Foot characteristics during walking in 6–14-year-old children

Mario Kasović1,2, Lovro Štefan1✉ & Martin Zvonár2,3

The main purpose of the study was to establish foot characteristics during walking in children. In this cross-sectional study, we recruited 1284 primary-school students aged 6–14 years (714 boys and 570 girls) randomly selected from five schools in the city of Brno, Czech Republic. Children walked across a pressure platform (EMED-xl; NovelGmbH, Munich, Germany) to collect the data for both left and right foot during three trials. After the procedure, the software generated several foot characteristic variables: (1) force-time integral, (2) pressure-time integral, (3) contact area, (4) contact time, (5) peak pressure and (6) average pressure for the total foot. Curves for the 5th, 10th, 25th, 50th, 75th, 90th and 95th percentiles were calculated using the Lambda, Mu and Sigma (LMS) Chartmaker software. Our results showed that boys had longer force-time integral, higher contact area and contact time values, and higher peak plantar pressure, while no significant differences in pressure-time integral and average plantar pressure between sexes were observed. Older boys and girls had higher values in all measured variables. Our results provide for the first-time sex- and age-specific foot characteristics during walking in 6–14-year-old children.

Foot characteristics in children have become well-studied in the past 15 years. Some of them, like plantar pressures, represent the force applied to the ground and its distribution over the foot plantar surface1. According to previous evidence, peak vertical ground reaction forces may generate up to 120% of body weight2, where several tenth or hundred tones can be absorbed by each foot. Since walking is one of the main biological needs of individuals, constant high loadings lead to pain and discomfort in the region of lower extremities3,4. Such conditions have been proven to effect on health-related factors, reducing the level of physical activity5 or gaining weight6.

Children are at vulnerable risk for developing acute and chronic foot diseases7, since their feet still have immature structure and are under developmental phase8. From a biological point of view, children experience normal growth and have flexible flat feet9. Despite that, studies have shown that parents are frequently worried about their children’s feet and seek additional medical attention9–11. The most common external factor influencing normal foot structure is ill-fitting shoes, which often deviate from normal function and increase plantar pressure distribution12. Moreover, previous evidence has suggested that foot pain and discomfort have been associated with higher levels of plantar pressures in adults13,14, leading to the conclusion that force and pressure beneath the foot are important determinants of the foot. Thus, including plantar pressure variables within health surveillance systems should be of important interest for health-related professions to screen appropriate loading and temporal properties of the foot.

After an extensive literature review, we found no studies that have established foot characteristics in children. Therefore, the main purpose of the study was to establish sex- and age-specific foot characteristics data for several plantar pressure variables in 6–14-year-old children.

Materials and Methods

Study participants. In this cross-sectional study, participants were 1284 primary-school children (6–14 years (age mean ± SD = 9.6 ± 2.3; 44.4% girls) randomly chosen from five public schools in the city of Brno, Czech Republic. The inclusion criteria were: (1) age 6–14 years, (2) without history of any diseases, (3) currently without any diseases and (4) attending school and class where the study was conducted. At the first stage, we contacted principals from each school to give permission for conducting the study. At the second stage, we introduced children and their parents with measurement protocol, potential contribution of the research, and possible
### Table 1. Basic descriptive statistics of the study participants, Czech Republic. *differences were calculated using Student t-test for independent (sex) samples. p < 0.05.

