The Effects of Walking Speed on Adult Multi-segment Foot Kinematics

Grant J and Chester V*

Andrew and Marjorie McCain Human Performance Laboratory, Faculty of Kinesiology, University of New Brunswick, Fredericton, New Brunswick, Canada E3B 5A3

Abstract

It has recently been shown that gait speed has an effect on multi-segment foot kinematics. To increase our understanding of these effects, it is critical to compare and develop a database of walking speed ranges. Therefore, the purpose of this study was to determine the effects of walking speed on multi-segment foot kinematics. A 12-camera Vicon motion capture system was used to collect kinematic data on 22 participants (mean age: 23 ± 2.6 years). Participants were asked to walk at 5 gait speeds; very slow, slow, free, fast, and very fast. Across speeds, significant differences were found in all absolute angles, 6 of 9 relative mean maximum angles, 11 of 13 timing to the maximum angles, and all temporal-spatial variables analysed. These findings suggest that clinical gait data that uses multi-segment foot models should be matched to a control group walking at a similar speed.

Introduction

To date, most gait studies have modeled the foot as a single rigid segment with one to two degrees of freedom. Previous research using such models has shown that walking speed influences ankle motion [1-6]. While multi-segment foot models are now more commonly used in gait analysis studies, relatively little is known about the effects of walking speed on subsegment kinematics. Differences in multi-segment foot kinematics have been found between control and clinical groups with foot and ankle impairments [7-11]. In many cases, these individuals may walk slower or faster than typical walking speeds. As a result, speed-mediated effects may be difficult to distinguish from those due to an injury, disease and/or disorder. Therefore, a greater appreciation of the effects of walking speed on multi-segment foot kinematics in control groups is needed.

Only a few studies have examined the effects of gait speed on multi-segment foot motion. Dubbeldam et al. [12] measured adult foot and ankle kinematics at self-selected walking speeds and at 75% and 50% of self-selected walking speeds. Results showedchanges in multi-segment foot kinematics in all three planes. As speed categories were based on a predetermined percentage of the subjects' self-selected speed, slower speeds may not have reflected each individual's natural movement patterns. Further, while patients usually walk slower than a control group, there are instances where they may walk faster, (e. g., in cases of cerebral palsy). Fast walking speeds were not tested as part of this study. A broader range of speeds would therefore be needed to provide speed-matched data when evaluating a patient. Tulchin et al. [6] studied sagittal plane multi-segment foot kinematics across a range of slow and fast walking speeds in adults using a two-joint model of hind foot and forefoot motion. They found significant changes in hind foot and forefoot motion as a function of speed. However, speed was controlled using a treadmill, which has been shown to impact the natural gait of individuals by altering the frequency and speed relationship [13]. In addition, as the use of treadmills is often impractical in clinical studies, data collected during over ground walking are often preferred for comparative purposes. Deviations in multi-segment foot motion may be related to changes in walking speed that are associated with gait pathology. Kinematic comparisons to speed-matched control data could provide more insight into the effects of pathology on gait. The appreciation of speed-mediated effects on multi-segment foot kinematics is critical for increasing our understanding of foot mechanics in typical and atypical populations. Therefore, the purpose of the present study was to examine differences in multi-segment foot kinematics as a function of walking speed using healthy controls. To facilitate natural gait patterns and applicability for future clinical studies, a broad range of self-selected walking speeds during over-ground walking were used.

Method

Participants

Twenty-two adults (11 female, 11 male) aged 18 to 28 years were recruited to participate in the study. One individual was removed from the dataset due to the presence of abnormal gait patterns (>3 S.D from control values) for a total of 21 participants(age=23.0 ± 2.6 years; height=1.73 ± 0.1 m; weight=72.1 ± 10.1 kg). One individual's data was removed only from the very slow speed condition due to the onset of toe walking at this speed. Further characteristics of each group are provided in Table 1. Individuals with history of diseases/disorders that could affect foot kinematics, including diabetes, neurological pathologies, joint replacement surgeries, chronic pain, and edema were excluded from the study. Participants were recruited through advertisements, emails, and word-of-mouth. This study was approved by the University Research Ethics Board.

Instrumentation

Data collection occurred at the Andrew and Marjorie McCain Human Performance Laboratory at the University of New Brunswick (UNB). A 12-camera Vicon T160 motion capture system (Oxford Metrics Group Ltd., UK), sampling at 100 Hz, was used to track the three-dimensional trajectories of reflective markers (diameter of 9 mm) placed on the participants' skin. Sixforce plates (Kistler Instruments,

*Corresponding author: Chester V, Andrew and Marjorie McCain Human Performance Laboratory, Faculty of Kinesiology, University of New Brunswick, Fredericton, New Brunswick, Canada E3B 5A3, Tel: 1-506-458-7589; E-mail: vchester@unb. ca

	Number of Participants	Age (years)	Height (m)	Weight (kg)
Male	11	22.4 (2.7)	1.78 (0.06)	76.8 (8.5)
Female	10	23.6 (2.5)	1.67 (0.05)	67 (9.4)
Combined	21	23 (2.6)	1.73 (0.1)	72.1 (10.1)

Table 1: Participant characteristics displayed as mean (S.D.).

Segment	Location
Hallux	Most distal and dorsal point of the head of the proximal phalanx
Forefoot	Head of the fifth metatarsal, dorso-lateral aspect of the fifth metatarso-phalangeal joint
	Head of the second metatarsal, dorso-medial aspect of the second metatarso-phalangeal joint
	Head of the first metatarsal, dorso-medial aspect of the first metatarso-phalangeal joint
	Base of the fifth metatarsal, dorso-lateral aspect of the fifth metatarso-cuboid joint
	Base of the second metatarsal, dorso-medial aspect of the second metatarso-cuneiform joint
	Base of the first metatarsal, dorso-medial aspect of the first metatarso-cuneiform joint
Midfoot	Medial apex of the navicular tuberosity
	Dorsal aspect of the cuboid
Calcaneus	Lateral calcaneus-midpoint between the lateral malleolus and floor
	Medial calcaneus-point between medial malleolus and floor at height of lateral calcaneus marker
	Posterior calcaneus-aligned vertically with Achilles tendon at same height as lateral calcaneus marker
Shank	Most lateral aspect of lateral malleolus
	Most medial aspect of the medial malleolus
	Most lateral prominence of lateral epicondyle
	Most medial prominence of the medial epicondyle
	Most anterior aspect of the tibial tuberosity

Table 2: Anatomical landmarks for the multisegment model of the foot and shank.

