DISTRIBUTION OF PLANTAR PRESSURES DURING GAIT IN DIFFERENT ZONES OF THE FOOT IN HEALTHY CHILDREN: THE EFFECTS OF LATERALITY[1]

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Summary.—The objective was to determine whether gait is symmetric in healthy children 6-7 years of age and to assess the effects of laterality and the anatomical zone of the foot. 46 children were subjected to gait symmetry analysis in which the plantar and lateral pressures associated with kicking a ball, static balance and dynamic support were measured. There were no significant differences in the average pressure exerted by the right and left feet based on the laterality of the child. Independent of each laterality test, a greater pressure on the right rearfoot was observed compared to the left rearfoot and on the left midfoot and forefoot compared to the right.

Gait is a basic requirement for the daily activities of human beings. In some studies, gait symmetry has been assumed so as to simplify analysis and data collection (Sadeghi, Allard, Prince, & Labelle, 2000). However, the study of possible gait asymmetries is important from clinical and sports perspectives and for establishing patterns of normality and abnormality for specific populations (Sadeghi, Allard, & Duhaime, 1997; Maupas, Paysant, Datie, Martinet, & André, 2002, Sadeghi, 2003; Seeley, Umberger, & Shapiro, 2008) and children (Bosch & Rosenbaum, 2010; Pulido-Valdeolivas, Gómez-Andrés, Martín-Gonzalo, López-López, Gómez-Barrena, Sánchez Hernández, *et al.*, 2013). Functional asymmetry of the lower extremities, which is defined as a discrepancy in the contribution of each limb in performing propulsion and control tasks during walking, may be the cause of observed asymmetries (Sadeghi, *et al.*, 2000). If gait is asymmetrical due to functional asymmetry, there should be an extremity that favors propulsion with a greater plantar pressure on the anterior area of the foot (metatarsals), and if there is one that favors support, greater plantar pressure should be observed on the posterior area of the foot (heel) in that extremity. In their symmetry study, Seeley, *et al.,* hypothesized that the vertical impulse (support) would be greater for the non-dominant limb and that the propulsive impulse would be greater for the dominant limb.

Functional asymmetries could be related to laterality, i.e., a preferential use of one limb in voluntary motor actions (Gabbard, 1997). The dominant limb contributes to propulsion, whereas the non-dominant limb contributes to support (Sadeghi, *et al.,* 2000; Seeley, *et al.*, 2008); however, current studies show conflicting results (see the review by Sadeghi, *et al.,* 2000), perhaps due to the type of test used to determine the dominant limb. According to some studies, there is no relationship between gait asymmetry and laterality (Maupas, Paysant, Martinet, & André, 1999; Zverev, 2006), whereas other studies have identified some relationship between these two factors: Sadeghi (2003) was affirmed that the role of the right knee moment was identified as stabilizing weight-bearing, while for the left knee, the role of the muscles was to absorb the impact; and Seeley, et al., (2008) was observed no significant bilateral differences existed between sample means for vertical or propulsive impulses at the slow or preferred speeds, except at the fast speed, where contributions to propulsion were greater for the dominant limb. Various tests are used to

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identify laterality. While most studies use a single test, it is currently accepted that the lower limbs perform different tasks (Peters, 1988; Gabbard & Hart, 1996; Seeley, *et al.*, 2008); thus, laterality can be determined using various tests that measure static balance, dynamic support, and precision of movement (Maupas, *et al.*, 2002; Zverev & Mipando, 2007).

The assessment of plantar pressure is a useful tool in the analysis of the biomechanics of the human foot (Rai, Aggarwal, & Bahadur, 2006). This type of assessment is used in the study of gait in children (Phethean & Nester, 2012) because it can evaluate the effects of structural changes that may occur in some specific foot pathologies and thus may be useful in preventing them (Cavanagh, Ulbrecht, & Caputo, 2000). Plantar pressure distribution during gait has been studied both in healthy children (Hennig, Staats & Rosenbaum, 1994; Kellis, 2001; Bertsch, Unger, Winkelmann, & Rosenbaum, 2004; Bosch & Rosenbaum, 2010; Cousins, Morrison, & Drechsler, 2012; Phethean, Pataky, Nester, & Findlow, 2014), showing gait patterns (Bosch, Gerß, & Rosenbaum, 2010) and, in some cases, the effects of walking speed (Goble, Marino, & Potvin, 2003; Burnfield, Few, Mohamed, & Perry, 2004), type of shoes (Fielder, Stuijfzand, Harlaar, Dekker, & Beckerman*,* 2011), fatigue (Bisaux & Moreto, 2008) or age (Bertsch, *et al.*, 2004; Bosch & Rosenbaum, 2010) affect these patterns. Some studies have assessed sex effects on the distribution of plantar pressure in children (Hennig, *et al.*, 1994; Bosch, Gerß, & Rosenbaum, 2010; Phethean & Nester, 2012). .