| Measure | Sex | Age | N  | P5  | P10 | P25 | P50  | P75 | P90 | P95 |
|---------|-----|-----|----|-----|-----|-----|------|-----|-----|-----|
| **Age (years)** |   |     |    |     |     |     |      |     |     |     |
|          | Boys | 6   | 38 | 77/76 | 80/83 | 89/94 | 108/111 | 126/130 | 143/151 | 155/161 |
|          | Girls | 6   | 58 | 78/75 | 82/81 | 93/95 | 110/112 | 133/135 | 159/171 | 200/200 |
| **Force-time integral (N*s; left foot)** |   |     |    |     |     |     |      |     |     |     |
|          | Boys | 6   | 130 | 106/107 | 114/113 | 126/127 | 142/148 | 146/146 | 161/162 | 207/216 |
|          | Girls | 6   | 80  | 95/98 | 101/100 | 110/110 | 128/128 | 143/143 | 171/171 | 216/216 |
| **Pressure-time integral (kPa*s; left foot)** |   |     |    |     |     |     |      |     |     |     |
|          | Boys | 6   | 116 | 89/92 | 85/85 | 90/90 | 100/100 | 126/126 | 143/143 | 167/167 |
|          | Girls | 6   | 70  | 113 | 116/120 | 132/132 | 145/145 | 167/167 | 193/193 | 223/223 |
| **Contact area (cm²; left foot)** |   |     |    |     |     |     |      |     |     |     |
|          | Boys | 6   | 116 | 130/130 | 140/140 | 152/152 | 175/175 | 200/200 | 225/225 | 250/250 |
|          | Girls | 6   | 38  | 94/94 | 114/114 | 132/132 | 150/150 | 170/170 | 190/190 | 220/220 |
| **Contact time (ms; left foot)** |   |     |    |     |     |     |      |     |     |     |
|          | Boys | 6   | 116 | 109/109 | 126/126 | 143/143 | 167/167 | 193/193 | 223/223 | 250/250 |
|          | Girls | 6   | 38  | 88/88 | 106/106 | 124/124 | 144/144 | 170/170 | 195/195 | 225/225 |
| **Peak pressure (kPa; left foot)** |   |     |    |     |     |     |      |     |     |     |
|          | Boys | 6   | 116 | 130/130 | 140/140 | 152/152 | 175/175 | 200/200 | 225/225 | 250/250 |
|          | Girls | 6   | 38  | 94/94 | 114/114 | 132/132 | 150/150 | 170/170 | 190/190 | 220/220 |
| **Average pressure (kPa; left foot)** |   |     |    |     |     |     |      |     |     |     |
|          | Boys | 6   | 116 | 116/116 | 132/132 | 150/150 | 175/175 | 200/200 | 225/225 | 250/250 |
|          | Girls | 6   | 38  | 88/88 | 106/106 | 124/124 | 144/144 | 170/170 | 195/195 | 225/225 |

### Table 2. Foot characteristics for left and right foot (L/R within the table) in force– and pressure– time integrals.
discomforts during the execution of the research. Those children whose' parents had given written informed consent entered the study. All procedures were in accordance with the Declaration of Helsinki and approved by the Committee of the Faculty of Sports Studies (Ethics code number: 2/2018).

Dynamic foot characteristics variables. Dynamic plantar distributions generated under left and right foot were quantified as the children walked over a calibrated EMED – XL pressure platform (frequency of 100 Hz, resolution of 4 sensors/cm², 1440 × 440 mm sensor area and pressure range between 10–1270 kPa; Novel gmbh, Munich, Germany). Children were asked to normally walk over the platform with previous familiarization, as done in previous studies8. In brief, an adult assisted each participant by holding their hand during walking over the platform, after which the adult walked beside the participants without holding the hand to ensure normal arm swing. Software generated the data for three successful trials for both feet as follows: (1) force - time integral (N s), (2) pressure - time integral (kPa s), (3) contact area (cm²), (4) contact time (ms), (5) peak pressure (kPa) and (6) mean pressure (kPa). Of note, force-time integral and pressure-time integral are variables which describe the cumulative effect of force and pressure over time in a certain area of the foot, additionally providing a value for the total load exposure of a foot sole area during one step15. Of note, previous studies have shown that cumulative effect of force and pressure can lead to tissue damage and increase the risk of skin trauma15. Contact area is defined as the area covered by foot during one step and contact time is defined as the time interval between initial ground contact and toe off. Normal foot tends to have larger contact area covered and shorter contact time, which in addition leads to less rigid and more stable foot to absorb impact16. Peak and average plantar pressures represent the maximal and average load in an area under the foot during one step17. Sex and age were collected.

