Three-Dimensional Midfoot Motion Facilitates Spring-Like Plantar Aponeurosis Dynamics in Walking

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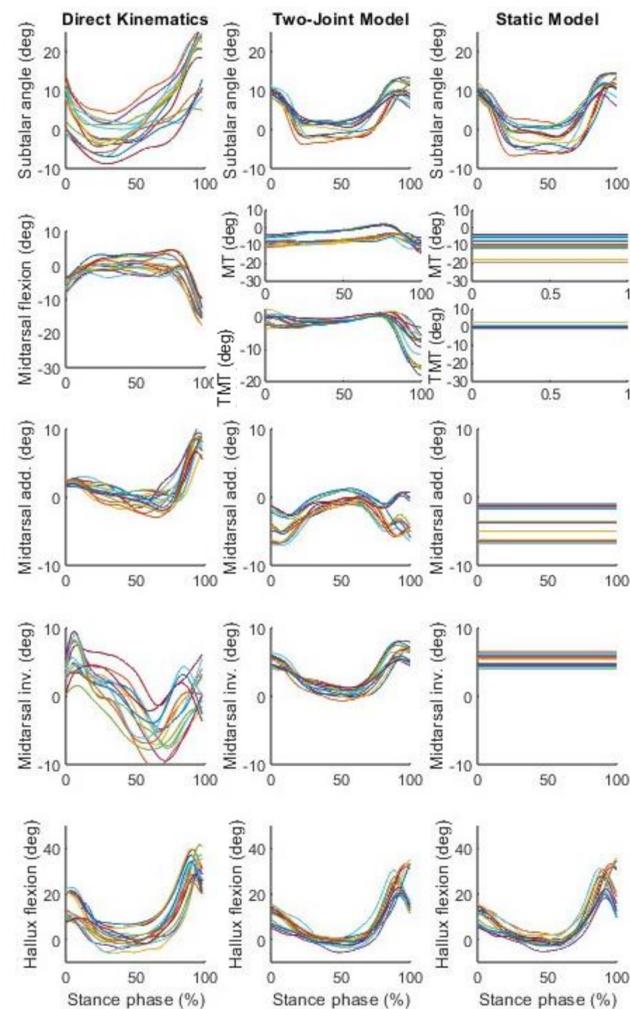
Introduction

The human foot has long been argued to behave as a rigid lever in walking. The plantar aponeurosis (fascia) is thought to facilitate this by functioning as a simple anatomical coupler between the hindfoot and forefoot, thereby stabilizing the midfoot and permitting the transfer of mechanical energy from the heel to toes during stance phase (i.e the windlass mechanism) [1]. However, recent experimental studies have found that there is considerable intrinsic foot motion during walking, and the associated muscle and tissue functions are likely more complex than previously assumed. It has been proposed that increased midfoot motion may enhance "push-off" at the end of stance phase, but this hypothesis is difficult to test directly [2,3]. Here, we use a novel experimental-modeling approach that integrates extensive marker-based 3-D measurements of intrinsic foot motion with a detailed model of the human foot skeleton to evaluate the effects of midfoot motion on plantar aponeurosis dynamics during the stance phase of a walking stride. We estimate length change, force and power output of the plantar aponeurosis when midfoot motion is permitted (mobile midfoot_ and restricted (rigid midfoot) to test the hypothesis that a mobile midfoot enhances 'push-off' mechanics [2,3].

Methods

An existing, generic 3-D skeletal model [4] of the human foot was modified to permit 3-D motion between the hind and forefoot (midfoot plantarflexion-dorsiflexion, abduction-adduction and inversion-eversion) as well as plantarflexion-dorsiflexion of digits 1-5. Total ranges of motion at the midfoot joint were based on previous experimental studies [3; Fig 1A]. A plantar apo\neurosis was modeled as a 5-element set of ligaments, extending from its origin on the calcaneus to its insertion on the proximal phalanges of digits 1-5, and included wrapping elements around the MTP joint heads to prevent ligament-bone interpenetration [Fig 1B]. A generic ligament model [5] was parameterized based on in vitro experimental measurements [6] or previous modeling studies of the plantar aponeurosis [7].

27 surface markers collected from three subjects (Mb = 64.1 kg, 62.6 kg, 69.5 kg) during walking at an average speed of 1.3 m/s across a level runway were integrated with the skeletal-ligament model [Fig 1C]. An inverse kinematics algorithm combined the experimental data with the model to generate 3-D hindfoot, midfoot and MTP joint motion. Kinematic calculations were performed when midfoot motion was permitted (mobile midfoot) and restricted (rigid midfoot).

Figure 1: Image of the dorsal surface of the foot model (A). Plantar view of the foot with five components of the plantar aponeurosis (green_ along with the wrapping surfaces (blue) (B). Forefoot, midfoot, and hindfoot are positioned at 0º (neutral position). Model with 27 surface markers fpr the human inverse kinematics calculations (C).

