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Repeatability of a Multi-segment Foot Model with a 15-Marker Set in Normal Children

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Background: The use of three-dimensional multi-segment foot models (3D MFMs) is increasing since they have superior ability to illustrate the effect of foot and ankle pathologies on intersegmental motion of the foot compared to single-segment foot model gait analysis. However, validation of the repeatability of the 3D MFMs is important for their clinical use. Although many MFMs have been validated in normal adults, research on MFM repeatability in children is lacking. The purpose of this study is to validate the intrasession, intersession, and interrater repeatability of an MFM with a 15-marker set (DuPont foot model) in healthy children.

Methods: The study included 20 feet of 20 healthy children (10 boys and 10 girls). We divided the participants into two groups of 10 each. One group was tested by the same operator in each test (intersession analysis), while the other group was tested by a different operator in each test (interrater analysis). The multiple correlation coefficient (CMC) and intraclass correlation coefficient (ICC) were calculated to assess repeatability. The difference between the two sessions of each group was assessed at each time point of gait cycle.

Results: The intrasession CMC and ICC values of all parameters showed excellent or very good repeatability. The intersession CMC of many parameters showed good or better repeatability. Interrater CMC and ICC values were generally lower for all parameters than intrasession and intersession. The mean gaps of all parameters were generally similar to those of the previous study.

Conclusions: We demonstrated that 3D MFM using a 15-marker set had high intrasession, intersession, and interrater repeatability in the assessment of foot motion in healthy children but recommend some caution in interpreting the hindfoot parameters.

Keywords: *Gait analysis, Repeatability, Multi-segment foot model*

Several three-dimensional multi-segment foot models (3D MFMs) have been developed for the analysis of dynamic foot kinematics.[1-11] The use of such 3D MFMs is increasing since they have superior ability to illustrate the effect of foot and ankle pathologies on intersegmental motion of the foot compared to single-segment foot model gait analysis.[4,12-15] However, considering the concerns about its reliability, validation of the repeatability of the 3D MFMs is important for their clinical use.[16,17] Although many MFMs have been validated in normal adults, research on MFM repeatability in children is still lacking.[18-23]

A 3D MFM using a 15-marker set (DuPont foot model [DFM]) was recently proposed by Henley and Miller[4,7,24] and was demonstrated to have comparable intrasession and intersession repeatability to those of other MFMs.[25] Segmental foot motion indices at the midstance phase during gait measured using this model were correlated with the conventional radiographic indices.[26] However, although validated in healthy adults, this model should also be validated in children prior to being used to assess the intersegmental motion of the foot in pediatric patients. The purpose of this study was to determine the reliability of DFM with a 15-marker set by assessing the

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subject's stride-to-stride (intrasession), visit-to-revisit (intersession), and observer-to-observer (interrater) repeatability in normal children.

METHODS

Subjects

This study was approved by Institutional Review Board of Seoul National University Hospital (IRB No. 1212-015-447). In this study, volunteers were recruited from the local area and all participants and their guardians provided written informed consent prior to participation. All participants were tested at the Laboratory of Human Motion Analysis in Seoul National University Hospital. The inclusion criteria of this study were as follows: (1) no history of fracture or surgery on the lower extremities; (2) no subjective symptoms during gait; (3) no abnormal findings on a simple radiograph of the foot; (4) no history of a general medical condition related to gait; and (5) normal function of the foot and ankle (American Orthopedic Foot and Ankle Society ankle-hindfoot score of 100 points). In a clinical examination, the alignment and range of motion (ROM) of the lower extremity joints (hip, knee, and ankle) were evaluated and a simple radiograph was checked by two orthopedic surgeons (HSS, JHL) to exclude abnormal conditions of the lower extremities.

