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Impact of foot progression angle on the distribution of plantar pressure in normal children

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ABSTRACT

Background: Plantar pressure distribution during walking is affected by several gait factors, most especially the foot progression angle which has been studied in children with neuromuscular diseases. However, this relationship in normal children has only been reported in limited studies. The purpose of this study is to clarify the correlation between foot progression angle and plantar pressure distribution in normal children, as well as the impacts of age and sex on this correlation.
Methods: This study retrospectively reviewed dynamic pedobarographic data that were included in the gait laboratory database of our institution. In total, 77 normally developed children aged 5–16 years who were treated between 2004 and 2009 were included. Each child's footprint was divided into 5 segments: lateral forefoot, medial forefoot, lateral midfoot, medial midfoot, and heel. The percentages of impulse exerted at the medial foot, forefoot, midfoot, and heel were calculated.
Findings: The average foot progression angle was 5.03° toe-out. Most of the total impulse was exerted on the forefoot (52.0%). Toe-out gait was positively correlated with high medial ($r = 0.274$; $P < 0.001$) and forefoot impulses ($r = 0.158$; $P = 0.012$) but negatively correlated with midfoot impulse ($r = -0.273$; $P < 0.001$). The moderating effects of age and sex on these correlations were insignificant.
Interpretation: Foot progression angle demonstrates significant impact on the distribution of foot pressure, regardless of age or sex. Foot progression angle should be taken into consideration when conducting pedobarographic examinations and balancing plantar pressure as part of the treatment of various foot pathologies.

1. Introduction

Toe-out and toe-in gait abnormalities are among the most common reasons for visiting pediatric orthopedic clinics (Fabry et al., 1994; Ho et al., 2000). In addition to anatomic deformities of the foot, rotation profiles affecting the lower extremities, such as hip rotation and tibia torsion, also greatly impact the appearance of a child's gait (Fabry et al., 1994). The foot progression angle (FPA), which is measured from the longitudinal axis of the foot to the forward line of progression, is the summation of the rotation profiles and describes the shape of the foot. FPA tends to internally rotate in younger children, but the majority of these children will spontaneously shift to a neutral position or external rotation by the age of 8 years as femoral anteversion regresses (Ho et al., 2000).

Pedobarography, which provides detailed dynamic information specific to each segment of the foot, is essential for the evaluation of patients with foot complaints and rotational anomalies (Craxford et al., 1984; Rosenbaum and Becker, 1997). Plantar pressure distribution is affected by several factors, including the anatomical structure of the foot, body mass, sex, walking velocity, and joint range of motion (Bennett and Duplock, 1993). Studies focusing on relationship between FPA and foot pressure are rare. Craxford reported no significant correlation between limb rotation and foot pressure distribution in normal children (Craxford et al., 1984). On the other hand, FPA impacts ankle joint moment in the coronal plane during the late stance phase (Ho et al., 2000). The peak external ankle eversion moment increases with the severity of toe-out gait, which theoretically exerts additional force on the medial foot. A positive correlation between FPA and medial foot loading, which means that toe-out gait introduces additional force onto the medial foot, was demonstrated in children with neuromuscular diseases and adults with diabetic neuropathy-related foot ulcers (Chang et al.,

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2004; Hastings et al., 2010). Chang et al. also revealed that internal derotation osteotomy of tibia significantly reduces medial foot pressure in a 5.4-year-old girl with cerebral palsy and planovalgus foot (Chang et al., 2004). These reports convinced us that, in children without neuromuscular diseases, FPA will impact the distribution of plantar pressure and should be considered in treating foot pathologies associated with uneven plantar pressure. The null hypothesis of this study is that FPA does not impact the distribution of plantar pressure in normal children.

2. Methods

2.1. Participants

Approval for this study was obtained from our institutional review board. A retrospective review of the dynamic pedobarographic data included in our institution's database (Footscan® 3D pressure system, RSscan International, Brussels, Belgium) was conducted. Between 2004 and 2009, 77 normally developed children received pedobarographic examinations at our hospital in order to collect data and establish this database for comparison with children with pathological gait. All children received physical examinations to exclude neuromuscular diseases, congenital or acquired malalignment of the lower extremities, lower extremity pain that had presented within the 3 months, or any other disability that would affect gait (e.g., visual or hearing impairments, problems of the spine or lower extremities, any condition that necessitated the use of walking aids). In total, 32 girls and 45 boys were examined. The average age at the time of gait analysis was 9.7 years, ranging from 5 to 16 years. To exclude planovalgus or cavovarus foot, the Chippaux–Smirak Index (CSI) was used to assess footprints obtained using the Footscan® 3D pressure system (RSscan International, Brussels, Belgium). CSI was 0.178–0.434 for all children, within the normal range suggested by Forriol and Pascual (1990).

