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Study of foot support during gait in healthy children from neighbouring countries

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- Abstract. 11
- BACKGROUND: Healthy children's gait support patterns play a critical role in their development and overall well-being. 12

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- Therefore, in order to develop a correct gait, it is necessary to constantly update knowledge. 13
- **OBJECTIVE:** To identify differences in gait support among children in neighbouring countries. 14
- METHODS: 44 healthy children from Poland and Lithuania (4-11 years old) participated in the study. The spatiotemporal and 15 plantar pressure parameters of 88 neutrally aligned feet were analysed and compared. 16
- RESULTS: Statistically significant differences between stance, single-limb support, double support, swing duration, cadence, 17
- and velocity, max. force and pressure in the forefoot, as well as in the times of occurrence of max. forces in all three zones. 18
- Defined that age is related (p < 0.05) to cadence (R = 0.32), swing phase (R = 0.53), max. force under the midfoot (R = 0.35) 19
- and the heel (R = 0.47), max. pressure under the forefoot (R = -0.52), midfoot (R = -0.63) and heel (R = -0.47). 20
- CONCLUSION: The results can help caregivers, as well as clinicians and researchers, understand how gait mechanics change 21 with development and the growth course of the children of that country. Also, the results are important for the analysis and 22
- comparison of children's gait, as control reference data from the same country. 23
- Keywords: Support patterns, gait, healthy children, physical growth, motor skills 24

1. Introduction 25

- In children, the development of proper foot support and gait (walking pattern) is crucial for their overall 26 growth and movement [1]. During gait, healthy children can exhibit a variety of foot support patterns,
- 27 which can vary based on their age, developmental stage, and physical activity level [2–8]. The normal 28
- support pattern during gait typically goes through several stages as they grow and develop. Infants start 29
- by lying on their back and gradually progress to rolling, crawling, and eventually standing and walking. 30
- Infants rely on the support of their whole foot, including the heels, as they begin to take their first steps. 31
- Toddlers continue to refine their walking skills. By around 18 months, most toddlers develop a heel-to-toe