Participating subjects included 20 healthy children (10 boys and 10 girls) with 10–15 years of age. Demographic data of the participating subjects are presented in Table 1. The mean age was 12.2 years (range, 11 to 15 years) in boys and 11.1 years (range, 10 to 13 years) in girls. The mean weight was 43.4 kg (range, 30.4 to 76.8 kg) in boys and 43.7 kg (range, 35.8 to 61.1 kg) in girls. The mean height was 149.4 cm (range, 139.4 to 167.2 cm) in boys and 149.7 cm (range, 142.8 to 157.8 cm) in girls. The mean body mass index was 19.1 kg/m^2 (range, 15.6 to 31.8 kg/m^2) in boys and 19.4 kg/m^2 (range, 16.5 to 24.5 kg/m^2) in girls. The mean foot length was 22.7 cm (range, 21.6 to 25.2 cm) in boys and 22.5 cm (range, 21.7 to 25.0 cm) in girls. At last, the mean foot width was 9.2 cm (range, 8.3 to 10.6 cm) in boys and 9.0 cm (range, 8.3 to 9.9 cm) in girls. The data of the right foot were selected for the statistical analysis.

Table 1. Demographic Data of Participating Subjects

Variable	Male	Female
Demographic measurement		
Age (yr)	12.2 (11–15)	11.1 (10–13)
Height (cm)	149.4 (139.4–167.2)	149.7 (142.8–157.8)
Weight (kg)	43.4 (30.4–76.8)	43.7 (35.8–61.1)
Body mass index (kg/m^2)	19.1 (15.6–31.8)	19.4 (16.5–24.5)
Foot measurement		
Foot length (cm)	22.7 (21.6–25.2)	22.5 (21.7–25.0)
Foot width (cm)	9.2 (8.3–10.6)	9.0 (8.3–9.9)

Values are presented as mean (range).

Marker Set

The DFM examined here is composed of 15 optoreflective markers that were attached to the anatomical landmarks of each knee, tibial shank, ankle, and foot. It is the same model examined previously in a normal adult population,[25] but smaller markers were used for the pediatric participants. This system has six additional markers per foot than the conventional Cleveland Clinic Marker Set. The markers were placed as described below.

Five markers were placed around the knee and tibial shank for calculation of the shank coordinate system. Four markers were placed on the ankle and hindfoot (one on the medial malleolus, one on the lateral malleolus, and two on the calcaneus), two on the midfoot (navicular and cuboid), and four on the forefoot (three on the metatarsals and one on the hallux). A more detailed description of the marker placement is provided in Table 2 and shown in Fig. 1.[7] All marker placements were made by two operators: one was involved in the previous study of healthy adults and thus was experienced in marker placement; the other had experience handling the conventional Cleveland Clinic Marker Set with reference to the standardized protocol using photography and had no experience in placing these markers.

Experimental Procedures

The experimental procedures were the same as those in previous studies.[25,26] First, we explained the procedures and obtained written consent. We then collected each participant's demographic data including height, body weight, and foot length and width. The participants completed a 5-minute warm-up protocol of comfortable walking. After that, each child underwent attachment of the optoreflective markers to each foot and lower extremity. The subjects walked at a comfortable speed along an 8-m walkway. For static calibration, we took data for a static standing trial with the individual in the anatomical position. To collect kinematic gait data, we used 12 cameras with a 3D optical motion capture system (Motion Analysis, Santa Rosa, CA,

Table 2. Marker Placement of a Multi-segment Foot Model with 15-Marker Set (DuPont Foot Model)

Name of marker	Position of marker
Knee medial	In the middle of the medial knee joint line
Knee lateral	In the middle of the lateral knee joint line
Shank upper	Apex of the triangle at the lateral mid-point of lower leg
Shank front	Lower front of the triangle at the lateral mid-point of lower leg
Shank rear	Lower rear of the triangle at the lateral mid-point of lower leg
Ankle medial	Apex of the medial malleolus
Ankle lateral	Apex of the lateral malleolus
Heel proximal	Midpoint of the posterior aspect of the calcaneus at the height of the hallux marker
Heel distal	Midpoint of the posterior aspect of the calcaneus below the calcaneus 1 marker and just above the fat pad
Navicular	The most prominent point of the navicula
Cuboid	Just proximal and superior to the base of the 5th metatarsal bone
MTH1	Dorsal metatarsal head just proximal to the 1st metatarsophalangeal joint
Toe	Dorsal web space just proximal between the 2nd and 3rd metatarsophalangeal joints
MTH5	Dorsal metatarsal head just proximal to the 5th metatarsophalangeal joint
Hallux	In the middle of the hallux nail bed

Fig. 1. Marker placement of a three-dimensional multi-segment foot model with a 15-marker set. (A) Lateral view of marker placement. (B, C) The hallux marker was placed in the middle of the hallux nail bed and two calcaneus markers were applied to the hindfoot. We used smaller markers than those used in adults.