In research on plantar pressure, some studies have measured the average or maximum values of pressure throughout the foot (Goble, *et al.*, 2003; Bosch & Rosenbaum, 2010) or analyzed the peak pressure, maximum strength, contact area, and arch index (Bosch, *et al.*, 2010). Others have reported the distribution of pressure in various anatomical areas, considering it important to observe whether there are pressure differences between the extremities based on these measurements (Kellis, 2001; Perttunen, Anttila, Södergård, Merikanto, & Komi, 2004). While Warren, Maher, and Higbie (2004) and Phethean and Nester (2012) divided the foot into nine zones, Burfield, *et al.* (2004) divided it into eight zones; others, such as Stebbins, Harrington, Giacomozzi, Thompson, Zavatsky, and Thologis (2005), used five zones (medial heel, lateral heel, midfoot, medial forefoot, and lateral forefoot). Some studies measured the pressure throughout the foot and in the three anatomical zones rearfoot, midfoot, and forefoot (Burns, Crosbie, Hunt, & Ouvrier, 2005; Yan, Zhang, Tan, Yang, & Liu, 2013).

A number of recent studies have assessed gait patterns in healthy children. Some used plantar pressure distribution to assess the involvement of each foot during gait (Zhu, Werstch, Harris, Henry, & Alba, 1994; Perttunen, *et al.*, 2004; Bosch & Rosenbaum, 2010; Phethean & Nester, 2012; Yan, *et al.*, 2013). It would be interesting to know whether possible differences in involvement or asymmetries between the right and left feet vary among anatomical zones of each foot and/or by laterality, which is already developed at this age (Ferre & Aibau, 2002; Shaffer & Kipp, 2007). According to Phethean, *et al.* (2014), mature gait occurs at the end of the 4 to 7 years of age, when structural, morphological, and functional changes of the foot have occurred. According to Hennig, *et al.* (1994), the longitudinal arch development of the foot is almost complete before the age of 6 years. For that reason, a study of the distribution of pressure during gait at this age may have implications for young adults.

The goal of this study is to assess the symmetry of plantar pressure distribution during gait in children 6 and 7 years of age, to assess whether the involvement of the anatomical zones of the foot differs in the right and left limbs, and whether the laterality of the dominant lower extremity affects symmetrical or asymmetrical behavior in static and/or dynamic tests. Findings indicating that the observed distribution patterns in children's feet are not symmetrical with respect to the anatomical zone would be important in the therapy and orthopedics of children and young adults.

Hypothesis. The dominant limb should have a greater plantar pressure on the anterior part of the foot (metatarsals) and the non-dominant limb should show a greater plantar pressure on the posterior part of the foot (heel).

METHOD

Participants

A total of 46 healthy children (*M* age = 6.5 yr., *SD* = 0.5; *M* mass = 28.1 kg, *SD* = 6.4), 23 boys and 23 girls, underwent a laterality and gait symmetry evaluation. Informed consent was obtained from the parents or guardians of the children prior to the study. Of a total of 54 children evaluated, eight were excluded from the study, six because of foot or gait abnormalities and two because of inadequate data collection. The study was approved by the Research Ethics Committee of the Government of Aragon.

The age range of the children in the study was chosen for two reasons; first, gait in children has special characteristics that evolve while the nervous system matures, with adult gait characteristics being adopted at the age of 7 years (Andrés, Torres, Ramírez, García, & Álvarez, 2006; Cousins, et al. 2012; Phethean, et al., 2014); second, laterality hand and eye develops in children by the age of 6 to 7 years (Ferre & Aribau, 2002; Shaffer & Kipp, 2007), but some children show a dexterous tendency later on (Mayolas, 2011), probably cultural and environmental pressure against left-foot preference (Auerbach & Ruff, 2006; Zverev & Mipando, 2007); it was desirable to avoid this due to its possible effect on the results (Kershner & Chyczij, 1992).

The 45 children recruited into this study represent nine participants within each of the age groups; in previous studies similar numbers were used when investigating the reliability of repeated plantar pressure measurements in a healthy population of adults.

Measures

Laterality assessment.—Following the guidelines of Maupas, *et al.* (2002), laterality was assessed using three tests: kicking a ball with precision, static equilibrium, and dynamic support. Each child performed each test twice. The kicking-a-ball test is one of the most widely used tests for evaluating the laterality of the lower limb. It consists of kicking a ball toward an object located 8 m away. In the static equilibrium test, the child balanced on one foot for 10 sec. In the test for dynamic support, the child jumped on one foot for a straight distance of 5 m. The limb freely chosen to execute each of the tests was noted. A child was considered ambidextrous when two attempts were executed using different limbs.

Gait symmetry assessment.—Gait symmetry was determined by comparing plantar pressures using a previously validated registration system with instrumented insoles (PDM 240, University of Zaragoza, Spain); this instrument is an improved model of the PDS 93 electronic pedometer, and its reliability has been supported in previous studies (López, Pérez, & Orrite, 1996; Pérez, Herrera, & Orrite, 1997; Herrera, 1997). The insoles that were used with the children in this study were sizes 28 to 30, which are the equivalent of a foot length of 17.1 to 18.4 cm. The system consists of an acquisition module, a transmitter module, a receiver module, a microcontroller, a signal conditioning unit, software, and hardware. The insoles, which are placed between the soles of the foot and the shoe, have piezoresistive sensors of 1 cm Ø (Fig. 1). These enable the acquisition, analysis and registration of maximum and average pressures according to the zones of the foot that are to be determined. Using a radio frequency transmission power of 2 mW, the signal detected by the insoles reaches the microcontroller, which then transforms the signal to an RS232 format, i.e., transmitted to a receiver. Because there are no cables from the transmitter module to the computer, this transmission system permits the acquisition of pressure values without limiting the freedom of movement of the participant (Vilarroya, Torre, Pérez-García, Herrera, & Malillos, 2005). The system records values in g/cm^2, equivalent to an SI unit of 1 kPa = 10.20 g/cm^2. Pressure was normalized by dividing it by the child's weight.