Winterthur, Switzerland), embedded in the lab floor,were used to aid in the identification of key gait events. Three-dimensional force and moment data were sampled at a frequency of 1000 Hz. Two custom-made laser trip timers were used to provide the researcher with data on walking speeds during the gait trials. Two laser beams were placed 5 m apart, along the direction of progression, and were integrated with an A/D board and laptop computer. Two high-speed Basler digital video cameras (Basler Inc., Ahrensburg, Germany) were used to obtain front and side images of each participant during the gait trials. A weight scale and stadiometer were used to obtain anthropometric measures from each participant.

Procedures

Thirty four reflective markers were placed on the left and right foot and tibia of each participant (Table 2). For consistency, the same researcher was always responsible for placing markers on each participant in the study. Following this, a static capture of the participant during quiet standing in the anatomical position was recorded to permit the calculation of offset values for all joint rotations. These joint offset values were later subtracted from the appropriate joint rotations for the gait cycles of each participant. These offset calculations did not apply to the planar angles. Following the static trial, several practice gait trials were completed to allow the participants to adjust to the markers and the lab environment. For the gait trials, participants were asked to walk at five different speeds (very slow, slow, free, fast, and very fast). All participants performed free speed trials first to establish a baseline walking speed. Following this, participants were randomly assigned to walk either the slow conditions (e. g. slow, very slow) or the fast conditions (e. g. fast, very fast). Between each of the speed conditions, participants conducted free speed trials, which were not recorded, to aid in re-establishing baseline walking speed. During the gait trials, walking speed data was obtained from the laser trip timers at the completion of each trial. A separation of at least 0.2 m/s between

speeds was required. Verbal instructions to go faster or slower were given to participants to ensure this separation occurred. Participants were asked to perform at least 6 successful gait cycles (i. e. clean force plate strikes, marker visibility, and appropriate speed separation)at each speed for both the left and right limb (5 speeds × 2 limbs × 6 cycles=60 cycles per person). Following completion of the gait trials, height and mass were measured.

Data analysis

Data was analyzed using custom software created in Matlab (Mathworks, Inc. Natick, MA, USA). For each participant, trial selection involved the computation of cadence, velocity, and percent of cycle spent in single stance for each gait cycle. The single gait cycle that most closely approximated the individual mean of all gait cycles on these three measures was selected as the single trial for analysis for each participant. This was repeated for both the left and right limbs.

The rigid body model consisted of five segments: 1) the shank, 2) the total foot (single rigid segment), 3) the calcaneus, 4) the mid foot, and 5) the forefoot (included all 5 metatarsal bones). The hallux and metatarsal bones were modeled as line segments for the computation of planar angles. The anatomical landmarks (Table 2) and reference frames were consistent with the model developed by Leardini et al. [14], with the following exceptions: 1) the cuboid was not assumed to coincide with the base of the fifth metatarsal (Table 2), and 2) a neutral calcaneus was formed using a laser level technique to guide marker placement. This ensured the reliable placement of markers on a segment with few palpable anatomical landmarks. To achieve a neutral calcaneus, the vertical midpoint between the floor and the lateral malleolus was determined using calipers. A marker was placed at this point and referred to as the lateral calcaneus. A cross-hair laser was then used to aid in the placement of the posterior calcaneus marker. The vertical laser line was aligned with midsection of the Achilles tendon,

while the horizontal laser line was aligned with the lateral calcaneus marker. The intersection of the two laser lines formed the location for the posterior calcaneus marker. Lastly, the medial calcaneus marker was placed beneath the medial malleolus at the same height as the lateral and posterior calcaneus markers. The locations of the three non-collinear markers on each rigid segment were used to create embedded coordinate systems at the virtual joint centers [14]. Joint angles were computed from the relative orientations of the embedded coordinate systems using Euler angles in ayxz sequence, corresponding to flexion/extension, adduction/abduction, and internal/external rotation. Displacement data were filtered using a zero phase lag, second order Butterworth filter with a cutoff frequency of 6-9 Hz. Joint angle data were normalized to 100% of the gait cycle.

In accordance with Hof [15], gait speed was rendered dimensionless by using the following equation:

$$\hat{v} = \frac{v}{\sqrt{gl_0}}$$

whee v is the speed, g is gravity, and l_o represents the leg length of the individual. The leg length is measured from the greater trochanter to the ground. Speed ranges for each speed condition were determined with respect to these dimensionless values.

Statistical snalysis

Kinematic data were pooled only after a MANOVA, for the free speed group showed no significant differences ($p < 0.05$) in mean kinematic data between side ($p = 0.133$) and sex ($p = 0.366$). Data for all subjects were then combined and separated into 5 speed groups (very slow, slow, free, fast, and very fast). Repeated measures ANOVAs were used to test for significant ($P < 0.05$) differences in mean maximum/minimum joint angles and mean temporal-spatial parameters across the 5 speed groups. A list of dependent variables can be found inTable 3. Bonferroni adjustments were used to compensate for multiple comparisons, which resulted in a p-value of 0.002 or less as significant. All statistical tests were performed using SPSS (IBM Corporation, New York, USA).