USA) at a sampling rate of 120 Hz. Eva real-time software (EVaRT, Motion Analysis) was used for real-time motion capturing and post-processing and tracking of the marker data. The difference from our previous study is that we divided participants into two groups of 10 each. One group was tested by the same operator in each test (intersession analysis), while the other was tested by a different operator in each test (interrater analysis). Three representative strides from five separate trials were used for the analysis from each session. Retests were performed at 4-week in-

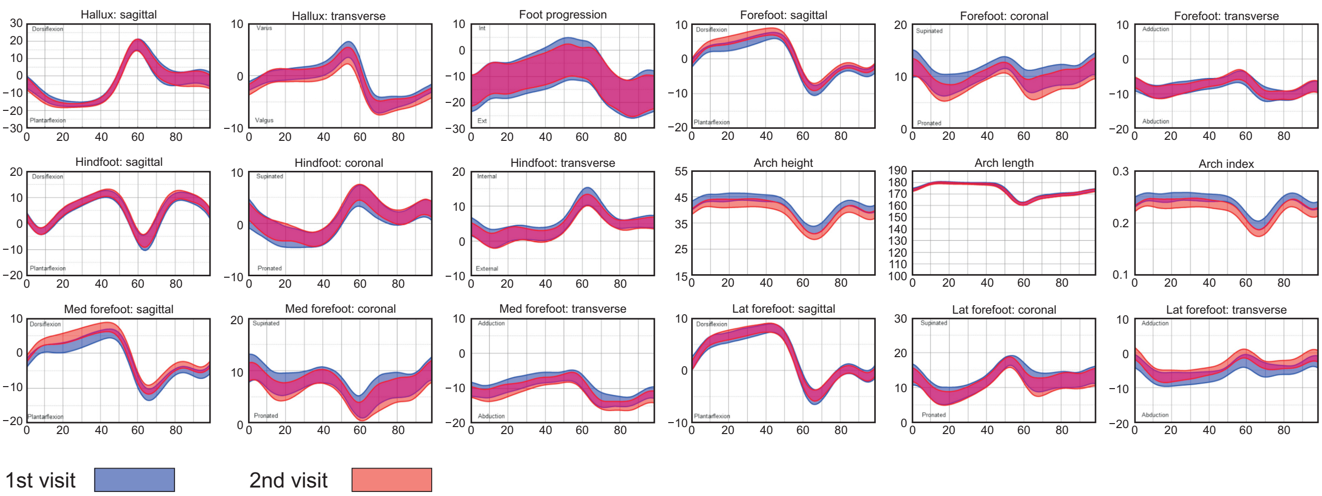

Fig. 2. Walking kinematics for the first and second visits (average with a range representing two standard devistions). Med: medial, Lat: lateral.

tervals to check the repeatability using the same protocol.

Foot 3D Multi-Segment Software (Motion Analysis) was used to collect and track the kinematic data of the foot segmental motion. The definition of coordinate systems based on these markers and the calculation method for joint rotation and arch parameters were described previously.[7,25)]

Data Analysis

In this study, we analyzed the intrasession, intersession, and interrater repeatability of the DFM using 17 parameters. We divided the time points of the gait cycle data into 100 segments (1% interval between time points) for analysis. We gained three representative stride values from five separate trials and the average of the three strides was considered the representative value from each session. The parameter components are hallux (flexion/extension and rotation), hindfoot (flexion/extension, pronation/supination, and rotation), forefoot (flexion/extension, pronation/supination, and rotation), medial forefoot (flexion/extension, pronation/supination, and rotation), lateral forefoot (flexion/extension, pronation/supination, and rotation), and arch parameters (arch height, arch length, and arch index).

The multiple correlation coefficient (CMC) and intraclass correlation coefficient (ICC) were calculated to assess the intrasession repeatability. Intrasession CMC and ICC values were calculated using data from the first session only. The intrasession CMC was calculated from the first two of three selected strides of the first session, while the intrasession ICC was calculated using the three selected strides.

For intersession repeatability, we obtained average data from the three trials for each visit. The intersession CMC and ICC values were calculated in the same-operator testing group. To assess interrater session repeatability, the same analysis was performed in the changed-operator testing group. The difference between the two sessions of each group was assessed for each time point of the gait cycle. Thereafter, the mean, standard error, and confidence interval of the difference were calculated for each group.