After walking freely for 1 min. to adapt to the pressure insoles, each child walked the length of a 10-m-long flat unobstructed marked hallway at a self-selected walking speed, the same distance used by other authors (Potdevin, Gillet, Barbier, Coello, & Moretto, 2008; Yan, *et al.,* 2010). According to Burnfield, *et al.* (2004), pressure in the foot, except for the arch and the lateral metatarsal bone, increases at higher walking speeds. According to Warren, *et al.* (2004), there is a linear relationship between walking speed and pressure peaks on the heel. In the current experiment, recording began when the child entered the measurement area, and two complete gait cycles, starting from the child's third step in the hallway, were captured for the analysis of plantar pressures; in this way, according to Burnfield, *et al*. (2004), the effects of acceleration and deceleration are eliminated.

The pressure sensors were placed on the medial and lateral sections of the forefoot below the heads of the metatarsals, on the medial and lateral heel, and on the lateral and medial midfoot below the plantar arch (Fig. 1). There was no evaluation of pressure on the toes because Cousins, *et al.* (2012) concluded in their study that data obtained from the toes had only moderate reliability and greater variability in children. For the analysis of plantar pressure patterns, the total plantar pressure, as well as the pressure distribution on three anatomical zones of each foot (forefoot, midfoot and rearfoot) (Fig. 1), was considered, as in the studies of Burns, *et al.* (2005), who studied different etiologies of *Pes Cavus* on foot pain and plantar pressure characteristics, and of Yan, *et al.* (2013), who studied the effects of obesity on dynamic plantar pressure distribution in Chinese prepubescent children during walking. The average pressure throughout the foot was also measured, following the method used by Bosch and Rosenbaum (2010), who studied children between 15 and 63 mo. of age. In their study a symmetry index was calculated based on the entire foot to eliminate the dependency of the load results on one single sensor.

To quantify gait symmetry and asymmetry, the value derived for a gait parameter at the right limb was divided by the associated value at the left limb (RI = XR/XL, called the Ratio Index). This method was applied to the mean average pressure (PPM) at each of the three anatomical zones and to the total average pressure exerted on each foot. This formula has been used in previous studies, including those of Seliktar and Mizrahi (1986), Wall and Turnbull (1986) and Andrés and Stimmel (1990), although other formulas have also been used (see the review of Sadeghi, *et al.* on the study of gait symmetry in healthy subjects). Although limited because zero pressure values cannot be used, this method offers a simple means of comparison between the feet; a value greater than 1 indicates more pressure on the right foot, and a value of less than 1 indicates more pressure on the left limb. The zero-pressure limitation did not affect the current study, because total average pressure of the foot and the distribution of the pressure in three anatomical zones was used, so in all cases, the values obtained were greater than zero.

Statistical Analysis

Statistical analysis was performed using SPSS Version 19.0. Descriptive statistics were calculated. Normality of the variables was tested using the Kolmogorov-Smirnov and Shapiro-Wilk tests. Percentage differences among the right-footed, left-footed, and ambidextrous children were obtained using the chi-squared test. Student's *t* test was used to compare the average pressure of the right and the left limbs and for the comparison of pressure between sexes. The *t* test was also used to analyze the average RI (Ratio Index) pressures with laterality on each test when normality of the data was assumed, while the Mann-Whitney *U* test was used when normality was not assumed; in this way, the differences in the variables between right- and left-footed children were established. Analysis of variance (ANOVA) was used to compare the values obtained from the three anatomical zones (forefoot, midfoot and rearfoot). When required, a *post hoc* Bonferroni test was used.

RESULTS

Most of the children in the study were right-footed, as observed on the three laterality tests (Table 1). Significant differences according to the chi-squared test ($p < .01$) were observed between right- and left-footed on the laterality tests of kicking a ball with precision and of static balance. The number of ambidextrous children was low, thus excluding *a posteriori* analysis.

The first analysis performed was a *t* test in which the exerted pressure on the right limb and on the left limb was compared. No significant differences were observed between the average pressure on the right foot (2743kPa ± 1669.86) and the average pressure on the left foot (3015 kPa ± 1924.60).

With the average pressures (PP), ratio index values were obtained (RI PP = PPR/PPL), with scores over 1 indicating greater pressure on the right foot and scores below 1 indicating greater pressure on the left foot. For the comparative study of plantar pressure and laterality, the average pressure throughout the foot and for the three anatomical zones (forefoot, midfoot and rearfoot) was calculated (Table 2). Based on the three evaluated zones of the foot, the RI of the rearfoot zone indicated more pressure on the right limb, and the RI of the forefoot and midfoot zones indicated more pressure on the left limb. The rearfoot RI was significantly higher than the RI of the forefoot and midfoot zones (Table 2).

With respect to children's sexes, no significant differences were observed in the average pressure for the total foot. The RI coefficient for this parameter was less than 1 for both boys and girls, i.e., there was greater pressure on the left limb than on the right. This was more noticeable in girls, for whom the RI was 0.92, compared to boys, for whom the RI was 0.97. When the three zones of the foot were analyzed, both boys and girls were found to apply more pressure to the left forefoot and midfoot. The right rearfoot had higher average pressure in both boys and girls, with an increased pressure on that zone of the right foot of the boys (Table 3).

