Repeatability of the Oxford Foot Model for Kinematic Gait Analysis of the Foot and Ankle

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repeatability in a four- segmented model. Two healthy subjects were recruited and tested on several days by two examiners. They reported a 95% confidence interval of repeated measures between days ± 0.6° to ± 6.4° and between ratters ± 0.7° to ± 7.0° for the different outcome parameters [2]. For the OFM Curtis et al. performed a repeatability study in eight children and Wright et al. in 17 healthy subjects with mixed results. Nowadays studies with clinical applications are published referring to these repeatability studies. [20-22]. However these studies have some trivial points by using children, one observer and different statistical test. Therefore, there is place for a more detailed evaluation of the repeatability of the OFM in healthy subjects.

This study assessed the repeatability of the OFM in healthy adults. For this study healthy adults were analysed by more than one observer on separate days which was different compared to previous repeatability studies with the OFM [31-33]. This study also assessed the number of trials necessary in one single patient for good results. The result were presented with the intraclass correlation coefficient (ICC), standard error of the measurements with 90% confidence bounds (SEM_{90}) and the minimal differences needed to be considered real (MD) with 95% confidence interval [31,34]. The ROM between forefoot-hindfoot, forefoot-tibia and hindfoot-tibia was presented in this study, because of its clinically importance.

Methods

Study population: Randomly nine healthy subjects (eight males and one female; aged 21-57 years) were recruited for gait analysis of the foot and ankle. Exclusion criteria were a history of ankle or leg injuries/operations, anatomical abnormalities and spinal or neurological injury. All measurements were performed by two independent researchers. They were experienced with the OFM model by training. All subjects signed an informed consent. This study was approved by the medical ethics committee of the Maastricht University Medical Centre (MEC azM/UM).

Equipment: Motion capture was conducted using the VICON system (Vicon Motion Systems Ltd., Oxford, UK). The VICON-system comprised eight cameras (six MX3 and two T20 running at 200 Hz) connected with a computer. A force plate (Kistler 9282E) was used to identify the foot contact with the floor. Reflective markers were placed on specific points on the subjects with regular double sided tape. The placing of the markers was conducted according to the guidelines of the OFM (Table 1). Vicon NEXUS was used to visualize and process the 3D motions.

Protocol: All healthy subjects were measured at the human performance laboratory of Maastricht University on two separate days (three weeks interval). On each test day the subjects were analysed two times with at least one hour between the consecutive tests. The following characteristics were registered: age, weight, height, knee width (measured between the two condyles of the knee), ankle width (measured between the two malleoli of the ankle) and leg length (measured from the RASI/LASI marker to the LMMA/RMMA marker (Table 1). The markers were placed on both legs, following the specification of the OFM with double sided tape (Table 1). After placement of the markers the calibration started. At least one static trial was performed with all 41 markers, with subjects in an anatomic neutral position. Thereafter six markers were removed according to the protocol. These markers were: LMMA/RMMA (medial malleolus), LD1M/RD1M (Medial aspect of the distal 1st metatarsal) and LPCA/ RPCA (Posterior calcaneus). Subsequently dynamic trials were conducted. The subjects were asked to walk barefoot at preferred 'normal' speed. First some practice trials were done. Subsequently, at least eight proper recordings were made during walking. Records were not used for further data output when patients failed to step in the middle of the force plate and when additional small or large steps were made to reach the force plate. The data of one whole step (heel strike or initial contact to toe-off) was divided in two intervals of 50%: the first interval of the step, the loading phase (initial contact/ heel strike – midstance) and the second interval of the step, the push-off phase (midstance-toe-off). Files were saved for further data analysis. All subjects' right feet were measured for outcome parameters. Inter-segment ROM parameters were analysed for the forefoot and hindfoot, forefoot and tibia and hindfoot and tibia in all the planes (sagittal, frontal and transverse, representing respectively flexion/extension, abduction/adduction and inversion/eversion) in the foot and ankle during walking [35,36] (Table 2). After the first session of this protocol performed by observer one all markers were removed. After one hour the second observer, blinded from the first, repeated the protocol.

Markers: Total of 41; 1 Centred and 20 Bilateral	
Marker diameter: 15 mm.	
Name	**Placing**
SACR	Sacral marker: middle of sacrum
RTHI/LTHI	Thigh: half of a straight line between major trochanter and RKNE/LKNE
RASI/LASI	Anterior iliac spine
RKNE/LKNE	Knee: lateral joint space of the knee
RHFB/LHFB	Head Fibula: placed directly on the proximal head of the fibula
RTUB/LTUB	Tuberosity: tuberosity of the tibia
RTIB/LTIB	Tibia: lateral on a straight line between marker RKNE/LKNE and RANK/LANK
RSHN/LSHN	Shin: anterior on the middle of the tibia
RPCA/LPCA	Posterior calcaneus
RANK/LANK	Ankle: lateral malleolus
RMMA/LMMA	Medial malleolus: medial aspect on malleolus
RCPEG/LCPEG	Wand marker on the heel pointing in cranial direction
RHEE/LHEE	Heel: on the most distal aspect of the heel
RSTAL/LSTAL	Sustentaculum tali
RLCA/LLCA	Lateral calcaneus
RP5M/LP5M	Proximal 5th metatarsal: lateral aspect
RD5M/LD5M	Distal 5th metatarsal: lateral aspect
RTOE/LTOE	Toe: on dorsum of the foot between phalanges 2 and 3
RHLX/LHLX	Base of hallux
RD1M/LD1M	Medial aspect of the distal 1st metatarsal

RP1M/RP1M	Medial aspect of the proximal 1st metatarsal

Table 1: Marker placement.