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walking pattern, where the heel strikes the ground first, followed by the midfoot and toes. The arches of 33 the feet start to develop during this stage, and the foot becomes more flexible. During the preschool years, 34 children's gait becomes more coordinated and efficient [9]. They refine their walking pattern and exhibit a 35 more natural heel-to-toe gait. The arches of the feet continue to develop, and the foot becomes more rigid. 36 providing better support and stability. School-age children generally have a well-established and mature 37 walking pattern. They have developed fully formed arches and a more adult-like gait. Their foot structure 38 and support are similar to that of adults, allowing for efficient and stable walking and running [10]. 39 Some of the most common foot support patterns seen in healthy children during gait include heel strike. 40 when the heel of the foot touches the ground first during the initial contact phase of gait. It is the most 41 common foot support pattern in healthy children [11-14]. The midfoot strike is when the middle of the 42 foot touches the ground first during the initial contact phase of gait. This foot support pattern is more 43 common in children who are barefoot or wearing minimalist footwear. Further, a forefoot strike when the 44 ball of the foot touches the ground first during the initial contact phase of gait is more common in children 45 who are running or sprinting. Flatfooted is when the entire sole of the foot makes contact with the ground 46 at the same time during the initial contact phase of gait. Flat feet, also known as pes planus, is a condition 47 where the arches of the feet appear flattened, causing the entire foot to make contact with the ground. Flat 48 feet are relatively common in infants and young children and usually resolve naturally as they grow [15]. 49 However, in some cases, flat feet may persist and lead to other foot related issues, requiring medical 50 attention. Toe Walking, when the child walks on their toes, without making contact with their heels or 51 midfoot is toe walking. It is common in toddlers who are still developing their gait pattern [5,16–18], but 52 if it persists beyond the age of three, it may indicate underlying neurological or musculoskeletal issues. 53 It's important to note that children can exhibit different foot support patterns during different phases 54 of gait, and variations in foot support patterns are not necessarily a cause for concern. Several factors 55 can influence support patterns in children and are broadly categorized into intrinsic factors and extrinsic 56 factors. Intrinsic are Growth and Development, foot structure, muscle tone and strength [15,19,20]. And 57 extrinsic stand for footwear, surface conditions and environmental factors [12,21]. There are several gait 58 parameters that can affect foot support patterns during gait in healthy children. Some of these parameters 59 include walking speed. The speed at which a child walks can affect the timing and amplitude of their 60 foot support patterns. Another one is step length, which can influence the amount of time each foot 61 spends in contact with the ground during gait. The cadence at which a child takes steps can also impact 62 the timing and coordination of their foot support patterns. Additionally, body weight: the weight of a 63 child can influence the distribution of forces on their feet during gait, which may affect foot support 64 patterns [22]. Very important seems to be foot posture, muscle strength and control and joint range of 65 motion. They can impact the mechanics of their gait and the support patterns they use. Understanding how 66 these gait parameters affect foot support patterns can help clinicians and researchers identify potential 67 problems or deviations from typical gait patterns in healthy children, and design interventions to address 68 them if necessary. Gait support patterns refer to the different ways in which individuals distribute their 69 body weight during walking [23]. It is influenced by various factors such as age, gender, body weight. 70 height, and cultural background [24,25]. There may be some differences in gait support patterns between 71 different populations [26–28]. There have been studies examining gait support patterns in children from 72 different countries, but there have been no studies comparing healthy Polish and Lithuanian children. 73 Gait studies of foot support patterns of healthy children from different countries can help parents and 74 medical professionals understand what changes in gait parameters occur as children develop and grow. 75 With such data, it is possible to adapt a supportive environment for children, encourage physical activity 76 or develop strong and effective movement support. Also, for the analysis and comparison of children's 77 gait results, it is important to have control reference data from children of the same country. 78



The purpose of this study is to better understand differences in gait support among children in neighbouring countries, which may influence the development of interventions or treatment methods tailored to specific populations. In order to achieve this goal, the work compares demographic, spatiotemporal,

⁸² and plantar pressure parameters, as well as finds related indicators to support patterns in kids.

83 2. Methods

84 2.1. Subjects

Eighty-eight neutrally aligned feet from Poland (PL) and Lithuania (LT) (aged 4–11 years) were examined. Healthy children (26 from PL and 18 from LT) were defined as individuals having no known musculoskeletal disease or abnormality and having not had any prior musculoskeletal manipulation, such as a surgical procedure. All subjects' parents gave written consent to participate in the study. The protocols were approved by the local ethical committees.

90 2.2. Measurement protocol

Before the measurement phase of plantar pressure distribution and spatiotemporal parameters, all 91 subjects were introduced to the gait analysis measurement system and the course of the study. Next, 92 the subjects' anthropometric and demographic data were determined, and lower limb muscle strength 93 (must be at least 5 points according to the Lovett scale) was assessed. Gait measurements were performed 94 barefoot using the Zebris FDM-T (Zebris Medical GmbH, Germany) pressure distribution measurement 95 platform with a sensor area of 149×54.2 cm, number of sensors of 11 264, and a sampling rate of 96 100 Hz. Then the subject was placed at the end of the platform and the measurement was started, which 97 is carried out for 2 minutes (the subject walks back and forth, i.e., dismounting at the end of the platform, 98 turning around and re-entering). Finally, the average of each person's data of all measured gait cycles 99 (calculated using the software of the measurement equipment) was saved for further analysis (Fig. 1). 100 Two groups of gait parameters were analysed in this study: (1) Spatiotemporal gait parameters and 101

¹⁰² (2) the maximum force, maximum pressure, and time of maximum force measured per each individual