There were no significant differences between the RI and the laterality of the children, the total average pressure (Table 4), or the pressure in any of the evaluated zones (Table 5). RI values below 1 were observed in both right- and left-footed children for each of the three tests performed (two dynamic and one static). These results indicate greater pressure on the left limb but show independence of pressure and laterality of the children ($p > .05$, all three laterality tests). In addition, when comparing the pressure in the assessed zones, no significant differences between right- and left-footed children were observed ($p > .05$). The differences in the RI in these anatomical zones were significant (Table 2) and independent of the laterality of the children (Table 5).

Discussion

The aim of the present study was to characterize the effect of laterality and of the different anatomical zones of the foot on the symmetry/asymmetry of gait in children 6 and 7 years of age through the measurement of plantar pressures. The results confirm that gait is asymmetrical with respect to the anatomical zones of the foot and that it is independent of the laterality of the child. These findings should be considered in future studies as well as in clinical applications. An explanation for the confusing results of studies showing symmetry or asymmetry of gait is the specific chosen parameters for analysis. The current results show a symmetrical gait when only the average pressure throughout the foot is considered, but they show an asymmetrical gait when the pressures on different anatomical zones of the foot are considered.

On the three laterality assessment tests, nearly 80% of the children were right-footed (Table 1) on the kicking-a-ball and balance tests. According to several authors, this is the percentage of right-footed adults (Nachshon, Denno, & Aurand, 1983; Carey, Smith, Martin, Smith, Skriver, Rutland, *et al.*, 2009). Because there were significant differences in the percentage of right- and left-footed children according to the laterality test ($p < .05$), the analysis of plantar pressures was performed according to the preference of the child for each test, in case the type of test affected results. The percentage of left-footed children was lower (kick a ball 11%, static equilibrium 22% and dynamic support 33%), and this may have affected the comparisons between these two samples.

When considering the average pressure throughout the foot, there was a slight tendency toward greater pressure on the left lower limb compared to the right lower limb, but the difference was not significant. Gait symmetry studies in adults have shown conflicting results. Potdevin, *et al.* (2008) concluded that gait is asymmetric after studying the ground reaction strength for both feet. Furthermore, a study conducted by Seeley, *et al.* (2008) compared bilateral ground reaction force impulses and concluded that the impulses were generally symmetrical except at a fast speed. Sadeghi (2003) claimed that symmetrical behavior of the lower limbs should be considered a consequence of local asymmetry because it indicates differing muscle activities at each joint during gait cycles.

Gait studies in children have also yielded contradictory results. Based on a study of 15- to 62-month-old babies, Bosch and Rosenbaum (2010) concluded that the load on the foot is asymmetrical when independent gait begins but that it shows greater symmetry with increasing age. In their longitudinal study of children 14 months to 10 years of age, Bosch, *et al.* (2010) evaluated plantar pressure changes during walking (maximum pressure of the foot, maximum relative strength, and foot length) and reported no significant differences between the two feet. Lythgo, Wilson, and Galea (2009), studied healthy children between 5 and 13 years of age and young adults; spatiotemporal measures of gait indicated that gait is symmetrical. White, Agourisa, Selbie, and Kirkpatrick (1999) assessed the ground reaction strength during walking in children 6 to 10 years of age with cerebral palsy and in a control group of healthy children, and concluded that the force platform parameters in both groups showed greater asymmetry in the horizontal plane; in the control group, these parameters showed symmetry on the rest of the planes. In a recent study by Pulido-Valdeolivas, *et al.* (2013) of right-footed children between 5 and 13 years of age, 16 variables were evaluated; significant differences were found on only two variables ('minimum hip flexion' R < L and 'maximum hip abduction' L > R), whereas the variables 'peak dorsiflexion in swing' and 'mean foot progression angle' showed a tendency toward asymmetry (R > L), but the differences were not statistically significant.

Regarding gender, no difference was observed between the total plantar pressure of boys and girls 6–7 years of age (Table 3). This agrees with previous results obtained with children 6–19 years of age (Hennig, *et al.* 1994) and 14 months to 10 years of age (Bosch, *et al.*, 2010). Furthermore, Phethean and Nester (2012) found no difference between boys and girls in plantar pressure and suggest that they should be unified into one group for further studies. Following these guidelines, Yan, *et al.* (2013) assumed the absence of differences between genders in plantar pressure distribution and grouped all cases in their study of the effects of obesity on dynamic plantar pressure distribution in prepubescent children during walking. According to Seeley, *et al.* (2008), prediction of the impact of gender on functional asymmetry may not be possible. However, in our study the sample size of boys was the same as that of girls.

We compared the plantar pressure distribution per zone for the right and left limbs using three zones (the forefoot, the midfoot and the rearfoot) following the guidelines of Burns, *et al.* (2005), who used these zones to assess the effect of *pes cavus* of different etiologies on foot pain and on plantar pressure characteristics. In the current data, an asymmetrical gait was observed with significantly higher pressure on the rearfoot of the right foot and higher pressure on the forefoot and midfoot of the left foot ($p < .05$) (Table 2). Petters' hypothesis, which was proposed in 1988 and has been assumed by several authors (Sadeghi, 2003; Potdevin, *et al.*, 2008; Echeverría, *et al.*, 2010), states that if a lower limb applies a constant propulsion impulse, it is logical to consider that the other limb will constantly apply a braking impulse so as to balance the speed on two consecutive steps. Thus, the hypothesis in the current study was that the dominant extremity would generate greater propulsion while experiencing greater plantar pressure on the anterior side of the foot (metatarsals), whereas the non-dominant extremity would have a greater braking function and would experience greater plantar pressure on the posterior side of the foot (heel).