Results

Post HOC analysis of walking speed

Speed ranges were determined in a post hoc manner by first computing the median walking speed for all trials. A percentage of the median value was then added and subtracted from the median value until approximately one fifth of the data was encompassed by the range of speed values (Table 4). These two initial boundaries defined the free speed range. To define the next speed group (e. g. fast), the percentage

Kinematics Variables	Very Slow Mean	SD	Slow	SD	Free Mean	SD	Fast Mean	SD	Very fast mean	SD
Max v2g (degrees)	68.5	9.08	77.73	7.42	80.25	6.98	84.82	4.85	85.6	4.65
Time to max v2g (%GC)	66.21	2.61	63.83	1.22	62.33	1.66	60.74	1.33	59.05	1.61
Max s2g (degrees)	93.27	8.75	101.77	8.6	105.9	7.92	109.55	6.23	111.3	6.26
Time to max s2g (%GC)	66.16	2.63	63.93	1.27	62.45	1.76	61.23	1.39	59.82	1.47
Max F2Ps (degrees)	45.05	9.28	47.35	8.4	47.75	8.16	49.55	8.5	51.86	7.1
Time to max F2Ps (%GC)	62.95	2.52	60.1	1.64	58.69	1.7	56.84	1.79	54.56	2.21
Min MLA (degrees)	158.31	4.28	156.99	4.6	61.32	5.17	155.83	5.29	154.97	4.56
Time to min MLA (%GC)	64.91	2.28	62.95	1.56	20.65	1.55	59.74	1.35	58.05	1.61
Max Foot-tibia PF (degrees)	15.05	5.28	19.65	6.16	61.95	5.99	22.19	5.05	22.73	5.41
Time to max Foot-Tibia PF (%GC)	53.44	25.1	60.76	12.9	9.98	1.67	60.53	1.5	58.59	1.79
Max Foot-tibia DF (degrees)	11.02	3.1	11.21	3.02	43.31	3.5	9.04	2.79	7.77	2.98
Time to max Foot-Tibia DF (%GC)	49.37	3.75	46.56	2.72	15.72	6.96	40.49	7.84	32.46	9.52
Max Calcaneus-Tibia PF (%GC)	11.38	3.69	14.7	4.88	54.05	5.03	17.01	4.16	17.17	3.75
Time to max Calcaneus-Tibia PF (%GC)	40.77	30.5	53.88	22.2	7.49	20.19	59.4	8.85	56.13	12.16
Max Calcaneus-Tibia DF (%GC)	8.74	2.88	8.63	2.82	43.05	3.26	6.62	2.83	6.08	2.68
Time to max Calcaneus-Tibia DF (%GC)	49.47	4.05	46.73	4.15	2.06	7.88	39.91	8.44	32.15	9.64
Max Mid foot-Calcaneus EVE (degrees)	1.58	1.08	1.76	0.99	2.06	1.19	1.96	1.34	2.1	1.39
Time to Max Midfoot-Calcaneus EVE (%GC)	58.23	9.12	54.34	10.5	55.88	7.3	52.33	10.27	49.56	13.59
Max Mid foot-Calcaneus PF (degrees)	8.8	2.34	9.85	3.2	10.09	3.17	10.1	3.25	10.52	3.92
Time to Max Midfoot-Calcaneus PF (%GC)	65.19	2.38	62.85	1.41	61.36	1.79	59.81	1.4	58.13	1.89
Max Fore Foot-Midfoot Calcaneus EVE (degrees)	2.5	1.57	2.73	1.74	2.9	1.91	2.79	1.88	2.99	1.77
Time to Max Fore Foot-Midfoot Calcaneus EVE (%GC)	47.95	19	50.76	17	50.05	17.36	51.26	14.21	54.08	12.26
Max Fore Foot-Midfoot CalcaneusPF (degrees)	10.83	2.84	12.29	3.24	12.5	3.37	12.7	3.44	13.6	3.9
Time to Max Fore Foot-Midfoot Calcaneus PF (%GC)	64.07	2.3	61.61	1.55	60.36	1.71	58.65	1.46	57	1.85
Max Fore foot-calcaneus ADD (%GC)	4.79	2.46	5.67	2.85	5.09	2.9	4.84	2.99	4.2	3.13
Time to Max Fore Foot-Midfoot Calcaneus ADD (%GC)	50.14	21.8	54.34	12.1	48.86	17.66	49.93	12.35	37.23	22.56
Stride Length (cm)	103.68	10.3	123.02	7.58	136.5	8.65	151.24	9.97	166.85	11.48
Toe-Off (%GC)	66.33	2.88	63.95	1.26	62.45	1.76	61.26	1.42	59.87	1.47
Single leg Stance (%GC)	35.02	3.23	36.8	1.61	38.31	1.6	39.67	1.46	41.09	1.7
Cadence	106.10	14.3	125.1	8.32	140	8.09	153.18	8	171.23	12.73

Table 3: Descriptive statistics for joint angle and temporal spatial data as a function of walking speed.

Speed Groups	Dimensionless Speed	Number of Trials
Very Slow	v ≤ 0.382	43
Slow	0.382<v ≤ 0.495	41
Free	0.495<v ≤ 0.581	42
Fast	0.58<v ≤ 0.721	43
Very Fast	v>0.721	39

Table 4: *Post hoc* classification of walking speeds among the five speed categories.

Dependent Variable	Very Slow	Slow	Free	Fast	Very Fast
MaximumV2G (fifth metatarsal in the sagittal plane)	2,3,4,5	1,4,5	1,4,5	1,2,3	1,2,3
Time to maximumV2G	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4
MaximumS2G (second metatarsal in the sagittal plane)	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3	1,2,3
Time to maximumS2G	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4
Maximum F2Ps(hallux in the sagittal plane)	2,3,4,5	1,4,5	1,5	1,2	1,2,3
Time to maximum F2Ps	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4
Minimum MLA(medial longitudinal arch)	2,3,4,5	1,5	1	1	1,2
Time to minimum MLA	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4
Maximum Foot-Tibia PF	2,3,4,5	1,4,5	1,5	1,2	1,2,3
Time to maximum Foot-Tibia PF	2,3,4,5	1	1	1	1
Maximum Foot-Tibia DF	4,5	4,5	5	1,2,5	1,2,3,4
Time to maximum Foot-Tibia DF	3,4,5	3,4,5	1,2,5	1,2,5	1,2,3,4
Maximum Calcaneus-Tibia PF	2,3,4,5	1,5	1	1	1,2
Time to maximum Calcaneus-Tibia PF	2,3,4,5	1	1	1	1
Maximum Calcaneus-Tibia DF	3,4,5	4,5	1,5	1,2	1,2,3
Time to maximum Calcaneus-Tibia DF	3,4,5	3,4,5	1,2,5	1,2,5	1,2,3,4
Maximum Midfoot-Calcaneus PF	2,4,5	1	5	1	1,3
Time to maximum Midfoot-Calcaneus PF	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4
Maximum Forefoot-Calcaneus PF	2,3,4,5	1,5	1,5	1	1,2,3
Time to maximum Forefoot-Calcaneus PF	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4
Time to maximum Forefoot-Calcaneus ADD	5	5	5	5	1,2,3,4
Stride length	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4
Toe-off	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4
Single leg stance	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4
Cadence	2,3,4,5	1,3,4,5	1,2,4,5	1,2,3,5	1,2,3,4

