THE DEVELOPMENT OF A MULTI-SEGMENT KINEMATIC MODEL OF FOOTWEAR

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INTRODUCTION

In gait analysis, both shoe mounted and skin mounted markers have been used to quantify the movement of the foot inside the shoe (Reinschmidt et al. 1992). However, these models have not been demonstrated as reliable or accurate in shod conditions.

PURPOSE OF THE STUDY

The purpose of this study was to develop an accurate and reliable marker set to describe foot-shoe complex kinematics during stance phase.

METHODS

Sixteen participants, with a mean age of 21.2 yrs (± 2.6 yrs), height of 1.74 m (± 0.07 m) and body mass of 69.6 kg (± 10.3 kg) were recruited. An ASICS OT-Mexico 66 shoe was used. Our marker set (Table 1) and six-degree of freedom model (Cappozzo et al., 1995) defined four segments; the shank (tibia and fibula), the hindfoot (calcaneus), the forefoot (metatarsals 1-5) and the hallux. Markers were palpated through the shoe upper; it is this process that the accuracy phase of this paper explores. Joint kinematics were estimated using a XYZ Cardan sequence (Wu et al., 2002).

To test the accuracy of landmark palpation through the shoe an anterior-posterior and lateral x-ray was taken of the marker set in the barefoot and shod conditions. The co-ordinates of each landmark/marker were digitized and resultant distance calculated in Matlab (2010b, Mathworks, USA) with reference to the lateral malleolus.

Table 1 – Foot-Shoe Marker Set

Segment	Calibration Markers	Tracking Markers
Shank	R Lat Fem Epicondyle	Cluster (4 markers)on
	R Med Fem Epicondyle	distal 1⁄3 of segment
	R Lateral Malleolus	
	R Medial Malleolus	
Hindfoot	R Lateral Malleolus	R Lat Calc
	R Medial Malleolus	R Post-lat calc
	R Styloid Process	R Post-med calc
	R Navicular Tuberosity	R Med Calc
Forefoot	R Styloid Process	R med 1st Met Shaft (proximal)
	R Navicular Tuberosity	R med 1st Met Shaft (distal)
	R 1st Met Head (medial)	R lat 4th met shaft (mid)
	R 5th Met Head (lateral)	
Hallux	R 1st Met Head (medial)	Hallux trihedron
	R 5th Met Head (lateral)	
	R Hallux (apex)	
	R 2nd Toe (apex)	

To determine the reliability of the marker set, participants' attended two data collection sessions and a calibration trial was captured for each rater's marker set application. Five dynamic trials were captured. Kinematic data were captured using a 12 camera VICON MX40 system (Vicon Motion Systems Ltd., Oxford UK) at 100 Hz and processed in Visual3D (C-Motion Inc, USA). The kinematic data were low-pass filtered with a 4th order Butterworth filter at 7 Hz. A local coordinate system (LCS) for each shoe was defined with three fixed markers on the sole of the shoe. The Euclidean distance of each marker from the origin of the LCS was calculated as the

primary measure of reliability (ICC's). Segmental ROM was used as a secondary measure of reliability. Data were extracted at initial contact, loading response, midstance and propulsion.

RESULTS

Absolute error between the shod and barefoot mounted marker ranged from 0.0-3.9mm on the hindfoot and forefoot segments (Table 2). Larger distances were recorded on the hallux (0.1-10.1mm). Intra-rater reliability of the marker set ranged from good to excellent (R = 0.74 - 0.99) for the hindfoot and forefoot, and moderate to excellent for the hallux (R = 0.68 - 0.94).

Table 2 – Marker Placement Accuracy (mm)

Marker Name	View	Barefoot	Shod	S-M Thickness*	AE**
Styl Process	AP (x)	11.5 ± 1.4	18.1 ± 3.9	6.1	0.6
	Lateral (y)	4.0 ± 0.4	14.8 ± 2.8	8.9	1.9
5MTPJ Head	AP (x)	12.0 ± 0.6	22.9 ± 2.4	7.9	3.0
	Lateral (y)	4.9 ± 1.9	14.8 ± 6.0	6.0	3.9
Apex 2nd Toe	AP (x)	1.1 ± 0.7	9.8 ± 2.3	6.8	1.9
	Lateral (y)	4.9 ± 2.9	20.6 ± 3.3	6.3	9.4
2MTPJ Head	AP (x)	2.4 ± 1.1	7.2 ± 3.1	3.5	1.3
	Lateral (y)	7.3 ± 4.3	24.4 ± 3.9	7.4	9.7
Apex Hallux	AP (x)	1.5 ± 0.6	7.5 ± 0.7	5.9	0.1
	Lateral (y)	2.8 ± 1.9	19.2 ± 4.5	6.3	10.1
Med 1MTPJ	AP (x)	13.5 ± 1.2	23.9 ± 1.0	9.7	0.7
	Lateral (y)	6.6 ± 2.0	8.1 ± 0.6	1.0	0.5
Nav Tub	AP (x)	10.0 ± 1.9	14.6 ± 0.7	4.6	0.0
	Lateral (y)	3.8 ± 1.0	7.9 ± 3.0	2.6	1.5

S-M Thickness – distance from shod marker centroid to barefoot marker

****AE*** – Absolute error

Marker placement error of 4 mm between sessions resulted in a more inverted hindfoot at propulsion (2.24˚, P = 0.006). A marker placement error of 6 mm resulted in a more abducted hallux at propulsion (2.6˚, P < 0.001) and toe off (3.1˚, P = 0.002).

DISCUSSION AND CONCLUSION

The accuracy of marker placement was excellent on the hindfoot and forefoot, however this is with respect to literature reporting values for segments other than the foot. Reduced accuracy of landmark palpation on the hallux was identified. In conclusion, we present data to describe the accuracy and reliability of our current marker set.

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