The ROM of each foot segment was calculated for each subject. Intrasession, intersession, and interrater ICC were calculated to assess the intrasession, intersession, and interrater repeatability of the ROM measurements. The intrasession ICC was calculated using three selected strides of the first session, while the intersession ICC was calculated using the mean value of each session.

We classified 0.65 ≤ CMC (R) < 0.75 as moderate repeatability, 0.75 ≤ CMC (R) < 0.85 as good repeatability, 0.85 ≤ CMC (R) < 0.95 as very good repeatability, and CMC (R) ≥ 0.95 as excellent repeatability.[27)] We interpreted that an ICC < 0.5 suggests poor repeatability, 0.5 ≤ ICC < 0.75 suggests good repeatability, and ICC ≥ 0.75 suggests excellent repeatability.

RESULTS

Walking kinematics in children for the first and second visits were presented in Fig. 2.

Table 3 presents the intrasession, intersession, and interrater CMC by 1% intervals of the gait cycle. The mean intrasession CMC was 0.933 (standard deviation [SD], 0.034). The intrasession CMC of all parameters except forefoot pronation/supination showed excellent or very good repeatability. The mean intrasession ICC was 0.975

(SD, 0.028). The intrasession ICC of all parameters showed excellent repeatability.

The mean intersession CMC was 0.793 (SD, 0.077). The intersession CMC showed excellent or very good repeatability in hallux flexion/extension, hallux rotation, hindfoot flexion/extension, arch length, and forefoot flexion/extension and good repeatability in hindfoot pronation/supination, arch height, and arch index. However, forefoot pronation/supination and forefoot rotation had moderate repeatability (0.748 and 0.726, respectively), while hindfoot rotation had poor repeatability (0.371). The mean intersession ICC was 0.886 (SD, 0.123). The intersession ICC of all parameters showed excellent repeatability.

The interrater CMC was not presented in the previous study of healthy adults. However, in this study, interrater CMC values of all parameters were calculated. Interrater CMC values were generally lower for all parameters than intrasession and intersession CMC values. Only arch length had an excellent interrater CMC value. Hallux flexion/extension, hindfoot flexion/extension, arch height, arch index, and forefoot flexion/extension had very good interrater CMC values, while hallux rotation, hindfoot pronation/supination, and forefoot rotation had moderate interrater CMC values. On the other hand, hindfoot rotation and forefoot pronation/supination had poor interrater CMC values (0.623 and 0.482, respectively). Table 4 presents mean, standard error, and confidence interval values of the intersession difference of each time point in 1% intervals. The lowest intersession difference was forefoot flexion/extension (2.26°), whereas the highest value was hindfoot rotation (6.51°).

DISCUSSION

In this study, we demonstrated that the MFM (DFM) had substantial intrasession, intersession, and interrater repeatability in healthy children. Although children had

Table 3. Repeatability of Foot Kinematics

Variable	Intrasession CMC		Intersession CMC		Interrater CMC
	This study	DFM[25]	This study	DFM[25]	This study
Hallux					
Flex/Ext	0.962	0.971	0.859	0.769	0.880
Rotation	0.874	0.970	0.955	0.951	0.746
Hindfoot					
Flex/Ext	0.913	0.931	0.923	0.837	0.913
Pro/Sup	0.858	0.890	0.842	0.697	0.664
Rotation	0.892	0.927	0.371	0.728	0.623
Arch					
Height	0.954	0.959	0.788	0.798	0.862
Length	0.980	0.909	0.975	0.980	0.971
Index*	0.950	0.952	0.797	0.729	0.851
Forefoot					
Flex/Ext	0.956	0.978	0.943	0.840	0.888
Pro/Sup	0.786	0.993	0.748	0.687	0.482
Rotation	0.901	0.972	0.726	0.813	0.724

The CMC of intrasession and intersession were calculated and compared with those from previous research in normal adults.
CMC: multiple correlation coefficient, DFM: DuPont foot model, Flex: flexion, Ext: extension, Pro: pronation, Sup: supination.
*Arch index: arch height / arch length.