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Demographic and a	nthropometric da	ita (mean \pm SD
Parameters	LT children $(N = 18)$	PL children $(N = 26)$
Gender, boys/girls	6/12	13/13
Age (years)	8.17 ± 1.92	8.62 ± 1.88
Height (m)	1.32 ± 0.11	1.36 ± 0.15
Weight (kg)	29.19 ± 7.42	33.15 ± 10.09
BMI (kg/m^2)	16.42 ± 2.15	18.20 ± 3.99
Leg length (m)	0.71 ± 0.08	0.70 ± 0.08



Fig. 2. Definitions of different regions used in this study: 1- forefoot, 2 - midfoot, 3 - heel.

step under three anatomical foot zones. These zones represent the following anatomical plantar regions:
 forefoot, midfoot, and heel (Fig. 2).

Before the comparative analysis, spatiotemporal data (step length, stride length, cadence and velocity) were normalized based on the methodologies of other researchers [29,30], and maximum force were normalized to body weight (i.e., dimensionless quantities were compared).

108 2.3. Statistical analysis

Data allocation was verified by Shapiro-Wilk test. All results are expressed and represented as mean 109 \pm SD. Normally distributed parameters were compared between LT and PL children using t-test (p < 110 0.05), and non-normally distributed using the Kruskal-Wallis test (p < 0.05). The degree of correlation 111 between gait parameters were determined using the Spearman rank correlation. Considering the difficulty 112 of determining the influence of different external factors on the parameters of the foot, we investigated 113 the possibility of predicting the distribution of forces in the soles using a regression model. The model 114 coefficient was assumed to have no significant effect on output if the p-value was greater than 0.05. The 115 accuracy of the model was examined using a root mean square error (RMSE) plot between the measured 116 data (Y) and the model-calculated data (Y). Statistical analyses were performed using Statistica software 117 version 13.1 (StatSoft, Poland). 118

119 3. Results

120 3.1. Demographic data

The mean age of both children groups was 8.43 ± 1.89 years. The mean body height, weight, and BMI were 1.34 ± 0.13 m, 31.53 ± 9.21 kg, 17.19 ± 3.04 kg/m², respectively. Demographic and anthropometric data for each group are presented in Table 1.

Firstly, the difference between the left and right-side parameters was calculated and there was no statistical difference observed. That's why the spatiotemporal parameters (Table 2) and plantar loading during walking (Table 3) were assessed as an average value for both legs.

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K. Daunoraviciene et al. / Study of foot support during gait in healthy children from neighbouring countries. Table 2 Spatiotemporal gait parameters for PL and LT children (mean \pm SD) LT children PL children Parameters (N = 36)(N = 52) 0.71 ± 0.08 0.78 ± 0.07 Step length Stride length 1.42 ± 0.16 1.56 ± 0.13 Step width (m) 0.08 ± 0.02 0.10 ± 0.02 Stance phase (%) $61.34 \pm 1.75^{\circ}$ 60.76 ± 1.22 11.49 ± 1.36 11.63 ± 0.64 Load response (%) Single limb support (%) $38.35 \pm 1.50^*$ $36.73 \pm 3.38^{*}$ Pre-swing (%) 11.51 ± 1.35 12.40 ± 3.75 $21.46 \pm 2.30^{*}$ Double phase (%) $22.97 \pm 2.49^{*}$ Swing-phase (%) $38.66 \pm 1.75^{\circ}$ $39.16 \pm 1.39^*$ $0.53 \pm 0.03^{*}$ $0.58\pm0.06^*$ Cadence $0.38\pm0.06^*$ $0.45\pm0.05^*$ Velocity p < 0.05. Table 3 Assessing plantar loading during walking at a habitual speed (mean \pm SD) LT children PL children Parameters (N = 36)(N = 52) $1.01 \pm 0.05^{*}$ Normalised max. force forefoot $0.81 \pm 0.16^{*}$ 0.20 ± 0.09 Normalised max. force midfoot 0.19 ± 0.03 Normalised max. force heel 0.76 ± 0.07 0.82 ± 0.19 Max. pressure forefoot (N/cm²) $21.01 \pm 4.61^{*}$ $31.34 \pm 1.11^{\circ}$ 7.93 ± 1.65 6.96 ± 0.57 Max. pressure midfoot (N/cm²) 26.14 ± 6.65 Max. pressure heel (N/cm^2) 26.72 ± 2.98 Time max. force forefoot (% of stance time) $74.59\pm2.03^*$ $67.14 \pm 1.54^*$ Time max. force midfoot (% of stance time) $44.83 \pm 8.12^{*}$ $48.41 \pm 3.15^*$ Time max. force heel (% of stance time) $18.46 \pm 3.24^{*}$ $17.83 \pm 1.06^{*}$ $p^* p < 0.05.$

