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Short communication

Repeatability of a 3D multi-segment foot model protocol in presence of foot deformities

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ABSTRACT

Repeatability studies on 3D multi-segment foot models (3DMFMs) have mainly considered healthy participants which contrasts with the widespread application of these models to evaluate foot pathologies. The current study aimed at establishing the repeatability of the 3DMFM described by Leardini et al. [3] in presence of foot deformities.

Foot kinematics of eight adult participants were analyzed using a repeated-measures design including two therapists with different levels of experience.

The inter-trial variability was higher compared to the kinematics of healthy subjects. Consideration of relative angles resulted in the lowest inter-session variability. The absolute 3D rotations between the Sha-Cal and Cal-Met seem to have the lowest variability in both therapists. A general trend towards higher $\sigma^{sess}/\sigma^{trial}$ ratios was observed when the midfoot was involved.

The current study indicates that not only relative 3D rotations and planar angles can be measured consistently in patients, also a number of absolute parameters can be consistently measured serving as basis for the decision making process.

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1. Introduction

In gait analysis, the use of 3D multi-segment foot models (3DMFMs) has gained popularity in the last decade. Despite this interesting evolution, it should be emphasized that the literature lacks adequate repeatability studies [1,2]. Research groups considering the repeatability of their 3DMFM protocol mainly included healthy participants which contrasts with the major domain of application of 3DMFMs, being the assessment of foot and lower limb pathologies [3]. The latter is important as anatomical landmarks in the deformed and non-deformed foot may be difficult to palpate [4] or even be absent [5,6]. Furthermore, a small shift (e.g. 5 mm) in marker position may result in considerable kinematic differences [7]. Therefore, foot deformities may impede the repeatability of a 3DMFM protocol and thus the clinical utility of this method. Consequently, the main goal of this investigation was to analyze the repeatability of a recently published 3DMFM protocol [3] in presence of a wide variety of foot deformities.

2. Materials and methods

A cohort of eight persons (mean age 48 y ± 15.4), embodying the majority of foot deformities and gait deviations in specialized centers, was recruited. Participants walked at a self selected speed until five 'representative' walking trials were recorded. A representative walking trial was defined at the level of each participant, as some participants did not have a 'typical' walking pattern.

Marker trajectories were acquired using a 10 T-10 camera optoelectronic system (Vicon Motion System Ltd., Oxford Metrics, UK). The 3DMFM protocol proposed by Leardini et al. [8] was adopted in the current study.

A repeated measure design was used where each participant of the cohort underwent eight gait analysis sessions; i.e. four sessions conducted by each of the two staff podiatrists. The first two sessions occurred at the same day (1 h apart). The second day (one week later) again two sessions per subject and therapist was organized. A senior staff podiatrist with experience in 3DMFM protocols and a junior therapist with one year of clinical experience participated in this study in

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order to evaluate the intrinsic robustness of the method. The junior therapist practiced the protocol on seven staff members of the clinic as well as during a similar repeatability study including six healthy subjects [8].

Both relative and absolute 3D rotations and planar angles where quantified. For the former, offset values calculated during a static trial were subtracted from the kinematic waveforms whereas for the absolute angles no offset subtraction was applied. Considering both types of angles was done to illustrate the impact of offset between the different sessions. Matlab was used to normalize data in time to 100% gait cycle as well as to perform statistical analyses.

Repeatability of the 3D rotations and planar angles was determined by first calculating the inter-trial (σ^{trial}), the inter-session (σ^{sess}) and inter-therapist ($\sigma^{therapist}$) variability in accordance to Schwartz et al. [10]. A mean was calculated for these variability indices as these are normally point-by-point representations. To simplify data interpretation, $\sigma^{sess}/\sigma^{trial}$ and $\sigma^{therapist/trial}$ ratios were calculated. Mean range of motion values were calculated and this considering the complete gait cycle. Clinical use of the angles was further explored through z-score based analyses, which incorporates the normal variability as well as the strength of a non-dimensional value. First, a point-by-point z-score was computed considering the following ratio:

$$Z = \frac{\delta_k - \mu_k}{\sigma_k}$$

with μ and σ being respectively the mean waveform and associated standard deviation from a reference group recently measured [8], and δ denote the average waveform of one patient obtained for a specific session and therapist. Subsequently, an average z-score was calculated for the five sub phases of the gait cycle proposed by Perry [9]. Agreement between the z-scores of the four sessions was evaluated using the following benchmarks:

(1) z-score between −1 and +1
(2) $1.1 < z\text{-score} < 2.0$
(3) $2.1 < z\text{-score} < 3.0$
(4) $z\text{-score} > 3.1$
(5) $-2.0 < z\text{-score} < -1.1$
(6) $-3.0 < z\text{-score} < -2.1$
(7) $z\text{-score} < 3.1$