Table 5: Significant pairwise comparisons of temporal-spatial and joint angle data between speed conditions: 1-very slow, 2-slow, 3-free, 4-fast, 5- very fast (p<0.002).

was increased until an additional one fifth of the data was encompassed. This process was repeated for the remaining speed groups. The post HOC analysis of walking speeds allowed for the formation of relatively equal groupings of trials across speed conditions (Table 4).

Temporal-spatial Parameters

Significant differences (p<0.002) were found in the mean values of temporal-spatial variables across all speed conditions (Tables 3 and 5). As gait speed increased, mean stride length increased from 103.68 cm (very slow) to 166.80 cm (very fast), the mean percentage of the gait cycle at which toe off occurred decreased from 66.33% (very slow) to 59 9% (very fast), and mean single leg stance phase duration increased from 35.02% (very slow) to 41.1% (very fast) of the gait cycle. In addition, cadence increased from 106.10 steps per minute (very slow) to 171.23 steps per minute (very fast).

Joint angles

Descriptive statistics for joint angle measurements as a function of speed are provided in Table 3. Significant pairwise comparisons between speed conditions are listed in Table 5. Significant differences (p<0.002) in the mean maximum dorsiflexion and plantar flexion angles were found between speed conditions for the foot with respect to the tibia and calcaneus with respect to the tibia (Tables 3-5 and Figure

1). As walking speed increased, the mean maximum dorsiflexion angle (foot with respect to tibia) decreased from 11.02° (very slow) to 7.77° (very fast), while the maximum plantar flexion angle increased from 15. 05° (very slow) to 22.73° (very fast). The calcaneus, with respect to the tibia, exhibited similar results (Figure 1) with a significant decrease in the mean dorsiflexion angle from 8.74° (very slow) to 6.08° (very fast), and a significant increase in mean the maximum plantarflexion angle from 11.38° (very slow) to 17.17° (very fast). Significant differences in mean maximum joint angles were also found between speeds for the mid foot relative to the calcaneus and the forefoot relative to the calcaneus (Figure 1). As walking speed increased, the mean maximum mid foot-calcaneus plantar flexion angle increased from 8. 80° (very slow) to 10.52° (very fast). The forefoot with respect to the calcaneus demonstrated similar results with an increase in the mean maximum plantarflexion angle from 10. 83° (very slow) to 13.60° (very fast). Mean relative angles as a function of gait speed are provided in Figures 2 and 3. In the sagittal plane, significant differences (p<0.002) in the mean maximum absolute angles of the metatarsals and the hallux were found between gait speeds(Figure 4 and Tables 3 and 5). The mean maximum absolute angle for the fifth metatarsal (V2G) increased from 68.50° (very slow) to 86.60° (very fast), while the mean maximum angle for the second metatarsal (S2G) increased from 93.27° (very slow) to 111.30° (very fast).

The maximum absolute sagittal plane angle for the hallux (F2Ps) increased from 45.05° (very slow) to 51.86° (very fast) as gait speed increased. The medial longitudinal arch (MLA) showed significant changes in mean maximum angle as a function of speed, decreasing from 158.31° (very slow) to 154.97° (very fast). Figure 5 shows mean absolute joint angles across speed conditions. Mean time to maximum angles, as a percentage of gait cycle, were significantly different ($p<0.002$) for all measures except time to maximum mid foot-calcaneus eversion, and time to maximum forefoot-mid foot eversion (Tables 3 and 5). Across the 5 gait speeds, there was a decrease in the timing to maximum joint angle values as gait speed increased.