¹²⁷ When comparing the temporal parameters, there were significant differences between stance, single ¹²⁸ limb support, double support, and swing duration. No differences were observed only in the duration ¹²⁹ of the load response and pre-swing phases (p > 0.05). There were also significant differences between ¹³⁰ cadence (0.53 ± 0.03 for LT children vs. 0.58 ± 0.06 for PL children, p < 0.05), and velocity (0.38 ± ¹³¹ 0.06 for LT children vs. 0.45 ± 0.05 for PL children, p < 0.05).

There were no significant differences between the parameters of pressure distribution and max. force in midfoot and heel (p > 0.05). Differences in the forefoot were observed for the max. force (1.01 ± 0.05 for LT children vs. 0.81 ± 0.16 for PL children) and the max. pressure (21.01 ± 4.61 for LT children vs. 31.34 ± 1.11 for PL children), p < 0.05. There were significant differences in the times of max. forces between LT and PL children in all three zones.

137 3.2. Correlation coefficient investigation

Gait parameters were analysed using the correlation coefficient. As a result, age and some gait parameters have been found to be related. Age correlates with the leg length (R = 0.76, p < 0.05), and the stride length (R = 0.64, p < 0.05). This is a part of the normal growth and development process. The leg length growth is driven by the elongation of long bones, particularly the femur (thigh bone) and tibia (shin bone). Also, the stride length increase is influenced by increased leg length, improved muscle strength, 6 K. Daunoraviciene et al. / Study of foot support during gait in healthy children from neighbouring countries

coordination, and motor control. Cadence was positively correlated with age (R = 0.32, p < 0.05), 143 meaning that children with age become more proficient in walking, their steps become quicker and more 144 efficient, leading to a higher cadence. Also, the swing phase was positively correlated with age (R = 0.53). 145 p < 0.05). This is related with improved muscle control, increased strength, and enhanced coordination. 146 A correlation was found between age and plantar pressure parameters: max. force under the midfoot (R =147 (0.35, p < 0.05), and the heel (R = 0.47, p < 0.05). It can be explained by gain strength, coordination, 148 and motor control. Children with age develop better movement patterns, that's because they can exert 149 more force on the midfoot and the heel region, resulting in higher maximum force readings. Moreover, 150 the high correlation was observed between age and max. pressure under forefoot (R = -0.52, p < 0.05). 151 the midfoot (R = -0.63, p < 0.05), and the heel (R = -0.47, p < 0.05). A negative correlation would 152 indicate that as age increases, the plantar pressure under the foot regions decreases. For example, the 153 plantar pressure under the heel region maybe moved to the midfoot and the forefoot. 154

155 3.3. A model fitting results

A relationship between the dependent and independent variables can be approximately represented within the second-degree polynomial [31]:

$$\hat{Y} = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3 + \dots + a_n X_n + a_{12} X_1 X_2 + a_{13} X_1 X_3 + \dots + a_{1n} X_1 X_n + a_{23} X_2 X_3 + \dots + a_{2n} X_2 X_n + \dots + a_{3n} X_3 X_n + a_{11} X_{11}^2 + a_{22} X_{22}^2 + a_{33} X_{33}^2 + \dots + a_{mn} X_{mn'}^2$$

