

# Pressure Distribution Patterns Under the Feet of New Walkers: The First Two Months of Independent Walking

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## ABSTRACT

**In order to describe foot function during the first weeks of independent walking, spatio-temporal pressure distribution patterns were measured. These data give detailed information about roll-off of the foot, by determining the course of the center of pressure, and about load bearing, by calculating relative vertical impulses under the feet. During those first weeks of independent walking, roll-off is very unstable. Although infants can occasionally perform a mature roll-off, a consistent pattern has not yet developed and there is instability. To improve stability the entire plantar surface area contributes to load bearing – first, because a larger contact area will improve stability, and second, because a forward shifting of the load allows more muscular control to compensate for minor imbalances under the foot.**

**Key Words: Toddler; Pedobarography; Foot Function**

## INTRODUCTION

In adults, the initial heel strike is followed by foot flat and then by roll-off, generating push-off forces under the hallux (first metatarsal head and first toe). Mature walking is characterized by a stereotypic pressure distribution pattern (Fig. 1). The adult spatio-temporal plantar pressure pattern results in a specific course of the center of pressure (COP) characteristic for adult

gait. At first contact, the COP is found medially under the heel. During roll-off it moves laterally and to the front and when the forefoot is reached it quickly shifts medially again.<sup>1,2,13,16</sup>

Peak pressures and relative vertical impulses under infant feet have been described.<sup>9</sup> Otherwise, little is known about pressure distribution and loading patterns of the feet in young children during walking. Pedobarographic data for new walkers (first few weeks of independent walking) are almost nonexistent. Former studies on this age group focused primarily on neuromaturation<sup>8,12,18</sup> or used the dynamic systems approach to describe changes in spatio-temporal parameters or interlimb coordination.<sup>3–5,18,19</sup>

We measured spatio-temporal plantar pressure distribution patterns in order to describe the path of the COP, to determine changes in relative loading of the different foot regions, and to calculate relative vertical impulses. A comparison with mature foot function in adult gait was made. The aim of the present study is to add to the understanding of the ontogenetic development of human walking through the study of foot function during the first weeks of independent walking.

## MATERIALS AND METHODS

Seven able-bodied study subjects were included in this study. Their walking experience ranged from the early beginning of independent walking until approximately 2 months of experience in walking. We were able to follow one child from the first week of independent walking until 6 weeks. Detailed information about the study subjects is shown in Table 1. For comparison, data on adult gait were also collected (5 individuals, 13 footprints, data collection at the University of Ghent).

Two essentially identical setups were used. Each setup consisted of a walkway of which 2 m × 0.5 m was instrumented. We used a footscan platform (RS Scan International, 250 Hz, 3.5 sensors/cm<sup>2</sup>), functionally

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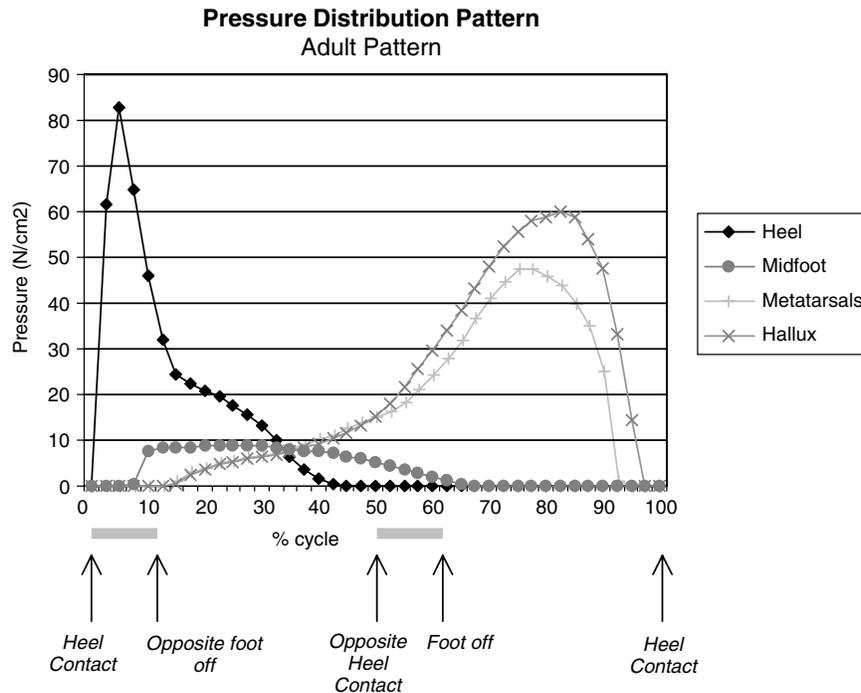


Fig. 1: The adult pressure distribution pattern reflects the roll-off of the foot. Arrows indicate important phases in the gait cycle; the double support phase is highlighted in gray.