Table 4. Repeatability of Foot Kinematics (the Gap between Two Sessions)

Intersession difference	This study, mean ± SE (range)	DFM[25]
Hallux (°)		
Flex/Ext	3.99 ± 0.12 (1.65–6.53)	4.0
Rotation	2.58 ± 0.06 (0.72–8.07)	3.6
Hindfoot (°)		
Flex/Ext	2.55 ± 0.05 (1.32–3.92)	1.3
Pro/Sup	3.85 ± 0.04 (0.86–10.22)	4.3
Rotation	6.51 ± 0.10 (1.31–11.32)	3.0
Arch (cm)		
Height	5.84 ± 0.05 (0.41–14.25)	4.9
Length	1.85 ± 0.03 (0.57–6.31)	2.0
Index*	0.03 ± 0.00 (0.00–0.08)	0.03
Forefoot (°)		
Flex/Ext	2.26 ± 0.04 (0.94–4.95)	2.6
Pro/Sup	3.51 ± 0.06 (1.39–9.75)	3.0
Rotation	4.27 ± 0.09 (2.20–7.53)	3.9

The mean intersession difference of intersegmental angle was calculated and compared with that from previous research in normal adults.
SE: standard error, DFM: DuPont foot model, Flex: flexion, Ext: extension, Pro: pronation, Sup: supination.
*Arch index: arch height / arch length.

different gait characteristics compared to adults, the intrasession and intersession CMC values were similar to those of healthy adults.[25]

In general, the repeatability of 3D MFMs is thought to be good in clinical setting in adult populations.[16,25,28] Among the widely used MFMs, the Oxford foot model (OFM), Milwaukee foot model, Heidelberg foot model, and modified Shriners Hospitals for Children Greenville foot model in pediatric populations have been used in previous studies.[18,19,21,23] The repeatability of MFMs is inferior in the pediatric population to that in the normal adult population.[20] In this study, hindfoot flexion/extension, pronation/supination and rotation showed lower intrasession CMC than those from adult study using same DFM model (Table 3). In particular, the intersession CMC of hindfoot rotation was significantly lower than that of adults. However, the intrasession CMC, which was slightly lower than adults, remains in the range of a very good repeatability. The gaps between two sessions in children was larger in all elements of the hindfoot than those of adults (Table 4).

The most contributing factors to increased variability in the pediatric population would be the small size of the foot and the increased gait variability in children.[22] It was difficult to attach the marker in the correct position in small children, leading to higher variability in making a segmental plane. The hindfoot markers are usually most vulnerable to inconsistent placement. This study showed some low CMC values and these values were affected by the markers attached to the hindfoot. In addition, the large gait variability in pediatric patients also affect higher variability in children. The gait of pediatric patients may vary by individual growth and development, while adults generally have a standardized gait. Particularly, in the hindfoot, the start of the stance phase of the walking cycle differs significantly in each individual. Although it is difficult to compare our results directly with other studies due to differences in the definition of axes and protocols, the sagittal plane was most repeatable and the highest variability was found in the transverse plane in a study using the OFM in children,[20] which were similar to our results. The modified Shriners Hospitals for Children-Greenville (mSHCG) foot model was demonstrated to have improved or nearly equivalent standard deviations for the hindfoot and forefoot segments in children when compared with the OFM.[19] However, it is impossible to compare data from the mSHCG foot model with this study because of the difference in the definition of segments and axes.

This study has some limitations. First, the ages of participants were between 10 and 15 years, which might be closer to the ages of adolescents or adults rather than young children. We agree with the belief that accurate marker placement would be more difficult in younger children. The effectiveness of MFMs in younger children still needs to be elucidated further. Second, we found that consistent placement of hindfoot markers would be most important for the repeatability of 3D MFM in children. However, we could not suggest a solution to improve the repeatability of hindfoot measurements in the analysis of segmental foot motions, which needs to be addressed in further research.

The intra- and intersession repeatability of DuPont foot model with a 15-marker set (DFM) in children were comparable to those in healthy adults. However, hindfoot rotation and pronation/supination showed lower intersession/interrater CMCs than those from adult studies using the same DFM model. We believe that the DFM would be applicable for use in the evaluation of intersegmental foot motions in children but careful interpretation is recommended for the hindfoot parameters.

CONFLICT OF INTEREST

No potential conflict of interest relevant to this article was reported.

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