Discussion

There have been numerous studies on the effects of walking
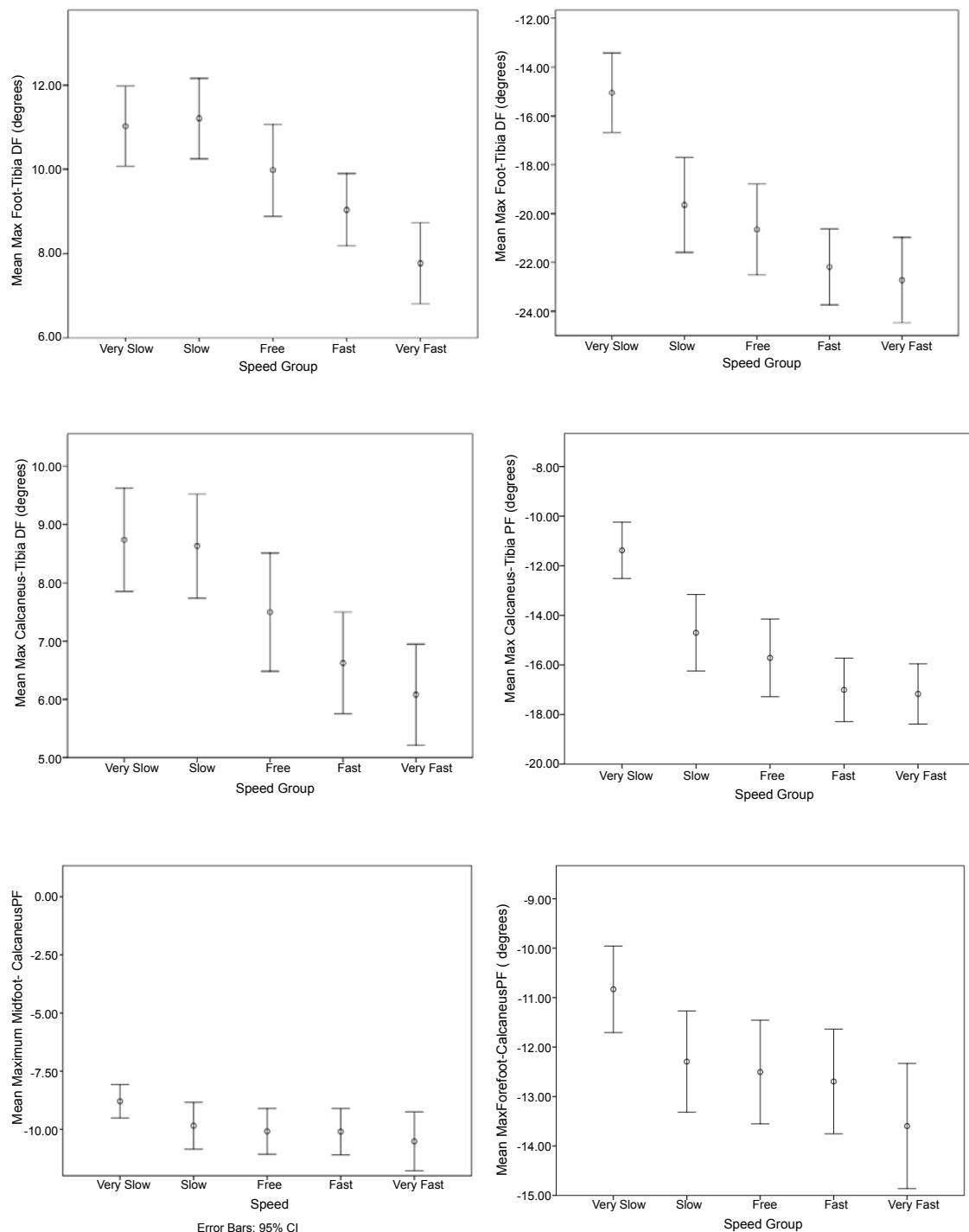
Figure 1: Mean maximum relative angles with 95% confidence interval for 5 gait speeds.

speed on lower extremity kinematics and kinetics [1-2,4,6,16-18]. Despite increases in the number of studies using multi-segment foot models, few studies have examined changes in multi-segment foot kinematics as a function of walking speed. Such data could be useful when comparing kinematic results between studies involving differing walking speeds and for clinical gait studies. Therefore, the purpose of this study was to determine the effects of walking speed on multi-segment foot kinematics in healthy adults. No significant differences ($p<0.05$) in multi-segment foot kinematics were found as a function of gender or limbs (left/right), therefore, the kinematic data was pooled
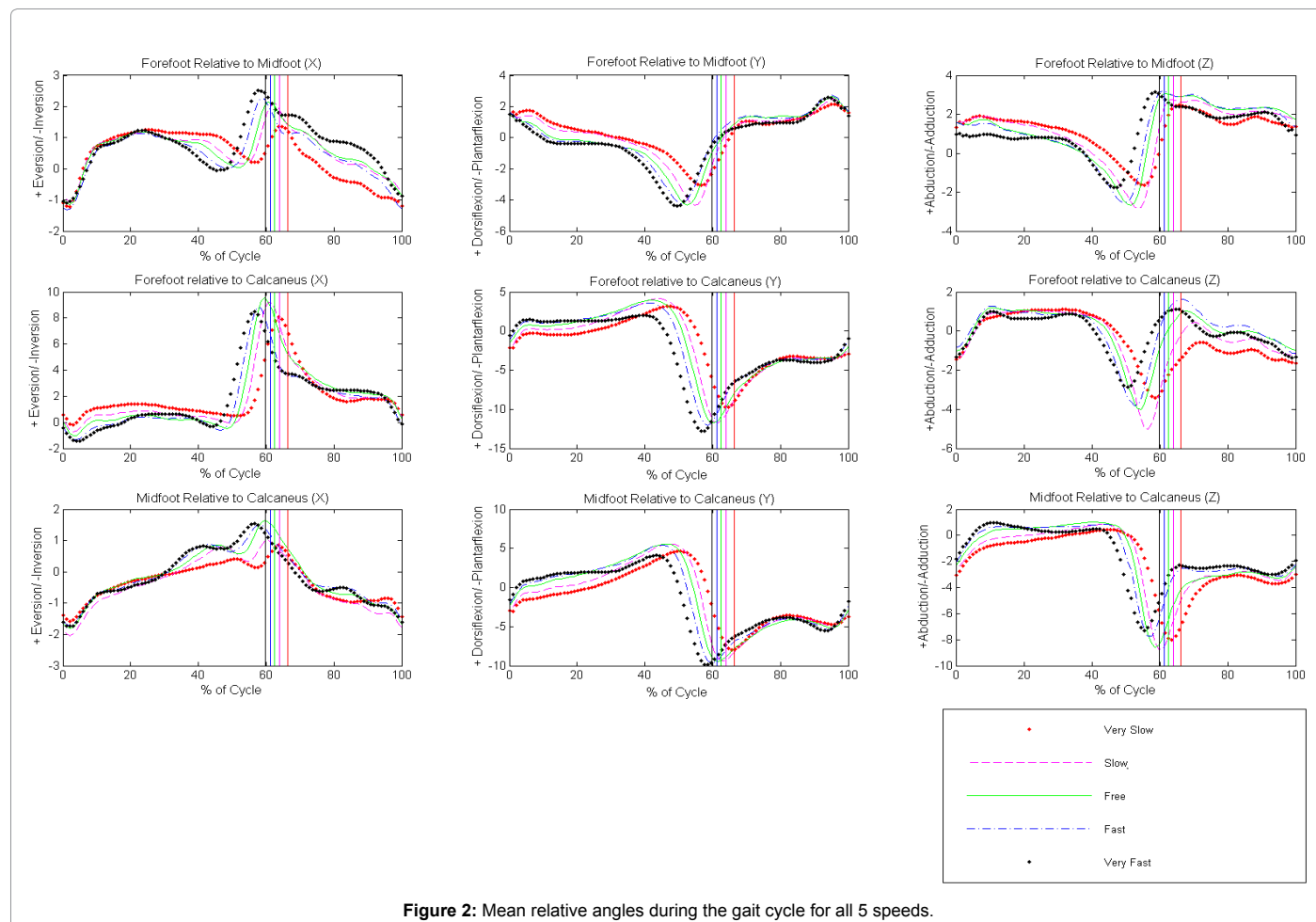

Figure 2: Mean relative angles during the gait cycle for all 5 speeds.

for all subsequent analyses. Data was collected across a wide range of walking speeds, from 0.6 m/s to 2.9 m/s.