**Table 1: Study subjects**

Child	Age (weeks)	# Footfalls	Remarks
1	0	12	Data collection at HILO (Ghent)
2	0	15	Data collection at Plankendael
	2	17	
	4	11	
	6	10	
3	2	15	
4	3	8	Data collection at HILO (Ghent)
5	8	14	Data collection at Plankendael
6	8	18	Data collection at Plankendael
7	0	24	Data collection at HILO (Ghent)

coupled to an AMTI force plate through a 3D box. The AMTI forces served to calibrate the pressures, thereby improving accuracy. The RS Scan software (6.2 and 6.3 for Macintosh) controlled the entire setup. One instrumented area was made up of 3 serial measuring

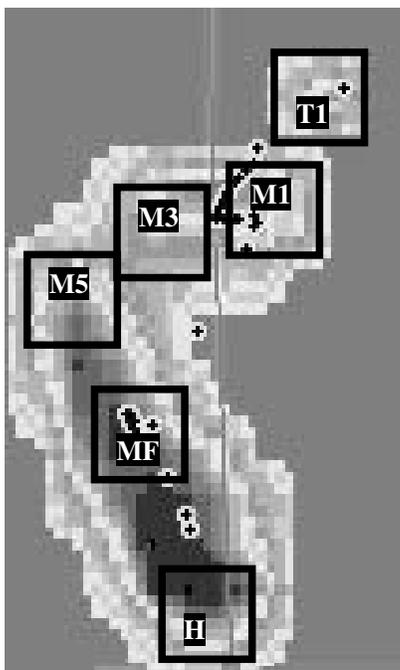
units,<sup>6</sup> and at the other a 2-m-long footscan platform was used. For reasons of uniformity the children were asked to walk barefoot.

Due to the small weight of the children, we were not able to record pressures under areas that bear little load with respect to the rest of the foot. However, this made little difference in our analysis of the course of the COP, peak pressures, and relative vertical impulses.

For analysis, the RS Scan software was used (6.3.3 for Macintosh). Footfalls were selected for analysis if the entire foot was placed on the same measuring unit. For each separate footfall a footprint and the course of the COP was retrieved from the footscan software. A footprint was defined as the image created by superimposing maximal pressures under the foot, measured by each sensor during contact time. On these images the course of the COP was visualized and qualitatively described. The COP path gave information about stability under the foot and roll-off. Maturity of roll-off was quantified by calculating two parameters,  $R_x$  (= square root  $(\sum \Delta x^2)/L$ ) and  $R_y$  (= square root  $(\sum \Delta y^2)/L$ ). Both values are a measure of the COP's deviations from the line of progression (a straight line, with length  $L$ , passing from the first point of contact under the heel to the last point of contact under the hallux region). On each footprint an orthogonal reference frame was defined with the  $y$ -axis along this line of progression and the  $x$ -axis perpendicular to it.  $R_x$  and

$R_y$  were calculated from the  $(x, y)$  coordinates of the COP. If the COP would pass exactly along the line of progression  $R_x$  would have a value of zero and  $R_y$  a value of one.

For temporal analysis of roll-off patterns and loading of the foot, the plantar surface was divided into six functional areas (Fig. 2): heel (H), midfoot (MF), lateral (M5), central (M3) and medial (M1) metatarsi, and first toe (T1). Absolute peak pressures under these areas were determined. To assess the roll-off pattern of the foot, changes in pressure under the respective foot areas during contact were evaluated. In these graphs pressures under first metatarsal head and first toe were averaged, since both areas are important for push-off. This region will be referred to as the hallux. Also pressures under the metatarsal heads were averaged. Functional loading of the foot was determined by calculating relative vertical impulses (RVIs) under each of the six functional areas. Relative impulses have the advantage to be independent of body weight and plantar surface area of the foot, allowing comparison between individuals and between infants and adults. The RVI under a certain area  $X$  equals  $I_x/\sum I_x$  with  $I = \int P_i(t) \cdot A_i(t) \cdot dt$  and  $x$  being one of the six functional areas under the foot (H, MF, M5, M3, M1, and T1). The RVIs were calculated during an entire foot contact to give detailed information about load distribution under the foot. We were also interested in load distribution



**Fig. 2:** For analysis of peak pressures and RVI, the foot is divided into six functional areas: heel (H), midfoot (MF), lateral (M5), central (M3) and medial metatarsi (M1), and first toe (T1).

between the two feet during the double support phase. Also for this purpose RVIs were used, in which case impulses under the six areas of the two feet were taken into account.