### Table 3. Foot characteristics for left and right foot (L/R within the table) in contact area and contact time.

| Measure     | Sex  | Age | N  | P5  | P10 | P25 | P50  | P75  | P90  | P95  |
|-------------|------|-----|----|-----|-----|-----|------|------|------|------|
| Contact area| Boys | 6   | 38 | 74/71| 76/75| 86/86| 92/94| 96/99| 102/103| 103/105|
|             | 7    | 92  | 76/74| 77/80| 87/89| 94/95| 100/101| 108/109| 115/115|
|             | 8    | 130 | 85/85| 87/88| 93/94| 101/101| 110/110| 119/116| 124/125|
|             | 9    | 116 | 84/79| 88/88| 98/98| 110/109| 118/119| 126/128| 129/133|
|             | 10   | 70  | 78/81| 82/86| 99/101| 107/110| 118/117| 131/130| 140/143|
|             | 11   | 64  | 92/86| 97/99| 107/110| 116/116| 134/132| 141/145| 147/150|
|             | 12   | 97  | 97/105| 106/110| 119/120| 129/129| 140/140| 156/155| 175/171|
|             | 13   | 48  | 114/117| 127/129| 139/139| 144/147| 158/155| 169/172| 172/179|
|             | 14   | 62  | 120/122| 122/125| 129/131| 145/146| 162/160| 177/181| 182/186|
| Contact time| Boys | 6   | 38  | 450/452| 490/509| 525/543| 570/585| 612/641| 734/721| 835/854|
|             | 7    | 92  | 489/486| 503/505| 557/560| 600/597| 637/637| 691/685| 761/736|
|             | 8    | 130 | 504/504| 520/530| 559/553| 600/600| 653/663| 720/709| 771/767|
|             | 9    | 116 | 509/503| 532/523| 570/573| 620/610| 660/663| 703/711| 740/758|
|             | 10   | 70  | 524/517| 540/543| 563/569| 620/617| 663/674| 706/710| 729/736|
|             | 11   | 64  | 538/534| 578/568| 611/617| 640/647| 676/673| 738/748| 786/783|
|             | 12   | 94  | 565/565| 597/602| 642/650| 693/690| 743/748| 790/803| 836/823|
|             | 13   | 48  | 621/610| 642/642| 678/684| 720/720| 756/750| 793/810| 840/850|
|             | 14   | 62  | 643/638| 647/644| 672/679| 710/713| 758/763| 836/868| 904/900|
| Contact time| Girls| 6   | 58  | 473/467| 492/490| 517/519| 580/583| 625/631| 673/687| 708/708|
|             | 7    | 80  | 494/490| 513/515| 541/554| 587/598| 642/644| 713/705| 763/757|
|             | 8    | 82  | 500/500| 519/510| 540/550| 578/588| 628/640| 687/717| 716/742|
|             | 9    | 68  | 506/516| 520/543| 563/557| 587/592| 647/656| 721/704| 749/744|
|             | 10   | 98  | 510/520| 523/533| 556/569| 610/618| 651/657| 693/664| 707/707|
|             | 11   | 60  | 531/537| 564/570| 588/591| 620/628| 681/672| 719/722| 733/740|
|             | 12   | 48  | 598/603| 606/613| 641/638| 665/668| 715/696| 764/759| 767/786|
|             | 13   | 38  | 516/510| 563/568| 601/607| 655/640| 688/683| 749/762| 771/791|
|             | 14   | 38  | 606/597| 610/603| 642/647| 680/692| 730/733| 771/777| 794/801|
prior the foot measurement protocol. The presence of foot pain was assessed by a single-item question: ‘Did you experience foot pain in one or both feet in the last 30 days’ with ‘Yes’ and ‘No’ answers.

