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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

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ABSTRACT

Quantifying morphological and functional development in children's feet, and thereby establishing development norms is difficult. In addition to practical challenges of experimentation on children, measurement equipment like plantar pressure (PP) platforms are almost exclusively geared towards adult-sized feet. These PP quantification problems may be exacerbated by typical regional data analysis techniques, which further reduce spatial resolution. The goal of this study was to quantify PP distributions in developing children, and also to compare the results obtained from typical (regional) techniques with those obtained from a higher-resolution (pixel-level) technique. Ninety-eight children between four and seven years of age were assessed in a cross-sectional design. Maximum PP distributions were collected for each child, and these pressures were linearly regressed against age. Present results agree with previous investigations in that maximum pressures and maximum pressure changes occurred in the forefoot. However, results from the present pixel-level technique suggest that these changes are limited to the central metatarsals, and that regional methods can suggest significance where none exists in the actual raw (pixel-level) data, due to signal aliasing and, in particular, to conflation of regional boundaries. We postulate that increased central metatarsal pressures are reflective of the coupling between generalised joint laxity decreases and relatively increasingly inclined central metatarsal bones with age.

1. Introduction

Plantar pressure (PP) distributions can be used to characterise foot function and have been shown to change during normal development towards adulthood. For example, several studies report that maximum PP (PP_{max}) increases under the total foot, the hindfoot and the forefoot between the commencement of independent walking and 13 years of age, but not under the midfoot [1–5]. Age-specific foot loading patterns for toddlers demonstrate the highest PP_{max} under the hallux; whereas in 7 year olds the highest PP_{max} is under the hindfoot [2,5]. These clearly identified foot loading patterns are considered to be part of the normal developmental stages of the growing foot [1,4,6].

Whilst there are child-specific variations in the precise timing of growth milestones, the period between four and seven years of age demonstrates considerable neuromuscular and skeletal change [7–9], including changes in foot structure, morphology and function [3,5,10,11]. This period spans the transition from immature to mature gait [12] and changes in bone length and structural composition occur alongside rotational changes in the transverse and frontal planes [7,8,10,11,13]. Changes in gait are seen in the temporal-spatial parameters, and in kinematics, electromyography and kinetics related to ankle joint motion [12,14,15]. Consequently, the changes occurring in this four to seven year old period suggest potential differences in the foot loading patterns within this period.

There are two potential problems with work to-date that both stem from potentially inadequate spatial (anatomical) resolution. This first is that the midfoot and forefoot were previously reported as whole regions of interest (ROI) [3,5], rather than with mediolateral subdivisions. This is a potential problem because we know that the adult foot demonstrates differences in the mobility of the medial and lateral midfoot and forefoot [16]. Thus smaller ROIs, and their more finely detailed anatomical information, may allow us to draw more definitive conclusions regarding

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the relation between PP and the maturation of the foot's multiple structures and articulations.

The second potential problem is that previously employed ROIs may have impinged upon neighbouring anatomical structures. For example, midfoot ROI definitions typically extend posteriorly towards the anterior heel and anteriorly towards the posterior forefoot. The problem is that there is typically a large pressure increase from the midfoot to both the anterior heel and the posterior forefoot. Therefore if midfoot ROIs are not carefully defined then midfoot results could be driven by the heel or forefoot, or both. Indeed, this phenomenon has been shown to have the potential to create, eradicate, and even reverse statistical and biomechanical conclusions [17].

We presently refer to the aforementioned problems as ''intra-region variation'' and ''inter-region conflation'', respectively. The cause of both is inadequate spatial resolution in ROI data. Healthy and pathological adult PP data have spatial wavelengths on the order of 30 mm [18] and 20 mm [19], respectively. Plantar pressures must therefore be measured with (Nyquist) resolutions of at least 15 mm and 10 mm, respectively, to avoid signal aliasing. Although original pixel-level data typically have adequate resolutions, on the order of 5 mm, ROI-level data typically have resolutions on the order of 50 mm, which are too gross. Problems associated with inadequate spatial resolution have been addressed elsewhere for adult feet [18,19], but spatial resolution has not, to our knowledge, been previously explored for children's data.

The purpose of this study was to investigate the effect of spatial resolution on the conclusions regarding PP development amongst children aged four to seven years of age. To this end we presently compare the results of hypothesis testing on pixel-level data vs. ROI-level data. The present null hypothesis was that age has no effect on PP distribution.