## RESULTS

### Center of Pressure Under the Feet

Overall instability was large in the new walker, reflected by the wobbling pattern of the COP under the feet. In most of the footprints the COP was located under the heel at initial contact. Plantar contact (COP under midfoot) and toe walking (COP under metatarsal heads) also occurred (Fig. 3). Toe walking was seen in 53% of foot strikes during the first week of independent walking, but with increasing walking experience initial heel strike became more important. After 2 weeks of independent walking, 70% of the foot strikes showed a COP under the heel at initial contact. Roll-off was dependent upon which area contacted with the ground first. In case of heel contact the COP moved forward by passing over the medial side of the foot. With increasing walking experience, the COP showed a tendency to shift laterally, moving over the middle of the midfoot region and when the forefoot was reached, shifting medially again towards the hallux. In case of toe walking, the roll-off pattern was more variable. Occasionally, the COP moved under the metatarsal heads, sometimes moved backward over the midfoot, followed by a roll-off pattern similar to that seen after initial heel strike.

In mature walking,  $R_y$  had a consistent value very close to one.  $R_x$  had an average value of 0.1 because of the medio-lateral shift of the COP. The average  $R_x$  value in infant walking was equally small as in adults but showed a greater amount of variation. It changed little with increasing walking experience. The average  $R_y$  value was larger than 1. There was a small but nonsignificant decrease in  $R_y$  with increasing walking experience. Variation in  $R_y$  was even larger than variation in  $R_x$ . Even at the onset of independent walking,  $R_y$  values of 1 were seen. However, they occurred together with extremely large  $R_y$  values of 4. (Results are presented in Figure 4.)

### Peak Pressures

On average, infant peak pressure values had a magnitude of 25–50% of adult peak pressures,<sup>9,10</sup> except for the midfoot, where pressures under the feet of new walkers rose above adult values (Fig. 5a). With increasing walking experience, peak pressures decreased under the first toe, first metatarsal head, midfoot and heel region, while pressures under the third and fifth metatarsal head increased (Fig. 5b).



**Fig. 3:** On each of these footprints roll-off is represented by the course of the center of pressure (COP, depicted by the black crosses). From left to right you can see: **toe walking** (COP at contact is under M1, it shows a backward roll-off followed by a forward roll-off on the medial side of the foot), heel contact with **immature roll-off** (the COP moves forward in a straight line over the medial side of the foot), heel contact with **mature roll-off** (the COP shows an increased tendency to move forward over the lateral side of the foot before shifting to medial when the forefoot region is reached).

### Pressure Distribution Patterns

A distinction can be made into three different roll-off patterns in the new walker: initial heel strike, plantar contact, and toe walking. In the initial heel strike pattern, at foot contact a peak in pressure was seen under the heel region. This peak rapidly decreased and was followed by a rise in pressure under the midfoot. Pressures under the metatarsal heads and hallux were elevated as well, but they reached their peak in pressure at toe-off (Fig. 6a). The second pattern, plantar contact, showed elevated pressures simultaneously under heel, midfoot, and metatarsals at contact. Roll-off was reflected by a decrease in pressure under the heel and the midfoot, together with a further rise in pressure under the metatarsals and hallux (Fig. 6b). With toe walking, at contact, peak pressures were seen under the metatarsals or hallux. These peaks disappeared when the foot performed a backward roll-off, accompanied by an increase in pressure under midfoot and heel. A forward roll-off movement, similar to the heel contact pattern (Fig. 6c) followed this backward roll-off. During the first week of independent walking, all three patterns were seen in children. After 2 weeks of walking experience, toe walking became rare. However, plantar contact still occurred. With increasing walking experience, a pattern with initial heel strike became the most important roll-off pattern under the foot. There was an evolution towards a more adult roll-off pattern, characterized by a delayed rise in pressure under the metatarsals and hallux, and by a more pronounced peak in pressure under the heel