Right-footed, left-footed and ambidextrous children's data were analyzed separately based on several tests (Harris, 1955; Iteya, Gabbard, & Okada, 1995; Gabbard & Hart, 1996; Maupas *et al.,* 2002) that include the analysis of the three main laterality factors of the lower limb: precision, dynamic support, and static balance (Maupas, *et al.*, 2002). The goal was to compare the distribution of the plantar pressure with the results of each of these tests, because many people have a lower limb that dominates the balance task while the other dominates the propulsion tasks (Table 1). The gait asymmetry associated with the different anatomical zones of the foot was not related to the laterality of children on any of the tests performed (Table 3).

According to a previous study conducted by Mayolas, Villarroya and Reverter (2011), lateral lower limb preference does not significantly influence the distribution of load on the foot in static balance position. In that study, no significantly increased average plantar pressure was observed for the left limb, nor was there increased pressure on the left limb in each of the three assessed areas (forefoot, midfoot, and rearfoot). A significant difference observed for the forefoot ($p < .001$) was not related to the laterality of the children.

In sports, Wong, *et al.* (2007) measured the difference in plantar pressure between the preferred and non-preferred foot in four soccer-related movements. They concluded the overall plantar pressure of the preferred foot was higher than that of the non-preferred foot. This would suggest a tendency of the preferred foot for higher motion force and of the non-preferred foot for a greater role in body stabilisation.

In the current study, the RI of the rearfoot zone indicated more pressure on the right limb, and the RI of the forefoot and midfoot zones indicated more pressure on the left limb. This showed bilateral task differences between the limbs during gait. Potdevin, *et al.* (2008) also observed bilateral differences that suggested a division of preferred actions of propulsion and braking in 71% of the assessed participants. In Zhu, *et al.*'s (1995) study of the effect of speed of walking on plantar pressure, a situation in which propulsion is predominant, greater pressure peaks were observed on the left foot than on the right foot in all the assessed zones of the foot except the first metatarsal; all were independent of speed. This asymmetry of the plantar pressure distribution was unrelated to the laterality of the child. Others studies also found no association of asymmetries during walking with laterality. Potdevin, *et al*. (2008) also observed bilateral differences not related to laterality. Zverev (2006) observed that the step length of the right and left feet was similar, whereas the gait angle was significantly higher for the left foot, but these results were not associated with the lateral dominance of the participants. Maupas, *et al.* (1999) showed that 51.6% of the subjects tested displayed asymmetry of the total flexion-extension movement of more than 5° between the two knees during free walking; the side favored (preponderance) by this asymmetry was not related to handedness or to other lateral dominance indicators. Seeley, *et al.*, whose purpose was to compare bilateral ground reaction force impulses to evaluate functional asymmetry as an explanation for gait asymmetries, concluded that the impulses were generally symmetrical, offering little support for the functional asymmetry idea except at fast speeds, where contributions to propulsion were greater for the dominant limb. Sadeghi (2003) concluded that the gait of able-bodied people is symmetric, while recognizing control and propulsion as the two major roles of the extensors and flexors (global gait asymmetry) based on different functional tasks comparing the right and left hips, knees, and ankles to control balance, and limb coordination and propulsion functions. Furthermore, Echeverria, *et al.* (2010) concluded from a scaling analysis of gait variability in healthy participants that asymmetry reflects a natural functional difference between the limbs and that this functional difference is not the consequence of abnormality but instead relates to the contribution of each limb to propulsion and control tasks.

This analysis may partially explain the contradictory results of previous studies on gait symmetry (Sadeghi, *et al.*, 2000; Echevarría, *et al.*, 2010). The effect of gait symmetry on anatomical zones should be considered in future studies because plantar pressure distribution needs to be addressed on a therapeutic and orthopedic level due to the risks associated with increased plantar pressure on the foot (Drerup, Szczepaniak, & Wetz, 2008). Future studies should be designed to identify other factors that may condition right- and left-footed individuals to have asymmetrical gait patterns with respect to the anatomical zones of the foot.

The results supported the functional asymmetry hypothesis and the propulsion and stabilising functions of the lower limbs. However, based on the results obtained when adequately controlling for laterality, we suggest that—contrary to expectations—the gait asymmetry that is associated with the different anatomic zones of the foot is not caused by subject laterality.

In conclusion, the results showed that gait is asymmetrical independent of laterality. The results revealed no significant bilateral differences existed between sample means of average pressure, but most of the children exerting greater pressure on the right rearfoot than on the left and on the left midfoot and forefoot than on the right. Additional studies with a greater number of participants of different ages and lateralities, as well as the use of other techniques to analyze laterality and gait symmetry, are required.

REFERENCES

Andrés, C., Torres, A., Ramírez, J. I., García L. F., & Álvarez, N. (2006) Descripción de un sistema para la medición de las presiones plantares por medio del procesamiento de imágenes [Description of a measurement system of plantar pressure by imaging processing]. *Revista Escuela de Ingeniería de Antioquía*, 6, 43-55.

Andres, R. O., & Stimmel, S. K. (1990) Prosthetic alignment effects on gait symmetry: a case study. *Clinical Biomechanics*, 5, 88-96.