The marker placement was performed with great care by the experienced observers. During calibrating in the stance phase axes of the knee and ankle were determined by the OFM model according the placement of markers. Small errors in these axes of the knee and ankle in stance phase can give error in the results. A small error in axes can lead to higher or lower flexion/extension between two segments and these errors can accumulate in ROM for abduction/adduction and inversion/eversion. This is caused by the manner of calculations of the ROM [35]. The important markers for the axes determination are placed on the side of each leg (LTHI/RTHI, LKNE/RKNE, LTIB/RTIB) and not linked to a specific anatomical bony landmark. Therefore the correct place for the markers is difficult to determine. By using the knee alignment correction in VICON NEXUS corrections in knee and ankle axes were performed to correct small mistakes, for a few millimetres [16]. The corrections were established after the recordings if axes were found to be incorrect by the examiner. The corrections were established in both static trials and dynamic trials. Axes in the dynamic trials were corrected on the moment of heel landing. Piazza et al. described an error which can occur when adapting these axes. The so called 'screw-home motion' of the knee can occur, when axes are incorrect. The axes of the knee can make a screw motion during gait leading to wrong results and errors [37]. All nine files of the nine healthy subjects were examined for the presence of this 'screw-home motion' during gait. None were found and all files of the healthy subjects were used for further data output.

	Loading phase	**Push-off phase**
Forefoot-hindfoot		
Sagittal plane (flexion/extension)	Dorsiflexion	Dorsiflexion
Frontal plane (abduction/adduction)	Abduction	Abduction
Transverse plane (inversion/eversion)	Supination	Supination
Forefoot-tibia		
Sagittal plane (flexion/extension)	Dorsiflexion	Dorsiflexion
Frontal plane (abduction/adduction)	Abduction	Abduction
Transverse plane (inversion/eversion)	Inversion	Inversion
Hindfoot-tibia		
Sagittal plane (flexion/extension)	Dorsiflexion	Dorsiflexion
Frontal plane (abduction/adduction)	Abduction	Abduction
Transverse plane (inversion/eversion)	Inversion	Inversion

largest error of measurement was seen between the hindfoot-tibia in the frontal plane (abduction/adduction) during push-off phase. The MD ranged from 1.44° to 4.21° in the loading phase of gait and ranging from 1.94° to 7.65° in the push-off phase indicating that a large increase or decrease in ROM is necessary to see a significant difference in one healthy adult.

Loading phase

	Day 1 Examiner 1	Day 1 Examiner 2	Day 2 Examiner 1	Day 2 Examiner 1
Forefoot-hindfoot				
Sagittal plane (flexion/extension)	8.54 ± 2.52 (5.95-11.99)	8.59 ± 2.6 (5.22-11.77)	9.25 ± 3.86 (5.95-16.69)	8.97 ± 3.97 (4.43-16.17)
Frontal plane (abduction/adduction)	4.21 ± 1.13 (2.33-5.35)	4.40 ± 1.31 (2.55-6.28)	4.95 ± 1.13 (3.14-6.98)	4.74 ± 1.07 (2.51-6.19)
Transverse plane (inversion/eversion)	7.17 ± 1.17 (5.25-8.77)	8.05 ± 1.83 (5.78-10.66)	7.83 ± 2.02 (4.76-12.14)	7.92 ± 2.50 (4.33-13.34)
Forefoot-tibia				
Sagittal plane (flexion/extension)	14.68 ± 2.82 (11.11-18.81)	15.23 ± 2.90 (9.74-19.01)	14.68 ± 2.59 (9.13-18.70)	15.12 ± 2.80 (8.16-17.55)
Frontal plane (abduction/adduction)	15.92 ± 4.12 (10.01-22.16)	15.99 ± 3.54 (11.76-21.07)	16.67 ± 3.46 (11.97-24.26)	16.84 ± 2.59 (13.68-21.00)
Transverse plane (inversion/eversion)	9.41 ± 3.02 (6.57-16.08)	10.21 ± 2.65 (6.29-15.00)	10.13 ± 2.32 (6.11-13.42)	10.79 ± 2.23 (7.78-13.39)
Hindfoot-tibia				
Sagittal plane (flexion/extension)	10.97 ± 2.94 (7.18-15.40)	10.84 ± 3.27 (6.76-15.75)	12.02 ± 2.34 (8.68-16.17)	11.94 ± 2.64 (7.94-15.78)
Frontal plane (abduction/adduction)	13.55 ± 3.15 (9.11-18.95)	14.03 ± 3.02 (9.21-17.52)	15.30 ± 3.03 (10.98-21.37)	15.15 ± 3.18 (11.26-22.80)
Transverse plane (inversion/eversion)	5.99 ± 2.45 (2.36-10.17)	6.29 ± 2.06 (3.81-10.05)	6.63 ± 1.42 (4.48-8.49)	6.67 ± 1.86 (2.63-9.28)