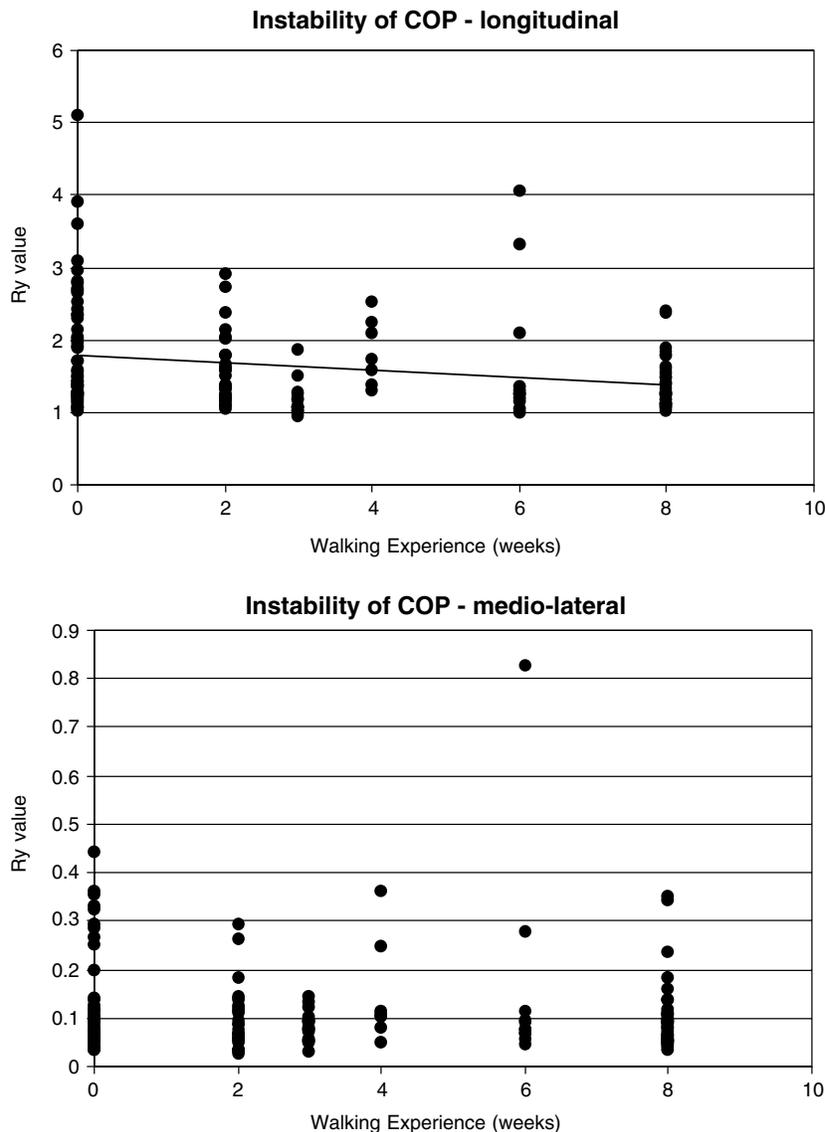
at initial contact. However, pressures under the midfoot remained elevated.

### Relative Impulses

During an entire foot contact, impulse was almost evenly distributed over the different foot regions. The highest values were found under the first metatarsal head (21.61%), followed by the heel (18.89%), midfoot (16.85%), and first toe (Fig. 7). In comparison with adults, the biggest difference was found in the loading of the midfoot. Impulses were nearly absent under adult midfoot (3.20%) while the infants' middle part of the foot carries a considerable amount of the load. In infants, the first metatarsal head was loaded considerably, while in adults the M3 was the major load carrier of the forefoot region. Impulse under the adult heel was larger than impulse under the infant heel. With increasing walking experience, impulse decreased under the hallux region, impulse under M3 and H increased, while impulse under M5 and MF stayed the same.

### Relative Impulse: Double Support Phase

In the adult during the double support phase, the contacting foot carried 57% of the load and the propelling foot contributed to 43% of the load bearing. The heel region of the contacting foot showed an RVI of 47%. The foot that performed toe-off had the largest impulse under the first toe (16.37%) and M3 (16.03%) followed by the first metatarsal head (6.56%). A smaller impulse was also found under the fifth metatarsal head (5.02%). Impulses under the rest of the foot regions were zero (Fig. 8).

