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Ontogenetic changes in foot strike pattern and calcaneal loading during walking in young children

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ABSTRACT

The assumption that the morphology of the human calcaneus reflects high and cyclical impact forces at heel strike during adult human walking has never been experimentally tested. Since a walking step with a heel strike is an emergent behavior in children, an ontogenetic study provides a natural experiment to begin testing the relationship between the mechanics of heel strike and calcaneal anatomy. This study examined the ground reaction forces (GRFs) of stepping in children to determine the location of the center of pressure (COP) relative to the calcaneus and the orientation and magnitude of ground reaction forces during foot contact. Three-dimensional kinematic and kinetic data were analyzed for 18 children ranging in age from 11.5 to 43.1 months. Early steppers used a flat foot contact (FFC) and experienced relatively high vertical and resultant GRFs with COP often anterior to the calcaneus. More experienced walkers used an initial heel contact (IHC) in which GRFs were significantly lower but the center of pressure remained under the heel a greater proportion of time. Thus, during FFC the foot experienced higher loading, but the heel itself was relatively wider and the load was distributed more evenly. In IHC walkers load was concentrated on the anterior calcaneus and a narrower heel, suggesting a need for increased calcaneal robusticity during development to mitigate injury. These results provide new insight into foot loading outside of typical mature contact patterns, inform structure-function relationships during development, and illuminate potential causes of heel injury in young walkers.

1. Introduction

It is assumed that the robust calcaneus of adult humans is adapted to withstand high, cyclical impact forces during walking and that these forces have shaped its morphology both during our evolution and during ontogeny [1]. For example, the robust calcaneal tuber with a prominent lateral plantar process is thought to provide a wide base of support over which ground reaction forces (GRFs) can be dissipated during adult heel strike [1]. Heel contact patterns develop gradually throughout bipedal development [2–9] but the lateral plantar process appears early in development, as the lateral plantar cornu [1], suggesting either that heel contact forces are the same throughout ontogeny or that the lateral plantar process develops in the absence of routine loading. Additionally, young children, some at the earliest stages of walking, experience calcaneal fractures and damage to the apophyseal plate [10–12], suggesting that high loading may occur in the absence of a well-defined heel strike. Yet little is known about changes in calcaneal loading throughout development, leaving functional features and clinical aspects of development unexplored. Such data are needed to address questions regarding the functional anatomy of the human calcaneus.

In adult walking, the heel makes initial contact with the ground at the end of swing phase and the foot and leg experience an impact transient [13–16]. Simultaneous vertical (Fz) and horizontal (fore-aft; Fy) forces result in an upward and backward (posteriorly) oriented braking GRF resultant (GRFr). The center of pressure (COP), which serves analytically as the anchor point of the GRFr, lies beneath the heel during heel strike in adults [17–20]. As such, the adult heel pad and underlying calcaneus experience, and must mitigate, relatively high magnitude GRFs that project through the hind foot at heel strike.

Hallemans et al. [4,5,21] showed that at the earliest stages of locomotor development, young children exhibit flat foot contact (FFC), in which the heel, midfoot, and metatarsals simultaneously experience peak pressure at touchdown. At later stages of development, children use an initial heel contact (IHC), during which peak pressure is roughly under the heel at touchdown [4,5,21]. However, little is known about

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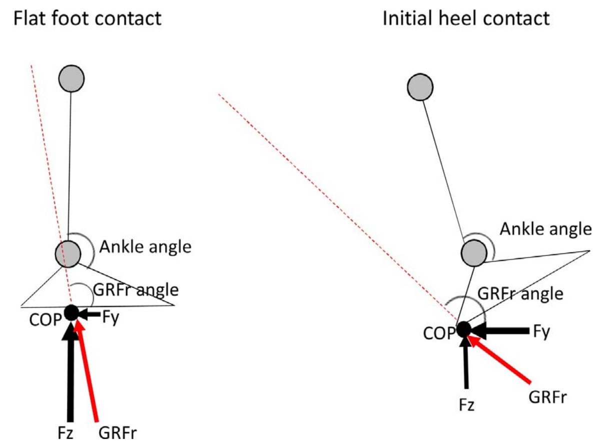

Fig. 1. Models of flat foot contact and initial heel contact. In the flat foot contact (FFC) model, the ankle angle is relatively large and the foot is placed beneath the body at touchdown. The center of pressure (COP) is beneath the ankle and the horizontal (braking) ground reaction force (Fy) is small compared to the vertical ground reaction force (Fz). In the initial heel contact (IHC) model, the ankle angle is relatively small (dorsiflexed) and the foot is placed anterior to the whole body center of mass at touchdown. The COP is beneath the heel and the braking force (Fy) is large compared to the vertical force (Fz). Red arrows represent the magnitude and angle of the resultant ground reaction force (GRFr) and dotted red lines are projections of the GRFr. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the peak forces and impact transients experienced during these early stages of walking and how they may affect calcaneal morphology. In this study, we investigate how initial heel contact configuration (FFC and IHC) influences the position of the COP and the magnitude and orientation of the GRFr at touchdown, at the time of vertical impact peak, and at the time of braking peak.

