1.6) and young adults (mean age = 35.1, SD = 9.5). Their preschoolers displayed VILR about 63.1 BW/s (SD = 11.8) and adults 59.4 BW/s (SD = 12.9). These authors did not find any differences in vertical instantaneous loading rate (VILR) during submaximal speed running between preschoolers and adults in their usual shod condition. However, they used a different method of evaluation of impact loading originally developed for adults.[50] Values of VILR in SRS of the current study were about 190 BW/s which is approximately three-fold greater compared to the preschoolers of Wei et al. [35]. Some authors [51] suggested that 70-75% children between 4.0-4.9 years of age reached the mastery level in running skill (qualitative assessment); however, our data showed that, from the impact loading perspective, they did not. Although, this study did not analyze age related changes of impact loading, there is an obvious trend of decreasing loading particularly in shod conditions. Therefore, future studies should focus to age related changes of impact loading in different footwear conditions.

Strengths and limitations of the study.

Because VGRF could have a different course and shape in preschool children than in adults as seen in the prior studies that revealed a higher VGRF impact peak (1st peak) than the active peak (2nd peak) and could occurred sooner than in adults [21, 25, 50]. We felt it was more appropriate to analyze the VGRF component as a continuous variable and combine it with discrete variables such as VILR [24]. Therefore, we suggest that this approach could allow a more comprehensive understanding of footwear/footstrike effect on impact loading phenomenon in young children.

In terms of limitations, even though all participants were considered as habitually shod, we did not collect information about their specific footwear type that they usually wore (e.g., experience with standard running shoes). Uniform footwear used during testing in this study could increase internal validity, but concurrently decrease external validity. In addition, all statistical tests used a conservative approach with alpha level correction for multiple testing, even though some researchers suggested no corrections for biological data [48, 49]. Moreover, we analyzed only an acute response to changing footwear conditions and we did not analyze age related changes of impact loading or morphological changes. Therefore, it is not feasible to draw any conclusions with recommendations for parents or teachers. On the other hand, the findings of this study could mark a starting line for further investigations. Future research should be addressed to investigate longitudinal changes of impact loading and morphological changes of the preschoolers and older children's bodies regarding to exposure to the different footwear conditions.

Conclusions

Based on the evidence from studies published on adult runners, it appears suggestions for running toddlers and preschool children to use true minimalist shoes along with barefoot when they start running. These suggestions have been done with the purpose of reducing impact loading and consequently minimize the risk of musculoskeletal system overload. However, in this study it was shown that running in minimalist shoes did not imitate barefoot running and did not lower impact forces compared to standard running shoes in 3-year-old children. On the contrary, increased impact loading was observed in minimalist shoes compared to barefoot and even standard running shoes in early running developmental stages. It seems that barefoot running could be safely

used in all preschool years based on an impact loading perspective. Those who work with children should be careful and consider specificity of minimalist shoes effect on loading when their children are exposed to run on hard surfaces.

Abbreviations

B

Barefoot

BFQ

Barefoot questionnaire

FFS

Forefoot strike

M

Minimalist shoes

MABC-2

Movement assessment battery for children 2nd edition

MFS

Midfoot strike

RFS

Rearfoot strike

SD

Standard deviation

SPM

Statistical parametric mapping

SRS

Standard running shoes

VGRF

Vertical ground reaction force

VILR

Vertical instantaneous loading rate

Declarations

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Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Author information

Affiliations

¹Department of Human Movement Studies, Human Motion Diagnostic Centre, University of Ostrava, Ostrava, CZ 702 00, Czech Republic.

Jan Plesek, Joseph Hamill, Denisa Blaschova, Julia Freedman Silvernail, and Daniel Jandacka

²Department of Kinesiology, Biomechanics and Motor Control Laboratories, University of Massachusetts, Amherst, MA 01003, USA.

Joseph Hamill

³Department of Kinesiology and Nutrition Sciences, University of Nevada Las Vegas, Las Vegas, NV 89154, USA.