Auerbach, B., & Ruff, C. (2006) Limb bone bilateral asymmetry: variability and commonality among modern humans. *Journal of Human Evolution*, 50, 203-218.

Bertsch, C., Unger, H., Winkelmann W., & Rosenbaum, D. (2004) Evaluation of early walking patterns from plantar pressure distribution measurements. First year results of 42 children. *Gait & Posture*, 19(3), 235-242.

Bisaux, M., & Moreto, P. (2008) The effects of fatigue on plantar pressure distribution in walking. *Gait & Posture*, 32(4), 464-468.

Bosch, K., Gerß, J., & Rosenbaum, D. (2010) Development of healthy children's feet – nine year results of a longitudinal investigation of plantar loading patterns. *Gait & Posture*, 32(4), 564-571.

Bosch, K., & Rosenbaum, D. (2010) Gait symmetry improves in childhood—a 4-year follow-up of foot loading data. *Gait & Posture*, 28, 693-698.

Burnfield, J., Few, C., Mohamed, O., & Perry, J. (2004) The influence of walking speed and footwear on plantar pressures in older adults. *Clinical Biomechanics*, 19, 78-84.

Burns, J., Crosbie, J., Hunt, A., & Ouvrier, R. (2005) The effect of Pes Cavus on foot pain and plantar pressure. *Clinical Biomechanics*, 20(9), 877-882.

Carey, D., Smith, D., Martin, D., Smith, G., Skriver, J., Rutland, A., & Shepherd, J. (2009) Footedness as a potential factor that contributes to the causation of corn and callus formation in lower extremities of physically active individuals. *Cortex*, 45, 650–661.

Cavanagh, P. R., Ulbrecht, J. S., & Caputo, G. M. (2000) New developments in the biomechanics of the diabetic foot. *Diabetes Metabolism Research and Reviews*, 16, 6-10.

Cousins, S. D., Morrison S. C., & Drechsler W. I. (2012) The reliability of plantar pressure assessment during barefoot level walking in children aged 7-11 years. *Journal of Foot and Ankle Research*, 5, 8.

Drerup, B., Szczepaniak, A., & Wetz, H. H. (2008) Plantar pressure reduction in step-to gait: a biomechanical investigation and clinical feasibility study Original Research Article. *Clinical Biomechanics*, 23(8), 1073-1079.

Echeverria, J. C., Rodriguez, E., Velasc, O. A., & Alvarez-Ramirez, J. (2010) Limb dominance changes in walking evolution explored by asymmetric correlations in gait dynamics. *Phisica A*, 389(8), 1625-1634.

Ferré, J., & Aribau, E. (2002) *El desarrollo neurofuncional del niño y sus transtornos*. [The neurofunctional child development and disorders] (Transl.) Barcelona, Spain: Lebon.

Fielder, K. E., Stuijfzand, W. J., Harlaar, J., Dekker, J., & Beckerman, H. (2011) The effect of shoe lacing on plantar pressure distribution and in-shoe displacement of the foot in healthy participants. *Gait & Posture*, 33, 396-400.

Gabbard, C. (1997) Coming to terms with laterality. *Journal of Psychology,* 131(5), 561-564.

Gabbard, C., & Hart, S. (1996) A question of foot dominance. *Journal General Psychology*, 123(4), 289-296.

Goble, D. J., Marino, G. W., & Potvin, J. R. (2003) The influence of horizontal velocity on interlimb symmetry in normal walking. *Human Movement Science*, 22(3), 271-283.

~~Gurney, J., Kersting, U., & Rosenbaum, D. (2008) Between-day reliability of repeated plantar pressure distribution measurements in a normal population. *Gait & Posture*, 27, 706-709.~~

Harris, A. J. (1955) *Harris tests of lateral dominance. Manual of directions for administration and interpretation*. New York, NY: Psychological Corporation.

Hennig, E., Staats, A., & Rosenbaum, P. (1994) Plantar pressure distribution patterns of young school children in comparison with adults. *Foot Ankle*, 15, 35-40.

Herrera, A. (1997) *Aplicación del equipo portátil PDM 240 para el estudio de la distribución plantar durante la marcha*. [Application of PDM 240 for the study of plantar distribution during gait] (Transl.) XXXVIII Reunión Científica de la Sociedad Española de Rehabilitación y Medicina Física: Madrid.

Iteya, M., Gabbard, C., & Okada, M. (1995) Lower-limb speed and foot preference in children. *Perceptual & Motor Skills*, 81, 1115-1118.

Kellis, E. (2001) Plantar pressure distribution during barefoot standing, walking and landing in preschool boys. *Gait & Posture*, 14(2), 92-97.

Kershner, J., & Chyczij, M. (1992) Lateral preference in six to nine year old children: relationships to language lateralization and cognitive ability. *Learning and Individual Differences*, 4(4), 347-367.

López, J. E., Pérez, J. M., & Orrite, C. (1996) Redistribution orthoses for metatarsalgia treatment: design based og high resolution pedobarography. *Medical & Biological Engineering & Computing*, 34(1), 333-334.

Lythgo, N., Wilson, C., & Galea, M. (2009) Basic gait and symmetry measures for primary school-aged children and young adults whilst walking barefoot and with shoes. *Gait & Posture*, 30, 502-506.