Push-off phase

	Day 1 Examiner 1	Day 1 Examiner 2	Day 2 Examiner 1	Day 2 Examiner 1
Forefoot-hindfoot				
Sagittal plane (flexion/extension)	17.76 ±4.37 (11.33-26.04)	18.49 ± 5.24 (11.13-26.19)	18.29 ± 5.95 (9.57-26.42)	17.44 ± 4.60 (8.64-24.17)
Frontal plane (abduction/adduction)	11.67 ± 2.28 (8.90-14.94)	11.82 ± 3.46 (7.05-17.98)	11.61 ± 2.63 (7.92-14.24)	12.30 ± 2.96 (7.59-16.08)
Transverse plane (inversion/eversion)	7.42 ± 2.18 (4.76-10.65)	8.70 ± 1.95 (5.65-11.77)	9.05 ± 2.89 (5.88-13.86)	9.51 ± 2.17 (6.35-13.20)
Forefoot-tibia				
Sagittal plane (flexion/extension)	29.07 ± 6.26 (19.97-41.40)	29.90 ± 6.11 (24.32-42.00)	30.62 ± 7.39 (20.45-41.13)	29.65 ± 6.35 (20.72-39.20)
Frontal plane (abduction/adduction)	13.51 ± 5.38 (5.41-22.11)	13.92 ± 5.11 (7.62-22.05)	14.78 ± 5.16 (8.62-24.95)	14.48 ± 5.83 (7.77-25.95)
Transverse plane (inversion/eversion)	15.39 ± 4.78 (11.24-24.18)	16.96 ± 3.68 (12.38-24.13)	16.67 ± 2.62 (12.19-19.98)	16.52 ± 2.97 (11.98-21.24)
Hindfoot-tibia				
Sagittal plane (flexion/extension)	12.19 ± 3.13 (8.54-16.93)	12.59 ± 2.88 (9.62-19.01)	13.03 ± 3.69 (7.95-19.83)	12.70 ± 4.08 (6.75-18.84)
Frontal plane (abduction/adduction)	11.54 ± 2.58 (7.51-14.85)	12.12 ± 3.05 (6.13-16.05)	11.08 ± 2.89 (6.86-14.92)	10.78 ± 3.79 (5.85-18.52)
Transverse plane (inversion/eversion)	9.87 ± 3.07 (3.53 [illegible] 6.p			

the ICC's in the frontal (abduction/adduction) and transverse plane (inversion/eversion) will be lower as seen in this study.

Inter-observer repeatability						
Loading phase				Push-off phase		
	ICC range	SEM_{90} variability (deg)	MD variability (deg)	ICC range	SEM_{90} variability (deg)	MD variability (deg)
Forefoot-hindfoot						
Sagittal plane (flexion/extension)	0.93-0.96	1.57-1.82	2.66-3.08	0.81-0.92	2.15-3.39	4.66-5.93
Frontal plane (abduction/adduction)	0.53-0.91	0.85-1.75	1.44-2.97	0.73-0.89	0.92-1.46	3.63-4.43
Transverse plane (inversion/eversion)	0.84-0.96	1.05-1.49	1.77-2.52	0.19-0.64	3.05-3.53	3.33-4.6
Forefoot-tibia						
Sagittal plane (flexion/extension)	0.95-0.95	1.41-1.49	2.28-2.52	0.74-0.83	2.74-3.20	5.43-7.65
Frontal plane (abduction/adduction)	0.92-0.94	2.00-2.18	3.38-3.69	0.72-0.89	2.94-3.84	3.58-3.71
Transverse plane (inversion/eversion)	0.88-0.91	1.60-2.31	2.72-3.91	0.74-0.90	1.80-3.21	2.47-6.38
Hindfoot-tibia						
Sagittal plane (flexion/extension)	0.95-0.97	1.25-1.30	2.11-2.19	0.84-0.85	2.44-2.82	3.74-6.15
Frontal plane (abduction/adduction)	0.88-0.95	1.61-2.49	2.72-4.21	0.64-0.86	2.80-4.40	1.94-3.24
Transverse plane (inversion/eversion)	0.65-0.95	1.18-2.26	2.00-3.83	0.52-0.89	1.56-3.17	3.05-3.80
Intra-observer repeatability						

Through the last decades many different multi-segment protocols and models for the kinematic analysis of the foot have been designed [2-16]. The results of the current study are comparable to others studies to the repeatability of the OFM. Carson et al. analysed the repeatability in a four- segmented model. Two healthy subjects were recruited and tested on several days by two examiners. They reported a 95% confidence interval of repeated measures between days of ± 0.6° to ± 6.4° and between ratters of ± 0.7° to ± 7.0° for the different outcome parameters. (2) They found the highest differences in

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