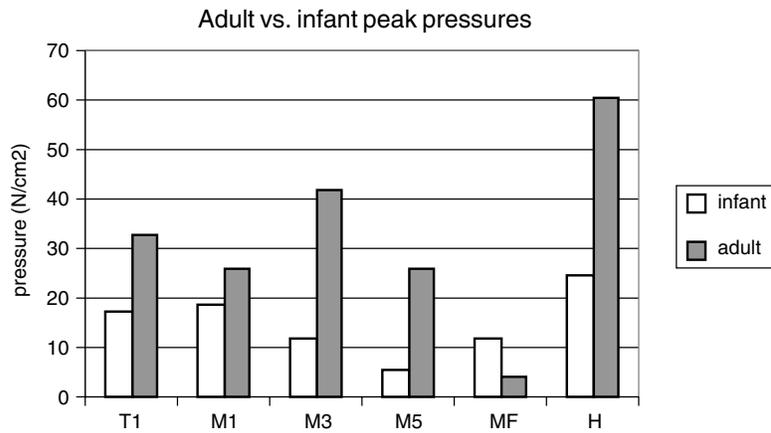


**Fig. 4:**  $R_x$  and  $R_y$  quantify the deviations from the COP path from the line of progression. Though infants are able to perform a relatively mature roll-off at the onset of independent walking ( $R_x$  small,  $R_y \sim 1$ ), instability is large. A consistent roll-off pattern as seen in adult gait ( $R_y$  always  $\sim 1$ ) has not yet developed.

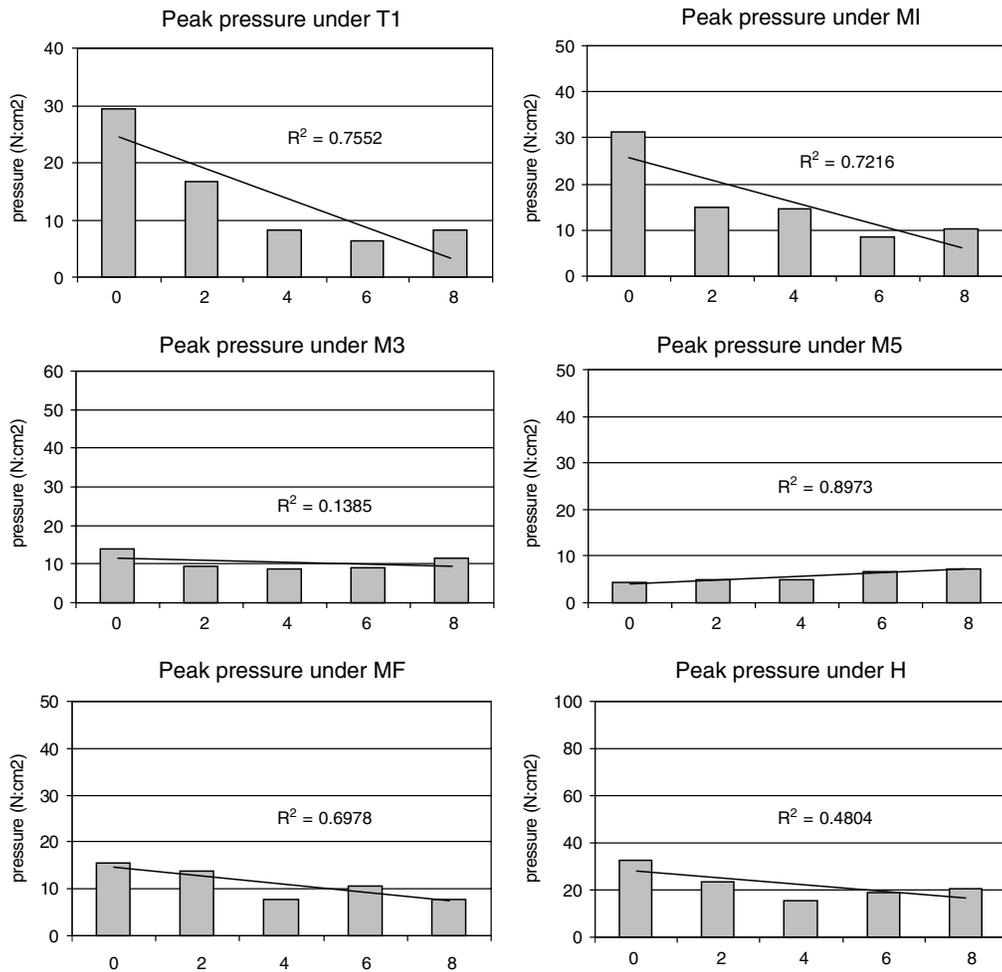
In the infant the contacting foot took 62% of the load; the propelling foot contributed 38% to the load bearing. For the striking foot, the impulse was largest under the heel (30.97%) but also significant under the midfoot (14.54%) followed by the first (5.68%) and third (7.24%) metatarsi. Impulse under the fifth metatarsal head and first toe was small. The propelling foot had the largest impulse under the first toe (13.02%) followed by the first and third metatarsal heads (7.43% and 8.34% respectively). Impulses under fifth metatarsal head, midfoot, and heel were smaller (1–4%) (Fig. 8).