Maupas, E., Paysant, J., Datie, A. M., Martinet, N., & André, J. M. (2002) Functional asymmetries of lower limbs. A comparison between clinical assessment of laterality, isokinetic evaluation and electrogoniometric monitoring of knees during walking. *Gait & Posture*, 16, 304-312.

Maupas, E., Paysant, J., Martinet, N., & André, J. M. (1999) Asymmetric leg activity in healthy subjects during walking, detected by electrogoniometry. *Clinical Biomechanics*, 14, 403-411.

Mayolas-Pi, C. (2011) Valoración de la lateralidad y su evolución en el periodo de dos años. [Laterality and its evolution over the period of two years]. *Human Movement*, 1,27-41.

Mayolas-Pi, C., Villarroya, A., & Reverter, J. (2011) Lateralidad de miembro inferior y su relación con la distribución de las presiones plantares en el equilibrio estático [Lower limb laterality and its relation with the distribution of plantar pressures in static balance]. *Retos. Nuevas tendencias en Educación Física, Deporte y Recreación*, 20, 5-8.

Nachshon, I., Denno, D., & Aurand, S. (1983) Lateral preferences of hand, eye and foot: relation to cerebral dominance. *International Journal of Neuroscience*, 18, 1-9.

Pérez, J. M., Herrera, A., & Orrite, C. (1997) Sistema electrónico portátil PDM 240 para el análisis estático y dinámico del apoyo plantar [PDM 240 portable electronic device for the static and dynamic analysis of the plantar support]. *Revista de Medicina y Cirugía del Pie*, 1 (XI), 55-59.

Perttunen, J. R., Anttila, E., Södergård, J., Merikanto, J., & Komi, P. V. (2004) Gait asymmetry in patients with limb length discrepancy. *Scandinavian Journal of Medicine & Science in Sports,* 14(1), 49-56.

Peters, M. (1988) Footedness: asymmetries in foot preference and skill and neuro-psychological assessment of foot movement. *Psychoogicall Bulletin,* 103(2), 179-192.

Phethean, J., & Nester, C. (2012) Results of a cross-sectional study of healthy children's feet. *Gait & Posture*, 36, 287-290.

Phethean, J., Pataky T. C., Nester C., & Findlow, A. (2014) A cross-sectional study of age-related changes in plantar pressure distribution between 4 and 7 years: a comparison of regional and pixel-level analyses. *Gait & Posture*, 39(1), 154-160.

Potdevin, F., Gillet, C., Barbier, F., Coello,Y., & Moretto, P. (2008) Propulsion and braking in the study of asymmetry in able-bodied men's gaits. *Perceptual & Motor Skills*, 107(3), 849-861.

Pulido-Valdeolivas, I., Gómez-Andrés, D., Martín-Gonzalo, J. A., López-López, J., Gómez-Barrena, E., Sánchez Hernández, J. J., & Rausell, E. (2013) Gait parameters in a reference sample of healthy Spanish schoolchildren: multivariate descriptive statistics and asymmetries observed in left and right cycles. *Neurología*, 28(3), 145-152.

Rai, D. V., Aggarwal, L. M., & Bahadur, R. (2006) Plantar pressure changes in normal and pathological foot during bipedal standing. *Indian Journal of Orthopaedics*, 40(2), 119-122.

Sadeghi, H. (2003) Local or global asymmetry in gait of people without impairments. *Gait & Posture*, 17(3), 197-204.

Sadeghi, H., Allard, P., & Duhaime, M. (1997) Functional gait asymmetry in able-bodied subjects. *Human Movement Science*, 16, 243-58.

Sadeghi, H., Allard, P., Prince, F., & Labelle, H. (2000) Symmetry and limb dominance in able-bodied gait: a review. *Gait & Posture*, 12(1), 34-45.

Seeley, M., Umberger, B., & Shapiro, R. (2008) A test of the functional asymmetry hypothesis in walking. *Gait & Posture*, 28(1), 24-28.

Seliktar, R., & Mizrahi, J. (1986) Some gait characteristics of below-knee amputees and their reflection on the ground reaction forces. *Engineering in Medicine*, 15(1), 27-34.

Shaffer, D., & Kipp, K. (2007). *Psicología del desarrollo. Infancia y adolescencia*. [Developmental psychology. Children and Adolescents] (Transl.) México: Thomson.

Stebbins, J. A., Harrington, M. E., Giacomozzi, C., Thompson, N., Zavatsky, A., & Thologis, T. H. (2005) Assessment of sub-division of plantar pressure measurement in children. *Gait & Posture*, 22(4), 372-376.

Vilarroya, A., Torre, C., Pérez-García J. M., Herrera, A., & Malillos, M. (2005) Comportamiento biomecánico de los metatarsianos durante la marcha en rampa. Distribución de las presiones plantares [Biomechanical behavior of the metatarsals during while walking uphill and downhill. Distribution of plantar pressures]. *Biomecánica*, 12(2), 88-96.

Wall, J. C., & Turnbull, G. I. (1986) Gait asymmetries in residual hemiplegia. *Archives of Physical Medicine and Rehabilitation*, 67, 550-553.

Warren, G. L., Maher, R. M., & Higbie, E. J. (2004) Temporal patterns of plantar pressures and lower-leg muscle activity during walking: effect of speed. *Gait & Posture*, 19(1), 91-100.

White, R., Agourisa, I., Selbie, R. D., & Kirkpatrick, M. (1999) The variability of force platform data in normal and cerebral palsy gait. *Clinical Biomechanics*, 14,185-192.