Plantar aponeurosis strain, force and power output over stance phase were estimated for the rigid midfoot (no midfoot motion) and mobile midfoot (measured midfoot motion) model conditions.

Figure 2. 3-D intrinsic foot kinematics over a stance phase of a walking stride.
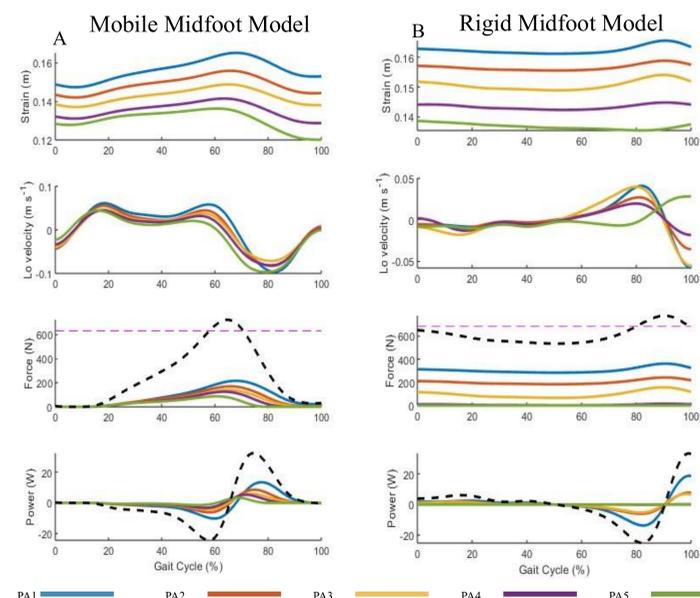
Figure 3. Plantar aponeurosis (PA) dynamics during stance phase with a mobile (A) and rigid (B) midfoot

		Max Strain	Max Force	%Timing Max	Min Power	%Min Timing	Max Power	% Timing Peak
		(m)	(N)	(%)	(W)	(%)	(W)	(%)
Mobile Midfoot	S01	0.09	580.9	65	-24.2	58	32.4	78
	S02	0.04	745.0	85	-26.5	78	44.6	94
	S03	0.06	998.0	78	-36.8	69	83.8	89
	Average	0.06	774.6	76	-29.2	68	53.6	87
Static Midfoot	S01	0.01	97.2	92	-2.0	86	2.3	97
	S02	0.03	584.6	95	-20.7	87	9.4	100
	S03	0.04	774.3	90	-20.5	82	33.4	99
	Average	0.03	485.4	92	-15.9	85	15.0	99

Table 1: The maximum strain, force and power for each subject with either a completely mobile or static midfoot. The maximum strain was taken for each of the 5 components of the plantar aponeurosis over the course of stance phase and averaged. The maximum force and power values were calculated by taking the sum of each plantar aponeurosis component during stance phase and determining the peak values.

Results

- Figure 2 shows an intrinsic foot motion over the stance phase of a walking stride, consistent with previous direct kinematic measurements [2]. These results highlight the significant increase in midfoot motion at "push-off" during the second double-support period.

- A mobile midfoot results in greater PA strain [Table 1], force and positive power output during the second double-support phase (Fig. 3A). A mobile midfoot allows the plantar aponeurosis to operate like a spring in walking, generating positive elastic power during push-off.

- A rigid midfoot results in lower PA strain, force and positive power output [Table 1]. A rigid midfoot induces the plantar aponeurosis to operate more like a brake in walking, absorbing mechanical energy late in stance (Fig. 3B)
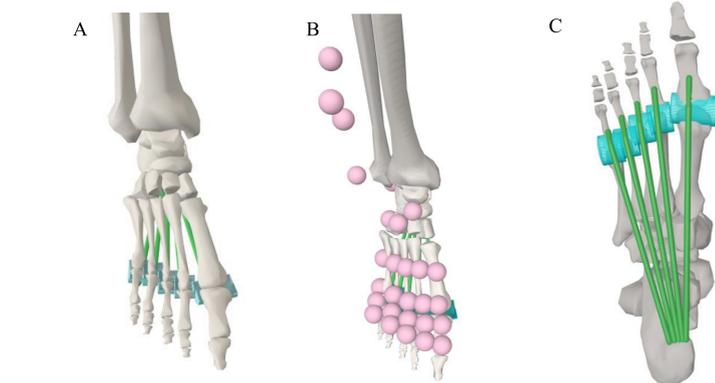
Discussion and Conclusions

These results suggest significant differences in plantar aponeurosis function with a rigid midfoot versus a mobile midfoot. When 3-D midfoot motion is permitted, the PA functions as a spring that absorbs mechanical energy during single-support and releases positive work during the second double-support. When 3-D midfoot motion is restricted, the PA functions as a brake the absorbs mechanical energy during the second double-support period. These results suggest that midfoot motion enhance the power-producing capabilities of the plantar aponeurosis of the foot. This work suggests that maintenance of intrinsic foot mobility may be an important component of a health, able-bodied gait [2,3,8]

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Acknowledgements