$$(1)$$

where: \hat{Y} is the dependent variable (model output), $X_1 \dots X_n$ are the independent variables (model 158 input), $a_1 \dots a_n$ are model coefficients. We proposed a model related to stability and balance, that's why 159 pressure distribution across the heel region is very important. The heel plays a crucial role in maintaining 160 stability during weight-bearing activities and absorbing impact forces during heel strike. We assumed 161 three independent variables for predicting the pressure distribution across the heel [N/cm²], including age 162 (X_1) , velocity (X_2) , and BMI (X_3) . The independency among three variables was confirmed by analysis 163 of correlation. The correlation between the variables was week (p > 0.05). Correlations between max. 164 plantar pressure under the heel (Y, dependent variable) and independent variables were $R_{x1,y} = -0.47$ 165 $(p < 0.05), R_{x2,y} = -0.04 (p > 0.05), \text{ and } R_{x3,y} = 0.43 (p < 0.05), \text{ respectively.}$ 166

Statistical analysis of the model's coefficients showed that the model coefficient a_2 (velocity) was not significant (p > 0.05) and, therefore, was excluded from the model. The final version of regression model is presented below:

$$\hat{Y} = 13.07 + 0.45X_1 - 0.96X_3$$
(1.89) (0.12) (0.06) (2)

The results suggest that the model could accurately fit the measured values (goodness of fit: $R^2 = 0.93$, test F = 137.14). The root mean square error between the model output (\hat{Y}) and the measured value (Y) was 2.06 N/cm². The model demonstrates differences in the plantar pressure distribution under the heel according to age, and BMI. The plantar pressure increases as age increases. Additionally, the results suggest plantar pressure reduction under the heel as BMI increases. It's important to consider that BMI and age are just two factor influencing plantar pressure under the heel. Other factors such as footwear can also contribute to the complex interplay of plantar pressure distribution.

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Comparison of our spatiote	Table 4 mporal results w	ith those present	ed in the literatu
Parameters	LT children	PL children	Literature [10]
Step length	0.71 ± 0.08	0.78 ± 0.07	0.79-0.84
Stride length	1.42 ± 0.16	1.56 ± 0.13	1.58-1.68
Step width (m)	0.08 ± 0.02	0.10 ± 0.02	0.07-0.09
Stance phase (%)	61.34 ± 1.75	60.76 ± 1.22	55.8-58.9
Single limb support (%)	38.35 ± 1.50	36.73 ± 3.38	41.7-44.0
Double phase (%)	22.97 ± 2.49	21.46 ± 2.30	11.8-17.5
Cadence	0.53 ± 0.03	0.58 ± 0.06	0.58-0.62
Velocity	0.38 ± 0.06	0.45 ± 0.05	0.46-0.52

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177 **4. Discussion**

Understanding gait support patterns in children from neighbouring countries enhances cross-cultural 178 understanding, promotes inclusive healthcare practices, and contributes to the development of more 179 effective interventions and services. It enables healthcare professionals, researchers, and educators to 180 address the unique needs of diverse populations and work towards improving the mobility and well-being 181 of children worldwide [26–28]. Various biomechanical parameters can be used to describe gait support 182 models in children. The choice of parameters depends on the specific objectives of the analysis and the 183 context in which it is performed. Spatiotemporal parameters are commonly used in combination with 184 others to capture various aspects of gait and to assess the overall quality of gait support in children. These 185 parameters are particularly useful for assessing gait abnormalities, monitoring rehabilitation progress, and 186 evaluating the impact of interventions or treatments on locomotion [12,17,32]. Comparing our results with 187 Lythgo and et. [10] according to the average age of LT and PL children, Polish is closer to Lythgo and et. 188 results than LT in almost all spatiotemporal parameters (Table 4). It turns out that PL children are closer 189 to other parameters found in the literature than Lithuanians. On the other hand, another scientific source 190 on children's gait and stance characteristics indicates that gait speed can influence stance patterns [33]. 191 Therefore, based on these results, it can be said that LT results could be related to walking speed. Since 192 walking speed was not limited in this study, perhaps the LT children simply walked more slowly. 193

