Repeatability analysis of a novel multi-segment model of the foot-ankle complex

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***Abstract*—Reliability of the existing kinematic models of the foot-ankle complex for gait analysis has been shown to be unsatisfying even for healthy adults. The aim of this paper is to propose a novel multi-segment kinematic model of the foot-ankle complex and to quantify the repeatability of its output. The experimental protocol used for the proposed model involved a reduced number of markers to track with respect to the existing models. Joint kinematics repeatability improved in comparison to the results obtained for other existing models fed with the same data. Despite the improvements with respect to the state of art, the results showed that foot kinematics should always be used with care as it is still the least reliable among the lower limb joints' kinematics.**

***Keywords*—Foot kinematics, repeatability, gait analysis.**

I. Introduction

THE observation of the foot-ankle complex is of clinical interest for various pathologies. A comprehensive modelling of the joints within the foot-ankle complex is relevant both for quantitatively assessing its status, and improving rehabilitation therapies [1].

In gait analysis, the foot is typically approximated as a rigid segment linked to the tibia. Although acceptable for some applications, it results unsuitable for problems where the multi-segmental anatomy of the foot cannot be ignored, such as the foot drop. A number of multi-segment models have been proposed in the past twenty years, which have been recently compared in terms of their repeatability in describing the foot and ankle kinematics. This comparison highlighted poor repeatability of the kinematics of the foot-ankle complex even on a healthy population [2]. The aim of this study is to propose a novel multi-segment model for the kinematics of the foot-ankle complex to overcome those limits, and assess its output repeatability.

II. Methods

Data used in this study have been published and used to compare the four most adopted existing models of the foot-ankle complex [2], allowing the comparison between the obtained results and those of the existing models. Data were collected from 13 healthy adults (age: 27.0±1.9 years, heights: 1.83±0.08 m, foot length: 28.5±1.0 cm) during two one month apart sessions by an expert operator. The subjects walked self-paced and barefoot on a treadmill. The kinematic model included four segments: Tibia (Tib), Hindfoot (HiF), Midfoot (MF), and Forefoot (FF), defined using the anatomical landmarks in Table I and Fig. 1. The model was integrated with the Plug-in-Gait model of the lower limb (Vicon Motion System Ltd – Oxford, UK). Variations from existing models included: the exclusion of wand markers; the absence of a joint between forefoot and midfoot, as it only permits a limited sliding between the joints [3]; the use of technical embedded coordinate systems (ECS), defined considering possible deformations of the segment to track during walking, and used to register the anatomical ECS. Segment tracking was performed using a least-square fitting approach [4]. Sagittal joint kinematics of Knee, Hindfoot-Tibia, Midfoot-Hindfoot, and Forefoot-Hindfoot were computed according to [5]. Kinematics repeatability was tested using the Linear Fit Method (LFM), which accounts for scaling (a_1), offset (a_0) and truthfulness of the linear model between the curves (R^2) [6]; and Mean Absolute Variability (MAV) [7] to quantify the absolute differences among curves.

TABLE I
Modelled segments and relevant anatomical landmarks

Segments	*Anatomical Landmarks*
Tibia (Tib)	LM: most prominent apex of the lateral malleolus
	HF: most prominent apex of the head of fibula
	TT: tibial tuberosity
	MM: most prominent apex of the medial malleolus (static only)
Hindfoot (HiF)	CA: posterior aspect of the calcaneus, avoiding the insertion of the Achille's tendon and the heel pad
	PT: peroneal tubercle
	LCA: lateral calcaneus, same height of CA (see also ST)
	ST: on the medial aspect of the calcaneus, at the same height and same distance from CA of LCA
Midfoot (MF)	TN: the prominence of the navicular on the medial aspect of the foot
	C: cuboid, laterally on the foot
	VMBl: on the lateral aspect of the fifth metatarsal base
	SMB: second metatarsal base
Forefoot (FF)	FMBd: on the dorso-medial aspect of the first metatarsal base
	FMH: first metatarsal head
	SMH: second metatarsal head
	VMH: most lateral aspect of the fifth metatarsal head (static only)

III. Results

The range of motion of the sagittal joint kinematics were: 49±13° for the Knee, 15±5° for HiF-Tib, 11±4° for MF-HiF, and 15±5° for FF-HiF. Table II and Table III show the results of the within- and between-subject repeatability, respectively.