## DISCUSSION

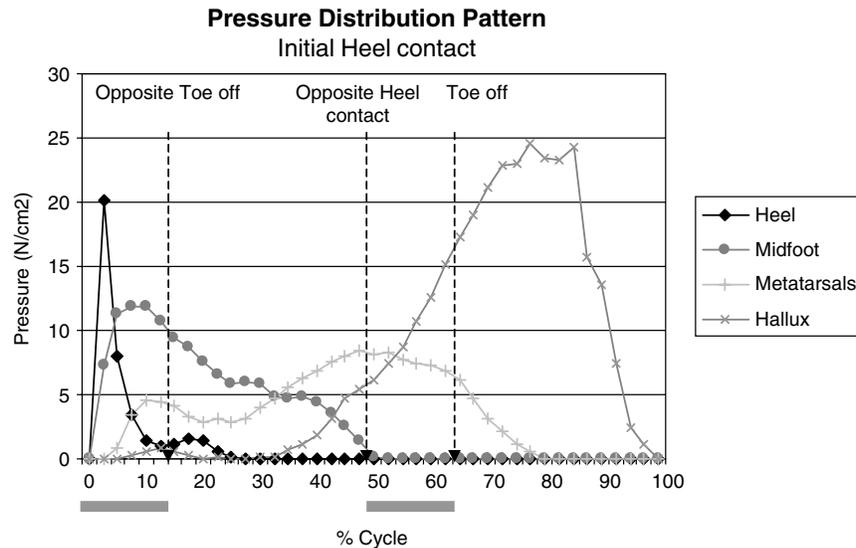
Walking is a skill that toddlers are just acquiring. The question that arises is: Do they solve the problem of propelling their body forward in the same way as adults do? Certainly a higher amount of variation might be expected since we are looking at a learning process. Anatomical differences in foot structure might be a reason to walk in a different way. At birth the skeletal tissue of the foot consists mainly of cartilage.<sup>14,15</sup> During the first 6 years of life, ossification and development towards a mature



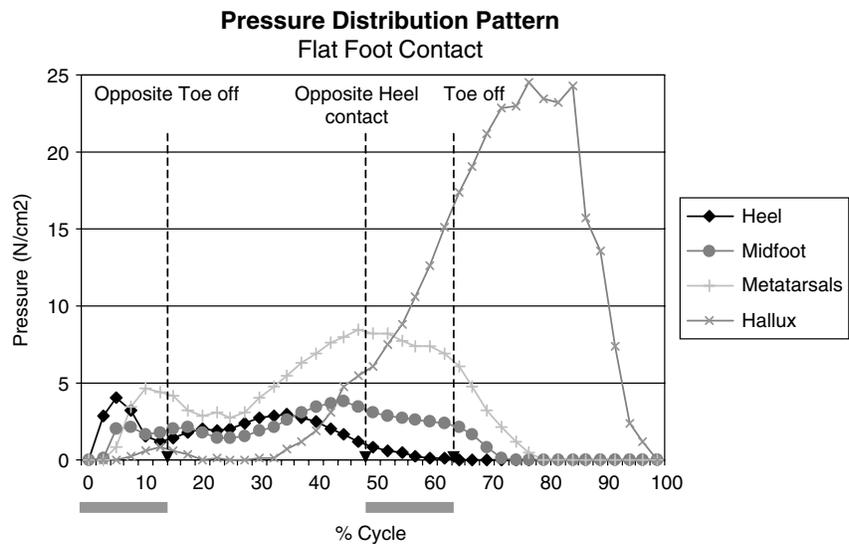
**Fig. 5a:** Under all functional areas peak pressures in infants are smaller than peak pressures in adults.