Data analysis. Basic descriptive statistics are presented as mean (x) and standard deviation (SD). Sex and age differences were calculated by using analysis of variance (ANOVA) with post hoc comparison test between the groups. To calculate correlations between age and all the study variables, we used Pearson coefficient of correlation (r). For each variable, we determined sex- and age-specific percentile values (5th, 10th, 25th, 50th, 75th, 90th and 95th) and used Cole’s Lambda, Mu and Sigma (LMS) method, in which the optimal power to obtain normality is summarized by a smooth (L) curve and trends in the mean (M) and coefficient of variation (S) are similarly smoothed18. Next, all three curves (L, M and S) are summarized based on the power of age-specific Box–Cox power transformations for normalizing the data18. All analyses were performed in Statistical Packages for Social Sciences (SPSS Inc., Chicago, Illinois, USA) and in LMS Chartmaker Pro version (The Institute of Child Health, London, UK). A p value of < 0.05 (two sided) was considered statistically significant.

Results

Basic descriptive statistics of the study participants are presented in Table 1. Boys were slightly older, compared to girls (p = 0.039). Boys also had higher force-time integral values, followed by higher contact time, contact area and peak pressure values for both feet. No significant differences between sexes in terms of pressure-time integral and average pressure for left foot were observed (p > 0.05). Of note, we found statistically significant differences between left and right foot in terms of force-time integral (t = −5.68, df=1283, p < 0.001), contact area

Table 4. Foot characteristics for left and right foot (L/R within the table) in peak pressure and average pressure.

| Measure | Sex | Age | N   | P5   | P10  | P25  | P50  | P75  | P90  | P95 |
|---------|-----|-----|-----|------|------|------|------|------|------|-----|
| Boys    | 6   | 38  | 236/206 | 245/223 | 281/263 | 304/318 | 354/375 | 439/426 | 494/518 |
|         | 7   | 92  | 210/203 | 232/234 | 290/265 | 349/330 | 403/410 | 456/554 | 549/616 |
|         | 8   | 130 | 226/206 | 252/237 | 295/288 | 363/349 | 454/437 | 573/530 | 632/585 |
|         | 9   | 116 | 243/250 | 265/271 | 305/308 | 380/368 | 443/442 | 511/524 | 537/560 |
|         | 10  | 70  | 269/257 | 297/297 | 357/355 | 430/407 | 500/508 | 689/665 | 755/733 |
|         | 11  | 64  | 276/276 | 309/295 | 379/357 | 432/420 | 527/486 | 591/590 | 697/702 |
|         | 12  | 94  | 290/271 | 312/288 | 355/353 | 432/430 | 535/549 | 613/597 | 690/693 |
|         | 13  | 48  | 281/287 | 303/310 | 381/344 | 445/406 | 515/482 | 600/642 | 807/726 |
|         | 14  | 62  | 307/330 | 340/342 | 377/391 | 450/465 | 593/525 | 730/676 | 894/791 |
| Girls   | 6   | 58  | 221/217 | 260/229 | 283/295 | 350/352 | 426/392 | 453/444 | 507/480 |
|         | 7   | 80  | 253/233 | 259/262 | 296/303 | 363/372 | 455/481 | 526/580 | 636/692 |
|         | 8   | 82  | 220/245 | 229/264 | 300/303 | 382/372 | 474/468 | 550/625 | 642/726 |
|         | 9   | 68  | 276/264 | 310/311 | 360/378 | 427/441 | 480/472 | 560/544 | 646/568 |
|         | 10  | 98  | 291/288 | 313/315 | 362/363 | 425/421 | 519/503 | 655/621 | 694/724 |
|         | 11  | 60  | 320/296 | 353/352 | 391/405 | 473/497 | 600/583 | 731/666 | 755/690 |
|         | 12  | 48  | 289/292 | 315/313 | 353/383 | 432/444 | 543/507 | 603/705 | 648/749 |
|         | 13  | 38  | 287/314 | 332/350 | 385/400 | 516/513 | 705/589 | 800/799 | 866/891 |
|         | 14  | 38  | 275/290 | 331/338 | 382/365 | 459/470 | 550/599 | 609/730 | 645/761 |

Table 4. Foot characteristics for left and right foot (L/R within the table) in peak pressure and average pressure.
(t = −5.404, df=1283, p < 0.001), contact time (t = −3.303, df=1283, p < 0.001) and average plantar pressure (t = −2.401, df=1283, p = 0.017), so we presented upcoming results specifically for left and right foot.