Temporal-spatial data

As expected, all of the temporal-spatial variables showed significant differences with changes in walking speed (Tables 3 and 5) ($p<0.002$). As gait speed increased, time to toe-off decreased from 66.33% to 59.90%, single leg stance time increased from 35.02% to 41.1% of the gait cycle, stride length increased from 103.6 cm to 166.8 cm and cadence increased from 106.10 to 171.23 steps/min. Similar results were found by previous researchers [5-6,12].

Joint Angle Data

Variation in walking speed significantly affected the magnitude and timing of the relative and absolute angles of the foot. All significant changes in the magnitude of angles occurred in the sagittal plane only. The relative angles between the calcaneus and tibia showed significant ($p<0.002$) changes in both dorsiflexion and plantar flexion as a function of gait speed (Tables 3 and 5 and Figures 1 and 3). As speed

increased, the mean maximum dorsiflexion angle decreased from 8.74° at very slow to 6.08° at very fast and the mean maximum plantar flexion angle increased from 11.38° at very slow to 17.17° at very fast. Similarly, Dubbeldam et al. [12] analyzed the talus with respect to the tibia and found that plantar flexion angles increased at toe-off as gait speed increased. In the present study, a plateau effect was observed between the very slow and slow speed groups for the mean maximum dorsiflexion angle and between the very fast and fast speed groups for the mean maximum plantar flexion angle. Similar results were found by Schwartz et al. [6] for mean ankle dorsiflexion at toe-off between the slow and slow speeds. It is possible that the point at which the angle plateau occurs may represent a structural limitation in the joint or the magnitude of separation between speeds is not sufficient to alter joint motion. Small but significant changes in mean maximum plantar flexion of the mid foot relative to the calcaneus was found across walking speeds (Tables 3 and 5 and Figures 1 and 2). The maximum plantar flexion of the mid foot-calcaneus changed from 8.8° at very slow to 10.52° at very fast. Dubbeldam et al. [12] also included the mid foot segment in their study but did not find significant differences in sagittal plane motion with changes in walking speed. However, they did
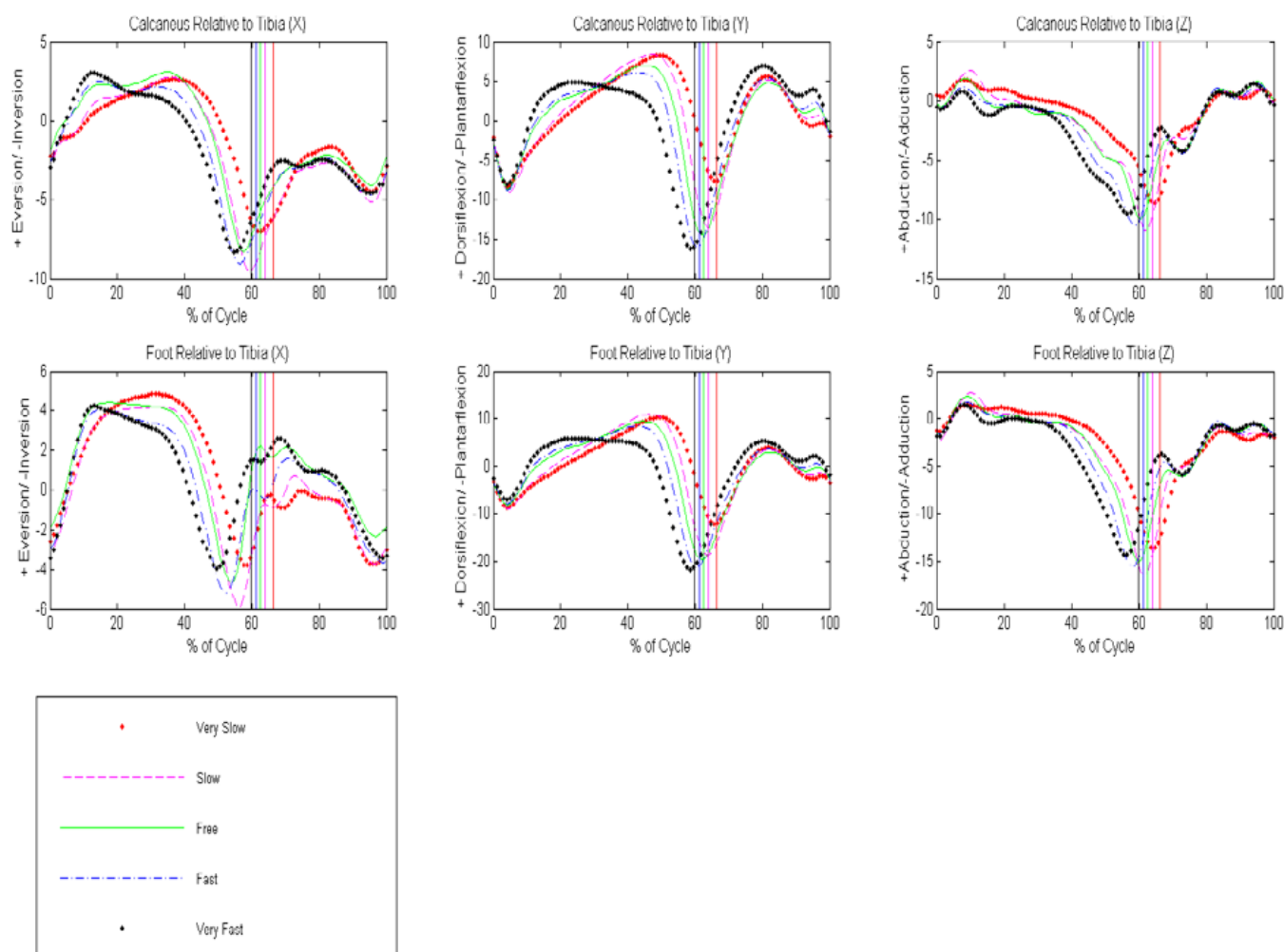
Figure 3: Mean relative angles during the gait cycle for all 5 speeds.