Julia Freedman Silvernail

Authors' contributions

JP, JH, JFS and DJ created design of the study; JP carried out the measurements and data collection; JP, DB, DJ performed data processing and data analysis; JP and DJ participated in the biomechanical analysis; JP and DB performed the statistical analysis, JP wrote first draft of the manuscript; JH, DB, JFS and DJ reviewed the manuscript and wrote some specific parts of the manuscript. All authors have read and approved the final version of the manuscript, and agree with the order of presentation of the authors.

Corresponding author

*Address for correspondence: Jan Plesek, Department of Human Movement Studies, Human Motion Diagnostic Centre, University of Ostrava, 702 00 Varenka 40a, Ostrava, Czech Republic (email: jan.plessek@osu.cz)

Declarations

Ethical approval and consent to participate

This study was reviewed and approved by the Ethical Board of the University of Ostrava, Faculty of Education (protocol ID: OU-54483/45-2019). This research was performed in accordance with all relevant guidelines and regulations in accordance with the principles of the Declaration of Helsinki.

Consent for publication

Consent for the publication of the manuscript was obtained from all children's parents or legal guardians.

Competing interests

Jan Plesek, Joseph Hamill, Denisa Blaschova, Julia Freedman Silvernail and Daniel Jandacka declare that they have no competing interests.

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Figures

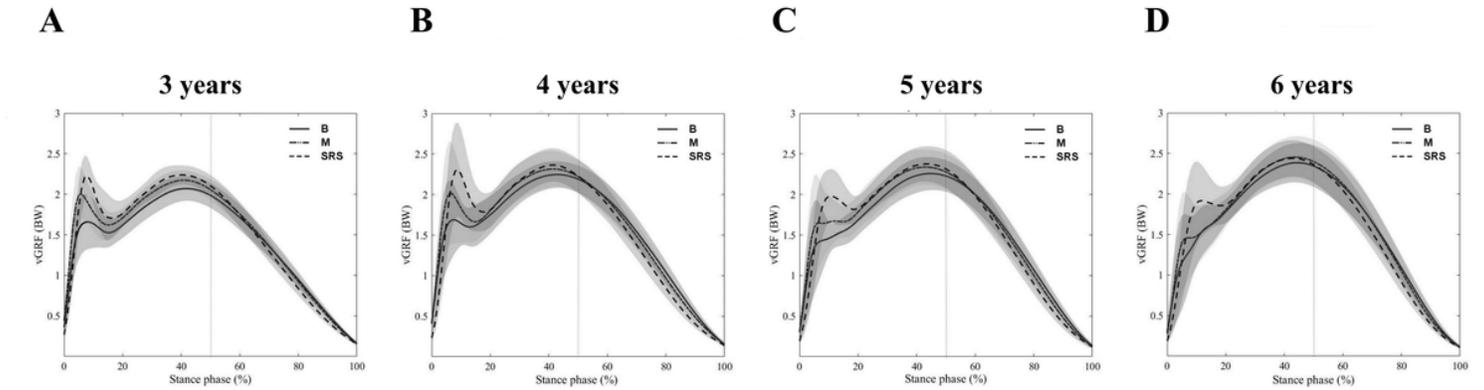


Figure 1

Vertical ground reaction force (VGRF) during stance phase. B–barefoot, BW–body weight, M–minimalist shoes and SRS–standard running shoes. (A) 3-years-old (B) 4-years-old (C) 5-years-old (D) 6-years-old children. Data are presented as mean and SD.