**Fig. 5b:** With increasing walking experience pressures fall under T1, M1, MF, and H, while pressures under M3 and M5 remain the same or show a slight increase.



**Fig. 6a:** Pressure distribution, of immature **heel contact**: at contact there is a peak in pressure under the heel. At toe-off, pressures under the hallux reach their maximal values.

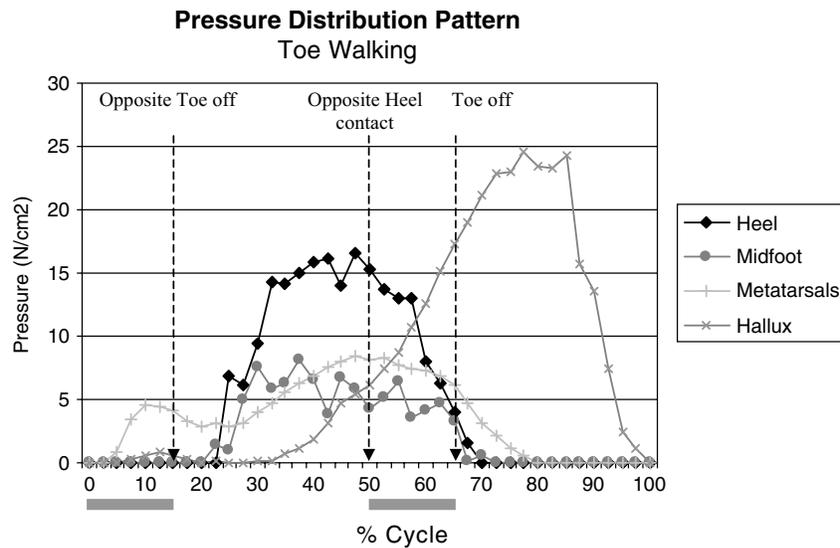


**Fig. 6b:** Pressure distribution, of **flat foot contact**: at contact there is a simultaneous rise in pressure under the heel, midfoot, and forefoot region.

foot structure occurs. At approximately 1 year of age, when children usually start walking, the talus, calcaneus, and some of the phalanges contain their primary ossification centers, still surrounded by cartilaginous tissue. Valgus inclination of the ankle at birth develops towards a neutral position by 3 years of age.<sup>14</sup> Absence of the longitudinal foot arch and as a consequence the presence of physiological flatfeet in infants might be a contributing factor to a different gait pattern.

The course of the COP, the footprints, and the pressure distribution patterns point towards a rapid

development of a gait pattern with initial heel strike in the new walker. During the first 3 weeks of independent walking, roll-off is still immature. Only the medial areas of the plantar foot surface participate significantly in load bearing and during the majority of contact time the entire plantar surface of the foot is in contact with the ground. Gradually the load shifts towards the lateral side of the foot, reflected in the course of the COP, the reduction in peak pressures under the hallux, and the increase in pressures under the lateral forefoot region. Also roll-off of the foot evolves towards a more adult-like pattern, indicated by the postponed loading of the



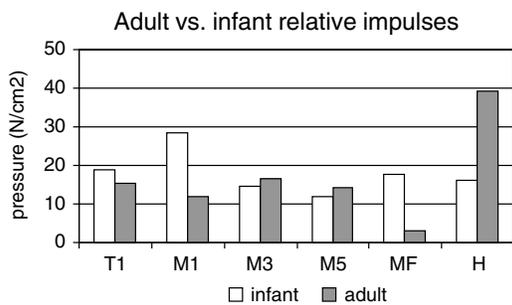
**Fig. 6c:** Pressure distribution, of **toe walking**: at contact peak pressures are seen under the forefoot region, backward roll-off is followed by a forward roll-off pattern where the forefoot reaches its second peak at toe-off.

metatarsi and the reduction in peak pressures under heel and midfoot.