Infant stepping is characterized by high degrees of hip and knee flexion [3] resulting in a hip lift and foot drop with each step. We hypothesized that this vertical landing path, along with minimal ankle dorsiflexion, leads to an FFC that positions the COP close to the vertical projection of the whole body center of mass at touchdown. Thus, in FFC steps, we predicted that this vertical transfer of a large proportion of total body weight results in a relatively high vertical ground reaction force (Fz) but relatively low horizontal (braking) GRF (Fy) (i.e., the ratio of Fy/Fz is small) (Fig. 1). Further, as the sagittal orientation of the GRFr (GRFr angle) is a function of the magnitude of the Fy and Fz, we predicted that the GRFr would project only slightly posterior in FFC steps. Early walkers (with less than 6 months walking experience) might also be expected to have relatively higher mediolateral (Fx) GRFs because of wide steps [22] and abducted hips [23]. Therefore, we calculated Fx forces, but Fy and Fz forces were the focus of our study, as they are most relevant to distinguishing between FFC and IHC foot strike patterns.

In contrast, to achieve initial heel contact (IHC), we hypothesized that a long stride allows the leg to swing through a large arc and, coupled with an adducted hip [23] and a dorsiflexed ankle, positions the heel as the point of contact at touchdown. In this model, the heel contacts the ground relatively far in front of the whole body center of mass, compared to FFC steps, and the COP is under the heel at touchdown (Fig. 1). With this more forward position of the COP relative to the body, a relatively lower proportion of total body weight is immediately transferred to the stance foot. As such, we predicted that for IHC walkers, 1) mediolateral (Fx) and vertical GRF (Fz) would be relatively low compared to FFC steps and 2) horizontal (Fy, braking) GRF would be relatively high (i.e., the ratio of Fy/Fz is large). If Fy/Fz differs between foot strike patterns, then the angle of the GRFr must also differ, with a more posteriorly directed GRFr predicted for IHC compared to FFC steps. Since a wide base of the calcaneal tuber is thought to be an adaptation to heel strike in adults, we predicted that, compared to children who use FFC, children who use IHC would have a relatively wide heel (i.e., the ratio of heel length to heel width would be small).

Table 1
Child walking data.

Subject	age (months)	months walking	body mass (kg)	hip height (cm)	heel length: foot length	heel length: heel width	steps
IHC							
8	16.8	5.6	7.3	32.8	0.34	0.75	3
12	30.2	17.2	11.4	38.7	0.31	0.80	5
9	33.8	20.3	13.9	38.5	0.31	0.94	5
7	36.4	25.9	14.5	42.8	0.38	1.10	2
1	38.7	24.2	14.5	45.5	0.31	0.86	2
2	40.2	28.2	13.6	44.5	0.25	0.93	2
6	43.1	35.1	14.1	42.6	0.34	1.00	5
Mean	**34.2**	**22.3**	**12.8**	**40.8**	**0.32**	**0.92**	
SD	**8.7**	**9.4**	**2.6**	**4.41**	**0.04**	**0.12**	
TOTAL							**24**
FFC							
18	11.5	3.0	10.2	29.7	0.33	0.94	2
3	11.7	0.5	10.0	31.5	0.31	0.84	2
13	12.3	1.6	9.8	32.1	0.32	0.80	5
15	12.7	1.7	10.9	30.6	0.30	0.76	2
14	15.3	0.8	9.9	32.3	0.33	0.91	5
17	15.8	3.0	11.4	31.9	0.31	0.72	2
19	16.3	0.3	11.0	31.7	0.33	0.99	5
10	16.9	4.9	11.1	31.5	0.25	0.65	5
11	18.0	5.0	10.2	34.9	0.30	0.76	3
4	21.5	7.5	11.9	39	0.25	0.86	4
5	26.4	12.4	11.4	39.6	0.28	0.81	4
Mean	**16.2**	**3.7**	**10.7**	**33.2**	**0.30**	**0.82**	
SD	**4.6**	**3.7**	**0.07**	**3.29**	**0.03**	**0.10**	
TOTAL							**39**

IHC = initial heel contact. FFC = flat foot contact. SD = standard deviation.

2. Materials and methods

Subject participation was approved by the Institutional Review Board, University of Texas at Austin, and informed consent was obtained from each participant's parent or legal guardian before participation. Cross-sectional data were collected on eighteen subjects (Table 1) at the Developmental Motor Control Laboratory in the Department of Kinesiology and Health Education at the University of Texas at Austin. Kinematic data were collected at 120 Hz via a 10 camera Vicon MX (Vicon, Centennial, CO) motion analysis system, synchronized with Bertec (Bertec, Columbus, OH) force plates. Reflective markers (6 mm) were placed on one foot following a modified foot marker set of Stebbins and colleagues [24], specifically validated for measuring foot biomechanics in children. Lower limb length was measured as the distance from the hip to the ground when standing and body weight was measured with a standing spring balance.

Barefoot subjects walked, unassisted, at a self-selected speed over two adjacent force plates that recorded GRFs at 1200 Hz. Trials in which only one foot was on the plate were reconstructed in Vicon Nexus 1.8.2. Raw kinematic and kinetic data were filtered using a fourth order zero-lag phase Butterworth low pass filter with a cut-off frequency of 12 Hz (kinematic) or 100 Hz (kinetic), as determined following methods of Winter [25].

Kinetic data were presented as the magnitude of the GRF vector in three dimensions (Fz = vertical, Fy = fore-aft, and Fx = mediolateral) and the location of the COP (COPx, COPy). Vertical, horizontal, and mediolateral ground reaction forces (N) were normalized to body weight (e.g., Fy/BW) and used to calculate the magnitude and direction of the GRFr. The GRFr angle was made a continuous variable (0°–180°) by calculating the angle between the ground and the GRFr in the