find that pronation of the mid foot relative to the calcaneus increased during midstance with a reduction in gait speed. There were significant differences in the mean maximum plantar flexion angles of the forefoot with respect to the calcaneus across speeds (Tables 3 and 5 and Figures 1 and 2). The mean maximum plantar flexion angle changed from 10.83° at very slow to 13.6° at very fast walking speeds. Only small changes in the mean maximum angle were observed between the slow, free, and fast walking speed conditions. Tulchin et al. [5] reporteda mean maximum forefoot-calcaneus plantar flexion angle of approximately 12° at very slow to approximately 17° at the very fast walking speed. Differences in walking speeds and the anatomical landmarks used to define the forefoot segment between studies may have contributed to the differential results.

The relative angles of the foot with respect to the tibia (foot as a single segment) showed similar results to that of the calcaneus relative to the tibia (Tables 3 and 5 and Figures 1 and 3). As gait speed increased, mean maximum dorsiflexion angle in the present study decreased from 11.02° at very slow to 7.77° at very fast. Similar results were found by Schwartz et al. [6] and Tulchin et al. [5]. In addition,

as gait speed increased, there was an increase in the mean maximum plantar flexion angle from 15.05° at very slow to 22.73° at very fast. This range is similar to that reported by Tulchin et al. [5], where the mean plantar flexion angle was approximately 15° at the very slow speed and approximately 25° at the very fast speed. Schwartz et al. [6] reported a mean plantar flexion angle of approximately 4°, at a very slow speed, and approximately 22° at a very fast speed. Differences in results at the slower speeds may be due to the varying walking speeds between studies.

There were significant changes in the mean maximum absolute angles as a function of gait speed (Tables 3 and 5 and Figures 4 and 5). The maximum S2G angle increased from 93.27° at very slow to 111.3° at very fast, while the maximum V2G angle increased from 68.5° at very slow to 86.6° at very fast. This increase in S2G and V2G indicated that the proximal end of metatarsals 2 and 5, were rotating towards the distal end of the foot as the foot progressed forward towards toe-off. The mean maximum value of F2Ps, dorsiflexion of the hallux, also increased from 45.05° at very slow to 51.86° at very fast as gait speed increased. As gait speed increased the mean minimum MLA angle
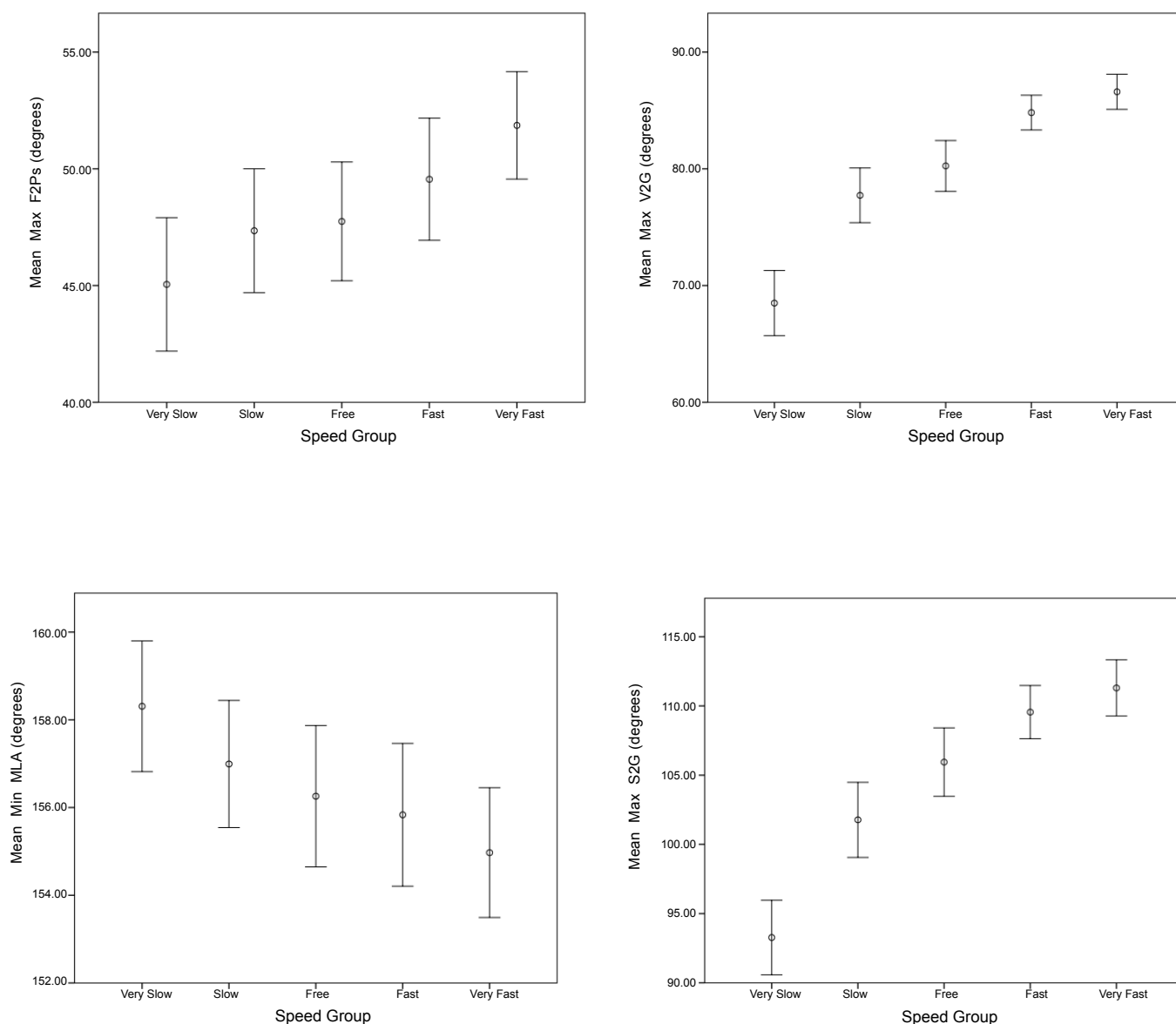
Figure 4: Mean maximum absolute angles with 95% confidence interval for 5 gait speeds.

changed from 158.31° at very slow to 154.97° at very fast. Similar results were reported by Dubbeldam et al. [12] for hallux dorsiflexion and the medial longitudinal arch angle.