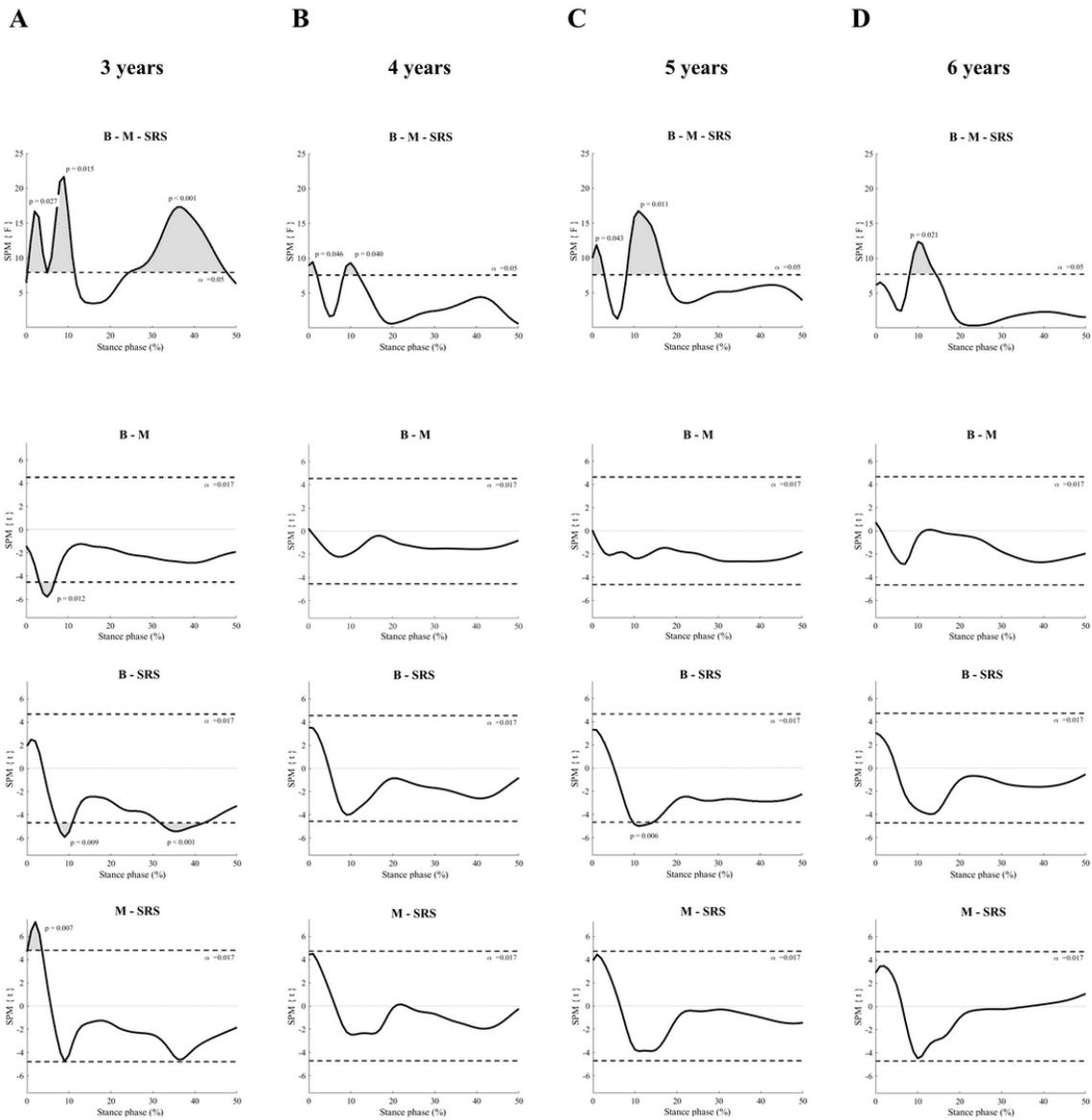


Figure 2

Statistical parametric mapping (SPM) – vertical ground reaction force during first 50 % of stance phase. Initial analysis: One-way repeated measures ANOVA (SPM (F)). Post Hoc analysis: Paired, two tailed t-test (SPM (t)). B–barefoot, M–minimalist shoes and SRS–standard running shoes. (A) 3-years-old (B) 4-years-old (C) 5-years-old (D) 6-years-old children.