2.2. Plantar pressure measurement and analysis

All children were evaluated using the same protocol. Each child's weight, height, as well as width and length of each foot were recorded. Plantar pressure was measured using the Footscan® 3D pressure system (RSscan International, Brussels, Belgium) at a sampling rate of 500 Hz. The floor mat measured 40×50 cm^2 and was the same color as the floor the child had to walk on in order to avoid targeting effects. Before each measurement, the pressure-sensitive mat was calibrated to the child's weight (Bowen et al., 1998). Each child started walking approximately 2 m before stepping onto the floor mat at a self-selected speed. Each child was instructed to look straight ahead, not at the floor, as they were walking. To reduce the estimate of error, three sets of dynamic pedobarograms were collected for each foot in the same day (Holmes et al., 1991). The collected data was processed using custom-written software. The contact time of each foot was determined using a force-time plot. Data indicating significant foot strikes were identified and cropped to a rectangle according to the measured length and width of the child's foot. The footprint was rotated using a two-dimensional rotation matrix such that the center of the heel was vertically aligned with the space between the second and the third metatarsal heads (longitudinal foot axis) (Chang et al., 2004). FPA was defined as the resulting angle of rotation. A medially rotated footprint demonstrated positive FPA (toe-out) and a laterally rotated footprint demonstrated negative FPA (toe-in). The data area was cropped to a rectangle according to the measured length and width of the child's foot. The rectangle was partitioned into medial and lateral halves by the longitudinal foot axis and into equal thirds along the longitudinal axis to indicate the forefoot, midfoot, and heel sections. The medial and lateral heel sections were treated as a single section, thus the following 5 segments for the entire foot were determined: heel, medial midfoot (MM), medial forefoot (MF), lateral midfoot (LM), and lateral forefoot (LF) (Fig. 1).

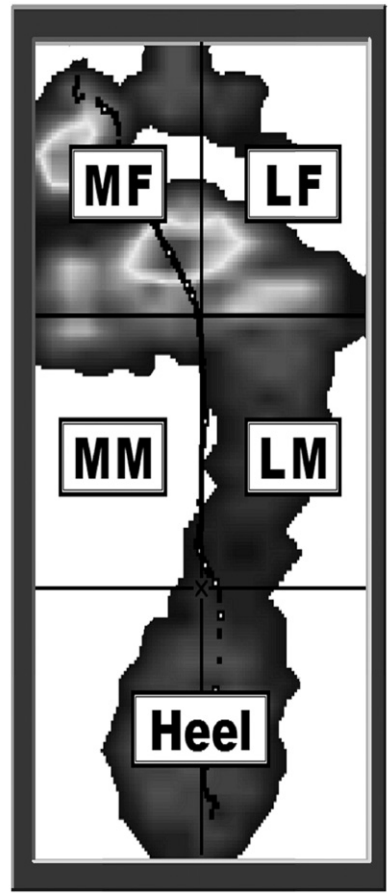

Fig. 1. Five-segment foot model. MM: medial midfoot; MF: medial forefoot; LM: lateral midfoot; LF: lateral forefoot.

Pressure impulse was calculated from cumulative pressure measurements taken during the stance phase, specifically the area under the curve of the pressure-time plot. Pressure impulse was divided by the total impulse of the whole foot and multiplied by 100 to determine the percent pressure impulse. The pressure impulse of a foot segment is the summation of each sensor's pressure impulse in that segment (Chang et al., 2002). The percent medial impulse (PMI)—the impulse percentage exerted on the medial aspects of the fore- and mid-foot—was calculated as $[(MM + MF) / (MM + MF + LM + LF)] \times 100\%$. In this model, PMI represents the relative loading on the medial column of the foot compared with the lateral column. This comparison of pressure in the coronal plane is highly correlated with clinical assessment and provides better information for differentiating clinical outcomes than radiography (Chang et al., 2002; Chang et al., 2004). Comparison of plantar pressure in the sagittal plane was similarly performed. The percent forefoot impulse (PFFI) was calculated as $[(LF + MF) / (MM + MF + LM + LF + H)] \times 100\%$, percent midfoot impulse (PMFI) as $[(LM + MM) / (MM + MF + LM + LF + H)] \times 100\%$, and percent heel impulse (PHI) as $100 - [PFFI - PMFI]$.

2.3. Statistical analysis

The statistical analysis of this study consisted of three parts: 1) the Pearson or point-biserial correlation coefficient was used to evaluate the associations between FPA and age and sex, as well as the relationship between FPA and plantar pressure distribution (PMI, PFFI, PMFI, and PHI) (Table 1.); 2) the moderating effects of age and sex on the relationship between FPA and plantar pressure distribution were