Wong, P., Chamari, K., Chaouachi, A., Mao, D. W., Wisloff, U., & Hong, Y. (2007) Difference in plantar pressure between the preferred and non-preferred feet in four soccer-related movements. *British Journal of Sports Medicine*, 41, 84-92.

Yan, S., Zhang, K., Tan, G., Yang, J., & Liu, Z. (2013) Effects of obesity on dynamic plantar pressure distribution in Chinese prepubescent children during walking. *Gait & Posture*, 37, 37-42.

Zhu, H., Werstch, J., Harris, G. F., Henry, M., & Alba, H. (1995) Walking cadence effect on plantar pressures. *Archives of Physical and Medical Rehabilitation*, 76, 1000-1005.

Zverev, Y. P. (2006) Spatial parameters of walking gait and footedness. *Annals of Human Biology*, 33(2), 161-176.

Zverev, Y. P., & Mipando, M. (2007) Cultural and environmental influences on footedness: cross-sectional study in urban and semi-urban Malawi. *Brain and Cognition*, 65, 177-183.

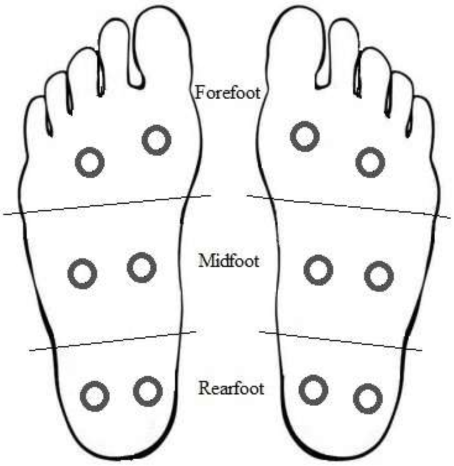

Fig. 1. The six sensors used in the pressure insoles define three anatomical zones of the foot: forefoot, midfoot and rearfoot.

TABLE 1
LATERALITY ON TESTS PERFORMED ($N = 46$) AND COMPARISONS ($N = 46$)

	Right	Left	Ambidextrous	*p*	*df*
Kick a ball	89	11	0	<.001	1
Static equilibrium	76	22	2	<.001	2
Dynamic support	59	33	8	.238	2

Note.—The values are expressed in percentages.

TABLE 2

RI OF PLANTAR PRESSURE WITHIN EACH ZONE ($N = 46$) AND COMPARISONS

Variable	*M*	*SD*	*t*	*df*	*p*	Cohen's *d*
RI PP total	0.95	0.23				
RI Forefoot	0.69	0.36				
RI Midfoot	0.62	1.16				
RI Rearfoot	1.11	0.28				
RI Forefoot vs RI Midfoot			0.41	45	.683	0.12
RI Forefoot vs RI Rearfoot			2.92	45	.005	0.87
RI Midfoot vs RI Rearfoot			6.13	45	<.001	1.83

Table 3

RI of Average Plantar Pressure Throughout the Foot and within each Zone (23 Boys and 23 Girls) and Comparisons by Gender

Variable	Boys		Girls		*t*	*df*	*p*	Cohen's *d*
	M	*SD*	*M*	*SD*				
RI PP total	0.98	0.29	0.92	0.14	0.88	44	.38	0.27
RI Forefoot	0.61	0.34	0.76	0.36	–1.47	44	.15	–0.44
RI Midfoot	0.80	1.31	0.45	0.64	1.01	44	.32	0.30
RI Rearfoot	1.21	0.32	1.02	0.19	2.38	44	.02	0.72

Table 4

Laterality (Right- and Left-Footed) and RI of Average Pressure

Test	Right-footed		Left-footed		*t*	*df*	*p*	Cohen's *d*
	M	*SD*	*M*	*SD*				
Kick-a-ball	0.94	0.23	0.92	0.19	0.74	44	.80	0.22
	n = 41		*n* = 5					
Static equilibrium	0.97	0.24	0.87	0.18	1.11	43	.74	0.34
	n = 35		*n* = 10					
Dynamic support	0.94	0.35	0.98	0.21	–0.53	40	.98	–0.17
	n = 27		*n* = 15					

Table 5

Laterality and RI of Pressure for each of the Evaluated Zones

Test and Zone	Right-footed		Left-footed		F_{45}	*p*	η^2
	M	*SD*	*M*	*SD*			
Kick a ball							
RI Forefoot	0.69	0.35	0.66	0.48	0.20	.888	0.00
RI Midfoot	0.66	1.21	0.30	0.67	0.43	.518	0.01
RI Rearfoot	1.12	0.29	1.07	0.16	0.13	.720	0.00
Static equilibrium							
RI Forefoot	0.71	0.37	0.54	0.25	2.20	.123	0.04
RI Midfoot	0.57	1.23	0.73	0.95	0.33	.725	0.00
RI Rearfoot	1.15	0.27	1.05	0.29	1.60	.214	0.02
Dynamic support							
RI Forefoot	0.66	0.40	0.67	0.29	1.04	.363	0.00
RI Midfoot	0.79	1.44	0.37	0.51	0.72	.491	0.03
RI Rearfoot	1.11	0.24	1.20	0.32	3.28	.047	0.03

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<<enote>>AQ1: References “Zang, 2013” and “Cousins, *et al.,* 2010” are not given in the reference list. Please provide the details for the same or delete it from the text.

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