Mean time to maximum angles, as a percentage of gait cycle, were significantly different (p<0.002) for all measures except time to maximum mid foot-calcaneus eversion, and time to maximum forefoot-mid foot eversion (Tables 3 and 5). As expected, mean time to maximum angles decreased as gait speed increased reflecting decreased stance phase duration. The lack of difference in timing for eversion is likely associated with the very small amount of motion between the foot segments in this direction of rotation. Tulchin et al. [5] also found that the timing to maximum hind foot dorsiflexion with respect to the tibia occurred earlier in the gait cycle as gait speed increased.

There are several limitations that must be acknowledged. First, ranges of walking speed may be achieved through numerous mechanisms. In the present study, verbal instructions (e. g. "walk fast" or "walk faster") were used to promote changes in walking speed for each subject. Compared to using treadmills or metronomes, it was hoped that this method would facilitate more natural gait patterns at each speed. The post hoc determination of speed groups (e. g. very fast vs. fast) also led to some unbalanced data. That is, some subjects had multiple trials (e. g. their slow and very slow trials) in the same speed group. This suggests that a greater separation may be needed between speeds. Finally, the walking speeds observed in the present study may not reflect those associated with certain gait impairments. Specifically, slower speeds may need to be examined in order to fully understand the impact on multi segment foot kinematics.

Few studies have examined the effects of walking speed on multi segment foot kinematics. Similar to the single rigid body model, walking speed was found to affect multi segment foot kinematics.
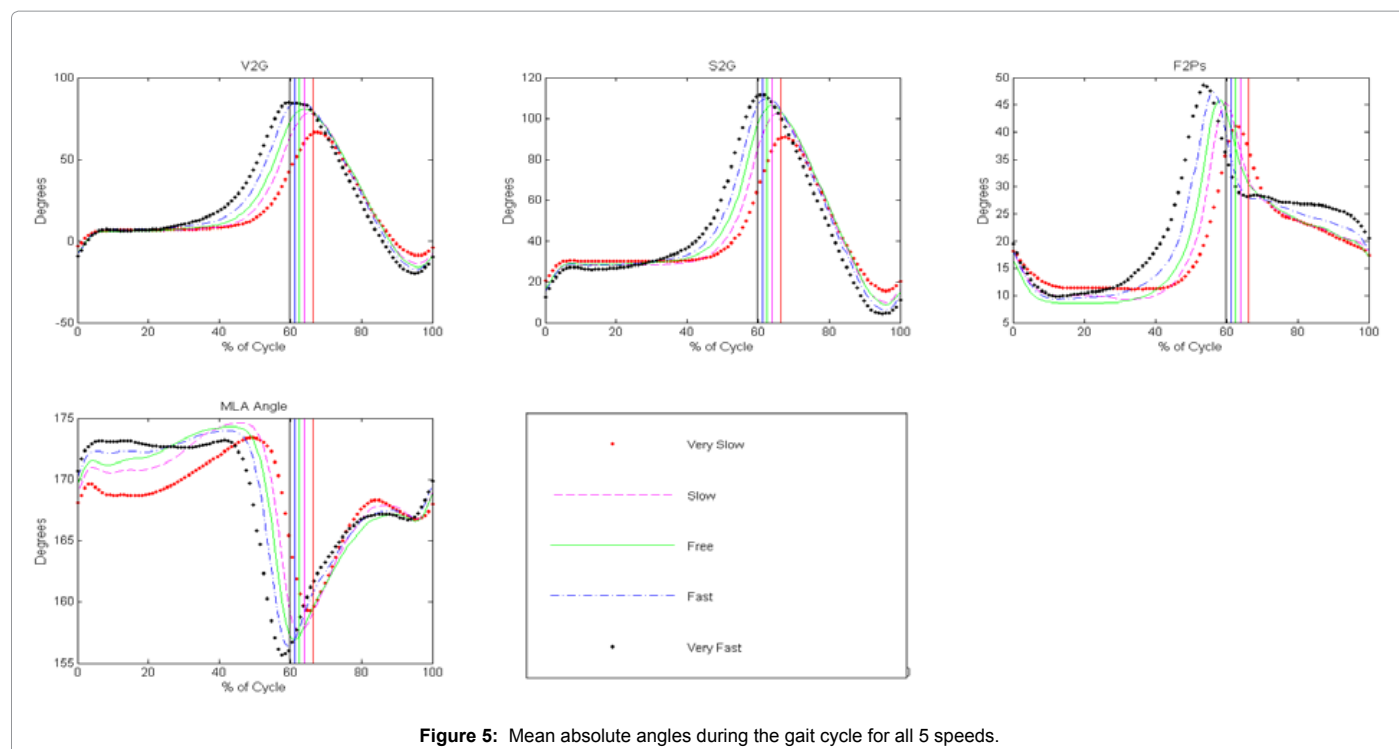
Figure 5: Mean absolute angles during the gait cycle for all 5 speeds.

These results have important implications for studies examining foot and ankle function in typical and atypical populations. The results suggest that speed-matched control data should be used for the analysis of multisegment kinematics, especially in clinical populations where walking speed is altered by pathology. Such data will also facilitate a greater understanding of gait deviations and the effects of treatment interventions. Future studies should examine the effects of walking speed on multisegment foot kinematics in varying age groups and clinical populations. In addition, changes in multisegment foot kinematics as a function of speed may be further understood through the examination of kinetic, EMG, and plantar pressure data.

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