Table 2 shows sex- and age-specific foot characteristics for left and right foot in variables force- and pressure-time integrals. The median value for force-time integral was between 108 N*s at age 6 to 348 N*s at age 14 in boys. In girls, similar patterns to boys in force-time integral till the age of 10 were observed, after which the differences to the age of 14 became larger. The median value for pressure-time integral ranged between 93 and 186 kPa*s in boys and between 95 and 179 kPa*s in girls, respectively. Similar patterns between sex and sex*age interaction were observed (p > 0.05). Chronological age was significantly correlated with force-time integral and pressure-time integral (r = 0.50–0.80, p < 0.001).

Table 3 shows sex- and age-specific foot characteristics for left and right foot in variables contact area and contact time. The median value for contact area was between 92 and 147 cm² in boys. In girls, the median value ranged between 86 and 127 cm². As expected, boys had significantly higher contact area values, compared to girls. The median value for contact time ranged between 570 and 720 ms in boys and between 580 and 692 ms in girls. Chronological age was significantly correlated with contact area and contact time (r = 0.37–0.74, p < 0.001).

Table 4 shows sex- and age-specific foot characteristics for left and right foot in variables peak pressure and average pressure. The median value for peak pressure was between 304 and 465 kPa in boys and between 350 and 516 kPa in girls. Interestingly, girls generated higher peak pressure between ages 6 and 9, had similar values at the age of 10 and continued to have higher values till the age of 14. The median value for average pressure ranged between 70 and 102 kPa in boys and between 75 and 104 kPa in girls, respectively. Although we found no significant differences between sexes in average pressure for left foot (p = 0.124), girls generated significantly higher average pressure for right foot, compared to boys (p = 0.016). As for the previous variables, chronological age was significantly correlated with peak pressure and average pressure (r = 0.32–0.63, p < 0.001). Of note, we additionally calculated foot asymmetries between left and right foot and sex*age interactions of the studied variables and found no significant differences (asymmetry index 2%–8%, p > 0.05 and sex*age interaction p > 0.05).

For all the data, sex- and age- specific foot characteristics data for force-time integral and pressure-time integral, contact area and contact time and peak pressure and average pressure for left (Fig. 1) and right (Fig. 2) foot in boys and for left (Fig. 3) and right (Fig. 4) foot in girls were created.

Figure 1. Percentile values for foot function (left) in boys.
Discussion

The main purpose of the study was to establish sex- and age-specific foot characteristics data in 6–14-year-old children. Of note, this is the first study exploring the aforementioned purpose on a sample of primary school children. The main findings of this study are: (1) boys had higher force-time integral, larger contact area and longer contact time values, compared to girls, (2) girls generated higher peak and average pressures, compared to boys and (3) older children had higher values in all the study variables, compared to younger children.

The biological growth of the structure and shape of a child’s foot is governed by soft tissue, followed by rapid transformation of cartilage develops into bone\(^5\). The foot is characterized by a highly unique structure which, in addition, can perform diverse movements\(^20\). However, a deviated foot; i.e. a foot that generates higher plantar pressure may potentially cause discomfort or pain\(^21\). Previous studies have reported that a few modifiable factors, like physical activity\(^20,22\) may influence on plantar pressure distribution in children. Specifically, a study by Mickle et al\(^20\) showed that higher levels of plantar pressure under the heel region were associated with lower total level of physical activity and less time spent in moderate-to-vigorous physical activity in boys, while in girls, higher levels of plantar pressure under the toe region spent the significant amount of time in sedentary behaviors. Similar findings were reported in a study conducted among overweight children, where higher levels of plantar pressure beneath the forefoot region were significantly correlated with moderate-, vigorous- and moderate-to-vigorous physical activity\(^22\).