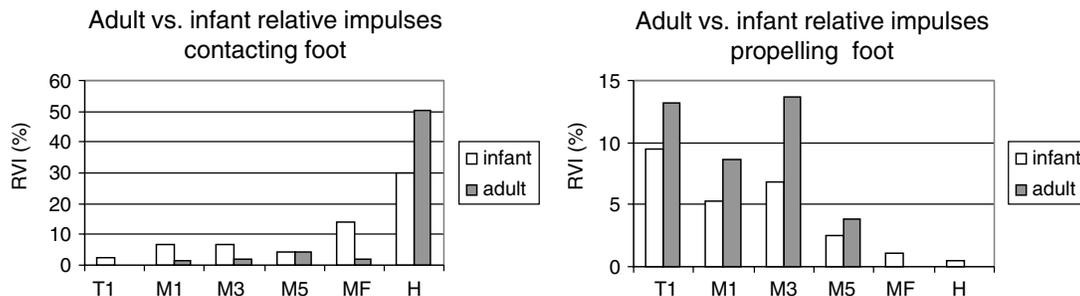
We can conclude that most of the instability under the infant foot is found along the longitudinal axis. Surprisingly, children are able to perform a relatively

mature roll-off at the onset of independent walking ( $Ry = 1$ ). However, this mature roll-off has not yet developed into a consistent pattern.

The smaller pressures under infant feet, compared to adult feet, are what we might expect. The differences in roll-off between new walkers and mature walkers can explain the smaller pressures in toddlers. As a consequence of the clear roll-off pattern seen in adults, contact area under the feet remains small. Infants spread the load more evenly over the entire plantar surface, thereby reducing peak pressures. The smaller plantar pressures in new walkers are generally assigned to the fact that their foot skeleton is largely made up of soft tissue.<sup>9</sup> This might be a contributing factor, however, not the only reason for reduced pressures under the feet. Higher pressures under the midfoot area in toddlers can be explained by the absence of the longitudinal foot arch. In normal adults this arch prevents the midfoot from carrying a large amount of the load.



**Fig. 7:** Comparison between adult and infant RVI during entire foot contact. In infants the load is shifted to the forefoot region, probably for reasons of stability.



**Fig. 8:** Comparison between adult and infant RVI during the double support phase. In infants the entire plantar surface contributes to load bearing at contact and generating propulsive forces during push-off while in adults these functions are restricted to the heel and the hallux.

Both pressure distribution patterns and relative vertical impulses point towards a forward shifting of the load under the feet of new walkers compared with adults. As a consequence, the load is more evenly distributed over the entire plantar surface. This forward shifting of loading can be explained for reasons of stability, as it is also seen in other situations of decreased stability, e.g., in ice walking, in gait of the elderly, and in Parkinson gait.<sup>11</sup> Forward shifting of loading brings along two phenomena that will contribute to increased stability.<sup>11</sup> First, the contact area under the foot will increase. Second, the forefoot region contributes more to load bearing. This region allows more muscular control to compensate instabilities than the stiffer rear- and midfoot regions. When we look at the gait of new walkers, plantar contact is not so much a feature of immaturity as a strategy to improve balance in a situation threatening it.

The relative vertical impulses during the double support phase show that in toddlers the contacting foot is most important in load bearing, much more pronounced than in adult gait. Endo and Kimura<sup>7</sup> also found high vertical impulses under infant feet.

The RVIs under first toe and first metatarsal head during contact are large in comparison to adults. Hennig and Rosenbaum<sup>9</sup> concluded from this observation that push-off under the hallux is more important in new walkers in comparison to adults. However, considering our results on RVI during the double support phase, T1 and M1 seem to be important for push-off though they are less important than in adults. In new walkers the entire plantar surface contributes to generating propulsive motion. The high RVI under the hallux region may be due to the forward shifting of the load for reasons of improved balance.

## CONCLUSION

Three major features can be attributed to infant foot function which clearly distinguish it from adult foot function. First, as expected at the onset of learning to walk independently, foot function characteristics show a large amount of variation. In contrast to adults, infant foot function does not show a stereotyped pattern.

Second, balance problems are reflected in foot function by an increase in the plantar surface contact area and a forward shifting of the load. These responses allow for more control of equilibrium thus preventing the infant from falling.

Third, differences in foot anatomy between adults and infants are also reflected in their respective foot function pattern. The large amount of soft tissue in young children's feet will lead to a reduction in peak plantar pressures at foot contact because the soft tissue will allow the load to be distributed over a larger area.

Apart from this, infant feet show large plantar pressures under the midfoot region (both absolute and relative) in comparison to adults due to the absence of the longitudinal foot arch.

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