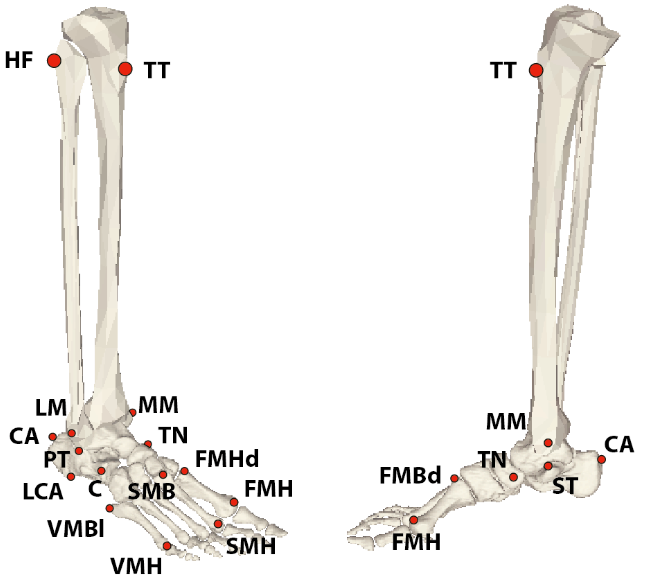

Fig. 1 – THE ANATOMICAL LANDMARKS USED TO DEFINE THE LOCAL EMBEDDED COORDINATE SYSTEMS. LATERAL (LEFT-SIDE) AND MEDIAL VIEW OF THE FOOT (RIGHT-SIDE).

TABLE II
LFM COEFFICIENTS AND MAV OBTAINED FOR THE WITHIN-SUBJECT REPEATABILITY ANALYSIS

Joints	*LFM coefficients*			*MAV (°)*
	a_1	a_0 (°)	R^2	
Knee	1.00 ± 0.08	0 ± 2	0.97 ± 0.04	7 ± 5
HiF-Tib	1.00 ± 0.11	0 ± 1	0.91 ± 0.09	3 ± 1
MF-HiF	1.00 ± 0.17	0 ± 0	0.93 ± 0.07	2 ± 1
FF-HiF	1.00 ± 0.14	0 ± 1	0.95 ± 0.05	2 ± 1

TABLE III
LFM COEFFICIENTS AND MAV OBTAINED FOR THE BETWEEN-SUBJECT REPEATABILITY ANALYSIS

Joints	*LFM coefficients*			*MAV (°)*
	a_1	a_0 (°)	R^2	
Knee	1.00 ± 0.20	0 ± 7	0.91 ± 0.07	27
HiF-Tib	1.00 ± 0.27	0 ± 1	0.69 ± 0.18	8
MF-HiF	1.00 ± 0.35	0 ± 1	0.82 ± 0.12	7
FF-HiF	1.00 ± 0.33	0 ± 3	0.83 ± 0.12	12

IV. DISCUSSION

The experimental protocol used for the proposed model was easier to implement than those analysed in [2], both for the reduced number of markers to be tracked and their visibility. In fact, all the markers were visible to the stereophotogrammetric system, both in static and walking trials, and extensive procedures of gap filling were not needed. Same consideration cannot be made for the medial markers of the models studied in [2]. Joint kinematics repeatability improved in comparison with the results obtained for the existing models using the same data [2]. The LFM correlation coefficient and obtained for the Within-Subject analysis on the joint kinematics MF-HiF, were higher than the model proposed in [8] ($R^2 = 0.77 \pm 0.20$ [2]). Obtained results for the between-subject analysis strengthen this consideration. Indeed, R^2 was higher than those obtained for both models in [8], [9] (0.79 ± 0.15 and 0.51 ± 0.28, respectively [2]). The above considerations prove the proposed modelling of the MF-HiF joint as an improvement of the state of art. The FF-HiF modelled the virtual joint that allows rotations between metatarsals and hindfoot bones, and showed slightly better performance than the existing models both for within- and between-subject analyses [2]. MAVs values obtained from all the joint kinematics estimated using the proposed model were overall comparable to those obtained through the other models [2]. The only exception was found for the MF-HiF with respect to [8], which resulted the least reliable kinematic with a ROM of 5°.

V. CONCLUSION

Despite the obtained improvements, foot kinematics is still the least reliable among the lower limb joints' kinematics, confirming the inadequacy of using normative data to interpret relevant results.

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