Beside physical activity, studies conducted among adults have shown that some of the factors of plantar pressure during walking include prominent metatarsal heads in the forefoot model, Charcot deformity in the midfoot model and hammer toe deformity in the lesser toes\(^23\). In children, one previous study has shown that peak plantar pressures and percentage of body weight supported (contact area) are significantly higher in children affected by the disease\(^24\). However, no study to date has systematically established significant factors associated with several foot functions in children and adolescents and apparently healthy individuals. Indeed, previous studies conducted among older adults have shown that fallers had a significant higher prevalence of foot pain and generated a significantly higher peak pressure and pressure-time integral under the foot, compared to non-fallers\(^25\), leading to risks of chronic degenerative diseases, disabled range of motion and premature death.

In general, children’s feet are significantly different compared to adults’ feet. Specifically, they suffer from more foot pain, due to pediatric fat pad under the midfoot region, which protects excessive pressure\(^26,27\). Also, deviated foot functions in children are hypothesized to be associated with foot discomfort in adulthood\(^28\), leading to the

Figure 2. Percentile values for foot function (right) in boys.
conclusion that gait patterns established in childhood often persist later in life. Indeed, studies have shown that the measurement of plantar pressure during dynamic conditions is considered a reliable method to evaluate foot geometry and function. Since previous evidence has shown that such conditions can be corrected, modifiable risk factors for plantar pressure, such as physical activity, should be organized for a ‘risky’ group of children and for those with deviated foot functions to prevent from future diseases.

Our study has several strengths. First, we collected the data from a large sample of 6–14-year-old children (N = 1284). Second, we used an objective measure to assess several plantar pressure distribution variables. Third, we presented the results specifically for left and right foot, as preliminary analysis showed significant differences between them.

However, our study has a few limitations. First, foot characteristics in growing children and adolescents should be obtained from longitudinal studies that give the possibility to assess natural changes in individual growth and development. Second, we did not collect the data regarding different foot regions, like heel, midfoot (medial and lateral), forefoot (medial and lateral), toes 2–5 and 1st toe, like done in previous studies in children. Previous evidence suggests that foot parameters need to be determined under specific regions of interests, in order to detect clinically relevant data to prevent developing foot pathologies in the future. However, if EMED® platform is used to assess foot function beneath different foot regions, future results can be comparable to ours by calculating the overall mean of a given variable. Although we did not collect the data regarding the structure and different foot regions, our additional findings show no foot asymmetries between the feet, participants reported no foot pain in the last 30 days and the prevalence of overweight/obesity in our sample was very small (4%), assuming that children and adolescents are apparently healthy individuals with no foot problems. Also, studies have shown that foot flatness significantly decreases after the age of 6. Since we based our findings on youth aged 6–14, it is possible that they have already established foot structure and function naturally.

In conclusion, this is the first study establishing sex- and age-specific foot characteristics data for force- and pressure-time integrals, contact area and contact time and peak and average plantar pressure in 6–14-year-old children. Our results should be of extreme interest for health-related professionals, including orthopedics and podiatrists, who can identify children with deviated foot function and give advice for special comfortable shoes or footpads. Also, kindergarten and primary school teachers (especially in physical education) should monitor and track annual foot changes, in order to detect preschool and primary school children who are at extreme...
risk and should enter special interventions that correct for potential deviations. The reported norms, for example >90th percentiles for each variable studied, can be used as an ‘alert’ with additional lifestyle factors entered as co-morbidities. Also, the results presented in this study were in percentiles, and may help children and adolescents to memorize the score and track the results over a longer period of time.

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M.K., L.Š. and M.Z. conceived the study, wrote the manuscript and analyzed the data. All authors reviewed the final version of the manuscript.

Competing interests
The authors declare no competing interests.

Additional information
Correspondence and requests for materials should be addressed to L.Š.

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