THE DEFORMATION OF THE FOREFOOT DURING THE STANCE PHASE OF NORMAL GAIT

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SUMMARY

Despite the fact that the forefoot plays a considerable role in the foot-to-ground interaction during normal gait, little is known about specific forefoot kinematics. A detailed description of the deformation occurring at the level of the forefoot during the stance phase of normal human walking shows that the forefoot deformation follows a specific pattern. This pattern of deformation is characterized by a transfer from a flexible configuration at the beginning of stance phase, to a stable configuration during midstance, into a rigid lever at final stance.

INTRODUCTION

The human forefoot is an elaborate kinematic structure comprising five metatarsal bones, supplemented with a large amount of fascia, ligaments, muscles and long muscle tendons. The forefoot plays a key role in providing the locus for lower-limb-ground interaction during locomotion [1,2], contributing to weight transmission and forward propulsion during human gait [3]. Despite the fact that the forefoot executes an important function [4], the knowledge concerning the deformation of the forefoot is limited. In previous research, forefoot deformation was addressed through foot-ground interaction by plantar pressure measurement [5,6], through marker distance [7] and three dimensional positioning of the bones during stance phase of human gait [8]. The aim of this study is to provide a more detailed description of the forefoot deformation during the stance phase of normal human walking. In addition, the existence of a specific deformation pattern will be explored.

METHODS

40 healthy subjects (23 male, 17 female; mean age 30.13 ± 13.15years; mean weight 73.24 ± 14.83kg) volunteered to participate in this study.

Kinematic data of the left foot was collected with a six camera motion capture system (Vicon®, Oxford Metrics, UK) at a sampling rate of 250 Hz, in a calibrated measurement volume of 0.2m^3. A total of 12 retro-reflective skin markers were attached to the subjects' foot of which we used five (Figure 1). The ground reaction force was measured through a force plate system (Kistler®) at a sample rate of 1250Hz to accurately define stance phase. Dynamic plantar pressure data was obtained using a footscan® pressure plate (RSscan International®, Belgium). The system was set at 500Hz. The measurement equipment was synchronized in time and space.

Figure 1: The marker protocol is characterized by twelve markers on the forefoot, of which we used five to determine inter-metatarsal distance and mediolateral metatarsal arch height.

Following a familiarization period, a static trial was performed. Subsequently, during the dynamic trials all subjects were asked to walk at a constant self-selected speed till ten trials of the left foot were registered. The outcome measures defining the deformation of the forefoot are: (1) plantar pressure parameters, (2) distance between the forefoot markers (caput metatarsal I, II/II & V and base metatarsal I & V) and (3) deformation of the mediolateral metatarsal arch (MLMA). The mutual distances and the arch height were normalized to the distance and height during static stance.

RESULTS AND DISCUSSION

Small but significant changes in arch height as well as in mutual distances are established during the stance phase of normal gait (table 1).

Table 1: Changes in mutual distance between the individual forefoot markers throughout the entire stance phase.

	Range	Min. distance	Max. distance
CMT I-V	0.11 ± 0.02	0.90 ± 0.02 (HC)	1.01 ± 0.01 (MS)
CMT II/III-V	0.14 ± 0.03	0.87 ± 0.05 (HC)	1.01 ± 0.04 (MS & IP)
CMT I-II/III	0.10 ± 0.02	0.91 ± 0.04 (HC)	1.01 ± 0.04 (MS)
BMT I-V	0.04 ± 0.01	0.97 ±0.01 (HC)	1.00 ± 0.01 (MS & IP)
MLH	0.32 ± 0.09	0.81 ± 0.06 (MF)	1.13 ± 0.08 (IP)

Reference: CMT = caput metatarsal, BMT = metatarsal base, min = minimum, max. = maximum, HC = heel contact, MF = metaforming, MS = midstance, IP = initial propulsion

The mean MLMA height is characterized by a decrease from the moment of heel contact till the metatarsal forming phase. During heel contact and metaforming phase, the mediolateral metatarsal distances increase due to the consecutive lateromedial loading of the metatarsal heads [5,9]. Despite the increased metatarsal distances the results remain below the value during static stance (Figure 2). The combination of the decrease in arch height, pointing towards a flattening of the arch, with mediolateral distances smaller than during static stance, pointing towards a compact structure, suggests that the metatarsal heads form an inverse arch during the heel contact and metatarsal forming phase.
Through midstance, the inter-metatarsal distances as well as the MLMA remain more or less stable (Figure 2).

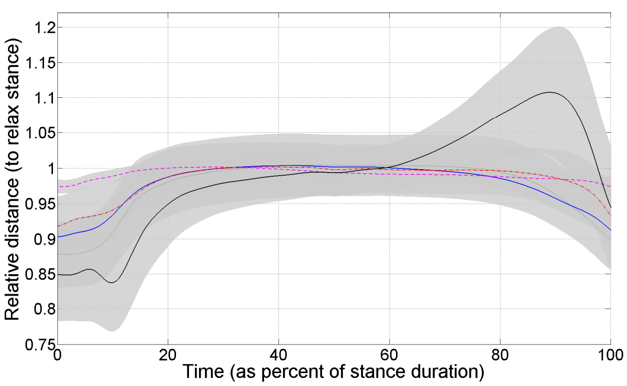

Figure 2: The averaged and time normalized changes in MLMA height and mutual distance of the forefoot markers of the left leg during stance phase in normal gait. At the Y axis from bottom to top (1) MLMA, (2) normalized distance between the metatarsal head II/III and V, (3) normalized distance between the metatarsal I and V, (4) normalized distance between the metatarsal head I and II/III (5) normalized distance between the metatarsal bases.

From heel off the MLMA height reaches its maximum prior to final propulsion phase. The increase in arch height is accompanied by a decrease in inter-metatarsal distances (Figure 2). Due to the high loads on the metatarsal heads and the fact that the metatarsophalangeal joints did not reach the extreme end of their normal range of motion during initial and final propulsion, this increase in MLMA height and inter-metatarsal distances can be achieved by active elements only. Erdemir et al. (2004) suggested that the plantar aponeurosis contributes to the stabilization of the mediolateral and longitudinal arch [10]. The fact that the distances between the metatarsal heads continue to decrease throughout the entire initial and final propulsion phase, even past the moment of maximum aponeurosis tension, can possible be attributed to the continuous decrease in loading of the trialing limb.
Onset, offset and duration of pressure underneath the metatarsal heads show high significant correlations ($r > .70$) with the timing of minimum and maximum distances in the different phases. This might indicate a relationship between foot-ground contact and forefoot deformation timing.
The second objective of this study was to determine whether the deformation of the forefoot follows a specific pattern. At initial stance the MLMA height decreases to a minimum, resulting in a flattening and even an inversion of the MLMA. In addition, inter-metatarsal distance increases due to loading of the metatarsal heads during metatarsal forming phase, suggesting the foot behaves as a relatively flexible configuration. Through midstance both the inter-metatarsal distances and the MLMA height remain constant despite the forward shift of the center of pressure, indicating a compact stable configuration. Final stance (initial and final propulsion phase) is characterized by tightening of the forefoot providing a rigid lever for forward propulsion [11]. This tightening of the forefoot is apparent through the increase in MLMA height and decrease in inter-metatarsal distances.

CONCLUSIONS

Through stance phase, the forefoot deforms according to a specific pattern. At the beginning of stance phase the largest deformation occurs, possibly indicating a flexible forefoot in the form of an inverse arch. Through midstance the forefoot remains stable and transforms into a tight configuration during initial and final propulsion phase.

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