MAXIMAL VERTICAL INSTANTANEOUS LOADING RATE

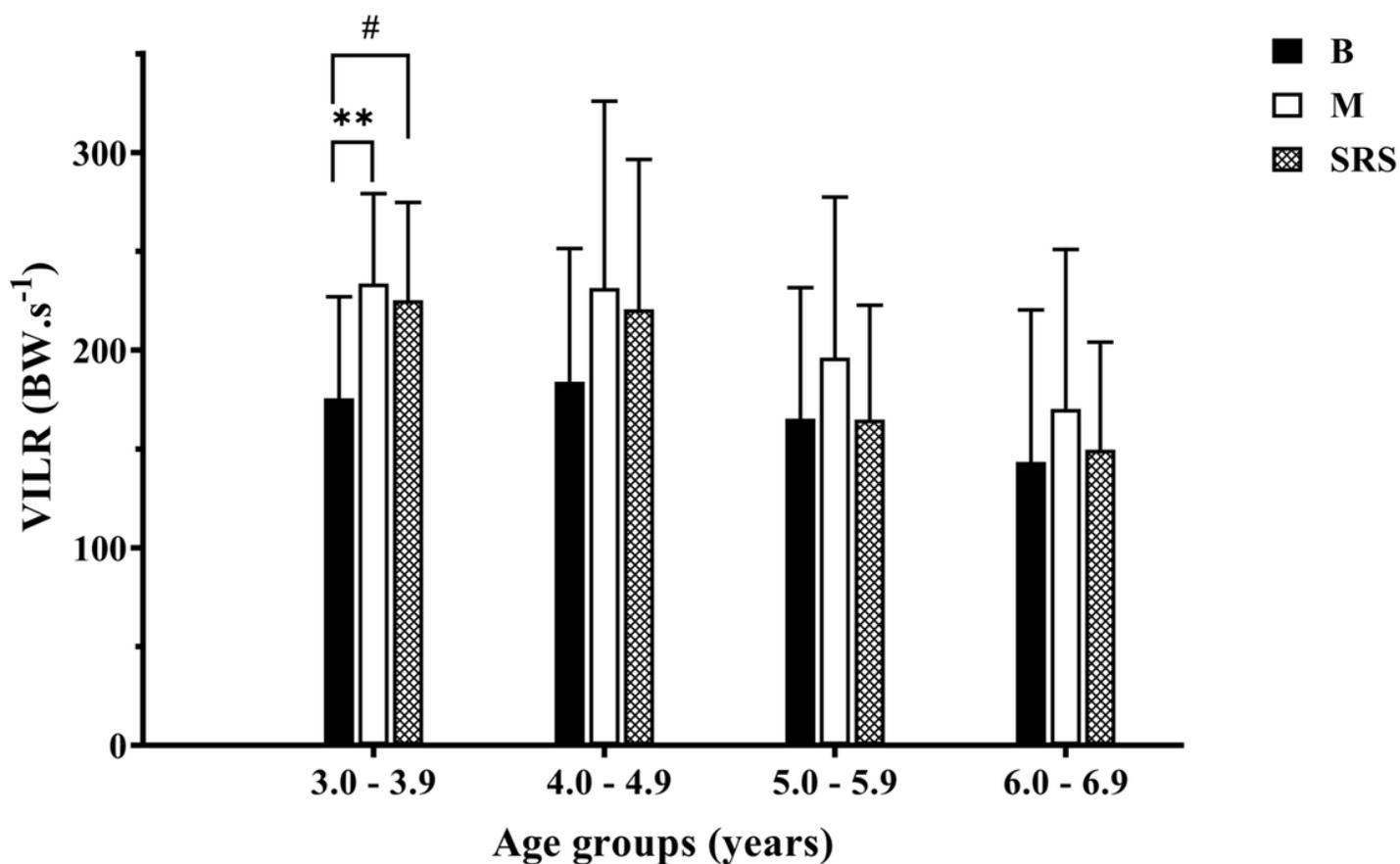


Figure 3

Maximal vertical instantaneous loading rate. One-way repeated measures ANOVA. Pairwise comparison of three footwear condition in each age group (Significant differences: *B-M, #B-SRS, with Bonferroni correction). B–barefoot, BW – body weight, M– minimalist shoes and SRS–standard running shoes, VILR – vertical instantaneous loading rate. Data are presented as mean and SD. *P < 0.05, **P ≤ 0.01, #P < 0.05, ##P ≤ 0.01