2. Methods

2.1. Participants

Subsequent to approval from the ethics committee at the University of Salford 46 girls and 52 boys aged between four and seven years old were recruited from nurseries, schools, university staff and students, and by word of mouth. Although not analysed categorically, mean ($\pm$st.dev.) ages for four-, five-, six- and seven-year olds were: 48.5 ± 1.1, 60.7 ± 1.0, 72.2 ± 0.8 and 84.4 ± 1.0 months, respectively. Parents and guardians gave informed consent in all cases. Since we previously found that gender failed to predict PP differences amongst children [20] genders were presently pooled.

Children met four criteria to be included: (1) normal gestational period of 37–42 weeks; (2) correct development of locomotion skills; (3) within 0.4th–99.6th centile for height and weight in relation to their chronological age; and (4) no gross gait abnormalities during visual inspection e.g. tiptoe walking, limping, tripping, excessive in/out-toed gait. Normal attainment of locomotion included walking prior to 17 months of age and appropriate age-related development of locomotion skills assessed by movement and balance, and stair tasks in accordance with the 'schedule of growing skills' [21]. Stature and weight reference curves [22] were used to determine height and weight centiles.

2.2. Procedure

PP data were collected within 60 days of each child's birthday, barefoot in mid-gait at natural walking speed [23] using an optical pedobarograph system (Biokinetics Inc., Bethesda, USA; now defunct). The pressure plate surface dimensions, resolution, and sampling frequency were: 57 cm $\times$ 48.5 cm, 3 mm $\times$ 2 mm, and 25 Hz, respectively. A familiarisation period minimised targeting of the plate and determined a start position that ensured five to six steps were taken prior to plate contact. Trials were excluded if the foot failed to contact close to the plate centre, and also if gait was observed to be irregular (e.g. targeting, excessive acceleration/deceleration, irregular cadence/stride length). Five trials were collected from each foot.

2.3. Region of interest (ROI) analysis

Nine anatomical ROIs were manually defined on each PP_{max} image: Heel, MedMF and LatMF (medial and lateral midfoot), Hallux, and MH1-5 (the five metatarsal heads). Constant-sized ellipsoids were used: 3.38 cm^2 (Heel), 2.16 cm^2 (MedMF and LatMF), 1.69 cm^2 (Hallux and MH1), and 1.09 cm^2 (MH2–MH5). The first set of ROI analyses (''Method A'') merged: (1) the MF region and (2) the MH region (Fig. 1a) to mimic previous developmental studies that did not sub-divide the midfoot or metatarsal regions [3,5]. The second set of analyses (''Method B'') assessed the nine ROIs separately (Fig. 1b). Although there was little or no foot contact in the medial midfoot region in some subjects, we employed a medial midfoot ROI to follow convention [24].

Maximum pressure values were extracted from each ROI, were averaged within-subjects, and were then linearly regressed against age. The threshold for significance was set at $\alpha = 0.05$, and Bonferroni corrections of 0.013 and 0.00568 were used to correct for multiple comparisons across the four and nine ROIs, respectively. The left and right feet were analysed separately for cross-validation.

2.4. Whole-foot (pixel-level) analysis

PP_{max} distributions for each step were first registered (i.e. spatially aligned) within-subjects and within-feet using a rapid frequency-based technique [25]. The resulting average distributions (one per-subject, per foot) were registered between-subjects using an optimal linear (scaling) transform. The chronologically first seven-year-old's feet were used as the registration templates, and then, to avoid potential bias from template peculiarities, all images were re-registered to the resulting between-subject mean. A linear transformation was utilised to retain subjects' original morphology.

At this point all images were registered to a common coordinate system, with a total of 196 mean images (one per subject, per foot). Identical to the regional data above, these images were regressed (in a pixel-wise manner) against age, yielding two linear correlation coefficient (r) distributions, one for each foot. The r distributions were then transformed into t distributions via the identity:

$$t = r\,(n-2)^{0.5}\,(1-r^2)^{-0.5} \quad (1)$$

where n is the number of subjects and t has the Student's t distribution with degrees of freedom: ($n - 2$). Since t is presently both parametric and pixel-specific it is referred to as a 'statistical parametric map' (SPM) [26]. Statistical significance was determined topologically as the probability that a purely random (Gaussian) spatial process, with identical smoothness, will produce suprathreshold pixel-clusters of the observed size [26]; presently a threshold of $|t| > 2$ was selected because this is the lowest threshold that has been shown to be valid for PP data [27]. Smoothness was estimated from the regression residuals using the average spatial gradient [26].