Studies [10,34] have shown that healthy children tend to have a longer stance phase, double support, and 194 cadence than adults due to a shorter stride length. They generally spend a shorter duration in single limb 195 support and typically exhibit shorter swing duration compared to adults. Cadence can vary among healthy 196 children from different countries. Cultural and environmental factors, including lifestyle, physical activity 197 levels, and walking surfaces, may influence cadence. As they develop, there is a gradual increase in the 198 duration of single limb support and swing, reaching adult values by adolescence [10]. In children with 199 typical support pattern, gait velocity falls within the expected range for their age and developmental stage. 200 Normal gait speed reflects and efficient and coordinated walking pattern with appropriate weight transfer 201 and support. Decreased gait velocity might be present due to (1) weakness and poor muscle control, or 202 (2) balance or stability issues. Often higher velocity in children provide insights into support patterns. 203 Kids with support issues, such as toe walking or other abnormal gait patterns, may adopt compensatory 204 strategies, i.e., increasing gait velocity to enhance stability and minimize time spent on one foot. Gait 205 velocity may differ between children from various countries due to variations in walking habits, physical 206 activity levels, and environmental factors [25]. 207

Other extremely important indicators of gait support model analysis are plantar pressure parameters [7, 8], which assess how forces are distributed on the sole surface of the foot during walking. Our study revealed significant differences between LT and PL children in plantar pressure parameters: the max.

force in the forefoot and the duration of occurrence of max. forces in all three zones (p < 0.05).

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These differences could be influenced by factors such as walking habits, body weight, and foot 212 biomechanics. Higher max, force in forefoot for LT children (p < 0.05) may suggest imbalances in weight 213 distribution. Normally, when approaching the gait characteristic of adults, the forefoot max. force is higher 214 than the heel, as the results of LT children showed us. And in PL children, we got a small difference. In 215 this case, LT's gait is more mature. Although the spatiotemporal parameters are characteristic of a more 216 mature gait in PL. It could also be a sign of structural abnormalities or biomechanical issues affecting 217 the distribution of forces through the foot. It is known that children with high arches may experience 218 increased forces in the forefoot due to reduced shock absorption and limited foot flexibility. Moreover, 219 children with flat feet may have a broader distribution of pressure across the entire foot, including the 220 forefoot, due to decreased arch support. 221

Correlation analysis confirmed that every age we studied is related to gait parameters: cadence (r = 0.32, p < 0.05), swing phase (r = 0.53, p < 0.05). moderate correlation between age and Plantar pressure parameters: max. force under the midfoot (R = 0.35, p < 0.05), and the heel (R = 0.47, p < 0.05). Age is strongly correlated with leg length (R = 0.76, p < 0.05) and stride length (R = 0.64, p < 0.05). Furthermore, a strong to moderate negative correlation was observed between age and max. pressure under the forefoot (R = -0.52, p < 0.05), midfoot (R = -0.63, p < 0.05) and heel (R = -0.47, p < 0.05).

It is important to note that these differences in gait support among healthy children from different countries are based on limited research, and more detailed studies are needed to identify clear patterns, as well as the underlying factors contributing to the observed differences. In addition, differences in gait support patterns may also be influenced by factors such as gender and individual biomechanics. Cultural, environmental, or similar differences between countries that may affect gait parameters were not fully assessed in our study.

235 **5. Conclusions**

Studying foot support patterns during gait in healthy children can help clinicians and researchers understand how gait mechanics change with development and may inform interventions or treatments for gait abnormalities. Seeing the differences in our results, it can be said that the characteristics of each country determine the characteristics of the gait support pattern and the growth course of the children of that country. Therefore, for analysis and comparison of children's gait results, it is important to have control reference data from children from the same country, and to ensure similar walking speeds.

242 Acknowledgments

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Conflict of interest

None to report.

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