3. Results

A synthesis of the clinical and medical data is provided in Table 1. The σ^{trial} of the patients were $<3.0^{\circ}$ for all 3D rotations whereas for the planar angles the σ^{trial} were $<8.6^{\circ}$. The $\sigma^{sess}/\sigma^{trial}$ of the relative 3D rotations ranged between 0.8 and 3.3 in the senior clinician and between 1.0 and 12.2 in the junior clinician (Fig. 1). With respect to the relative planar angles, the $\sigma^{sess}/\sigma^{trial}$ ranged between 0.5 and 3.4 in the senior clinician and between 0.8 and 8.1 in the junior clinician. A general trend towards higher $\sigma^{sess}/\sigma^{trial}$ ratios was observed for both absolute 3D rotations and planar angles. The $\sigma^{therapist/trial}$ ranged between 1.3 and 6.6 for the relative 3D rotations and between 1.4 and 4.0 for the relative planar angles (Fig. 1). A substantial increase of these ratios was observed for the absolute $\sigma^{therapist/trial}$ ratios. Mean range of motion values varied considerably between the participants (Table 2).

For the senior therapist, results of the z-score analyses showed that in 83% of the comparisons at least 3/4 absolute measurements had a similar z-score. The same computations for the junior therapist revealed a lower agreement, being 74% (Fig. 2).

4. Discussion

The purpose of this study was to assess, for the first time, the repeatability of a recently published 3DMFM [3] in presence of foot deformities. The σ^{trial} was found to be slightly higher in certain participants compared to recently published data from a non-pathological group [8]. A plausible cause for this may be the antalgic gait pattern, as three participants stated that barefoot walking became more difficult, or even painful, throughout the different test sessions of a day. The low $\sigma^{sess}/\sigma^{trial}$ ratios found in

Table 1
Clinical and medical data of recruited participants.

Subject/ age/sex	Disease	Body mass (kg)	Height (m)	Foot	Foot and ankle deformities/complaints	Therapeutic modalities/surgery	Clinical scale/score
1/39/F	Charcot-marie-tooth disease	72	1.74	R	Mild cavus foot with claw toes/loss of proprioception/ weakness in LL/mild foot drop/wasting of muscle tissues in LL	Triple arthrodesis left foot + EHL transfer first metatarsal (age: 26 y) Triple arthrodesis + EHL transfer first metatarsal right foot (age: 23 y) Confection shoes	AOFAS ankle-hindfoot scale = 53/100 AOFAS forefoot-scale = 62/100 SF-12HS: PCS: 31.9/MCS: 40.7
2/27/F	Spina bifida	71	1.71	L	Cavus foot/varus hindfoot, floating lesser toes/turf toe hallux toes	Triple arthrodesis bilateral EHL transfer first metatarsal bilateral Bespoke shoes	AOFAS ankle-hindfoot scale = 64/100 AOFAS forefoot-scale = 47/100 SF-12HS: PCS: 47.0/MCS: 51.8
3/71/M	Tibiotalar arthritis	95	1.67	L	Varus hindfoot, varus malalignment tibia, floating lesser toes	Tibiotalar artrodesis within two months Bespoke shoes	AOFAS ankle-hindfoot scale = 39/100 FADI: 49%
4/64/M	Diabetes mellitus (Type 1)	70	1.72	R	Neuropathic foot, mild cavus foot, fat pad atrophy in forefoot, pronounced metatarsal heads, claw toes (2–5), Limited joint mobility	Custom made insoles + confection shoes	10 g monofilament: 0/6 Good palpable pulses Foot risk category (IWGDF): 3
5/51/F	Ehlers-Danlos syndrome	59	1.61	R	Tailor's bunion, pes planus, arthritis midfoot	Custom made insoles + confection shoes	AOFAS midfoot scale = 75/100 AOFAS ankle-hindfoot scale = 85/100 SF-12HS: PCS: 37.7/MCS: 34.5
6/32/M	Facioscapulohumeral muscular dystrophy	77	1.90	L	Bilateral drop foot, mild cavus foot claw toes (2–4)	Ankle foot orthosis bilateral + running shoes	AOFAS forefoot score = 74/100 AOFAS ankle-hindfoot scale = 57/100 SF-12HS: PCS: 25.7/MCS: 46.5
7/55/F	Rheumatoid arthritis	71	1.60	R	Hallux valgus, splay forefoot, hindfoot valgus, dislocation and lateral deviation lesser toes, degenerative changes midfoot	Bespoke shoes	LFIS-RA: 12/21 foot impairment 12/30: activity scale FFI: 49% SF-12HS: PCS: 43.2/MCS: 57.1
8/45/M	Hallux limitus	64	1.77	R	Exostosis dorsal aspect first metatarsaophalangeal joint	Custom made insoles + confection shoes	AOFAS forefoot score = 63/100 SF-12HS: PCS: 40.4/MCS: 45

R, right; L, left; LL, lower limbs; EHL, extensor hallucis longus; AOFAS, American Orthopaedic Foot and Ankle Society; SF-12HS, SF-12 Health Survey; PCS, physical component summary; MCS, mental component summary; FADI, foot and ankle disability index; IWGDF, International Working Group on the diabetic foot; LFIS-RA, leeds foot impact scale-rheumatoid arthritis; FFI, foot function index.

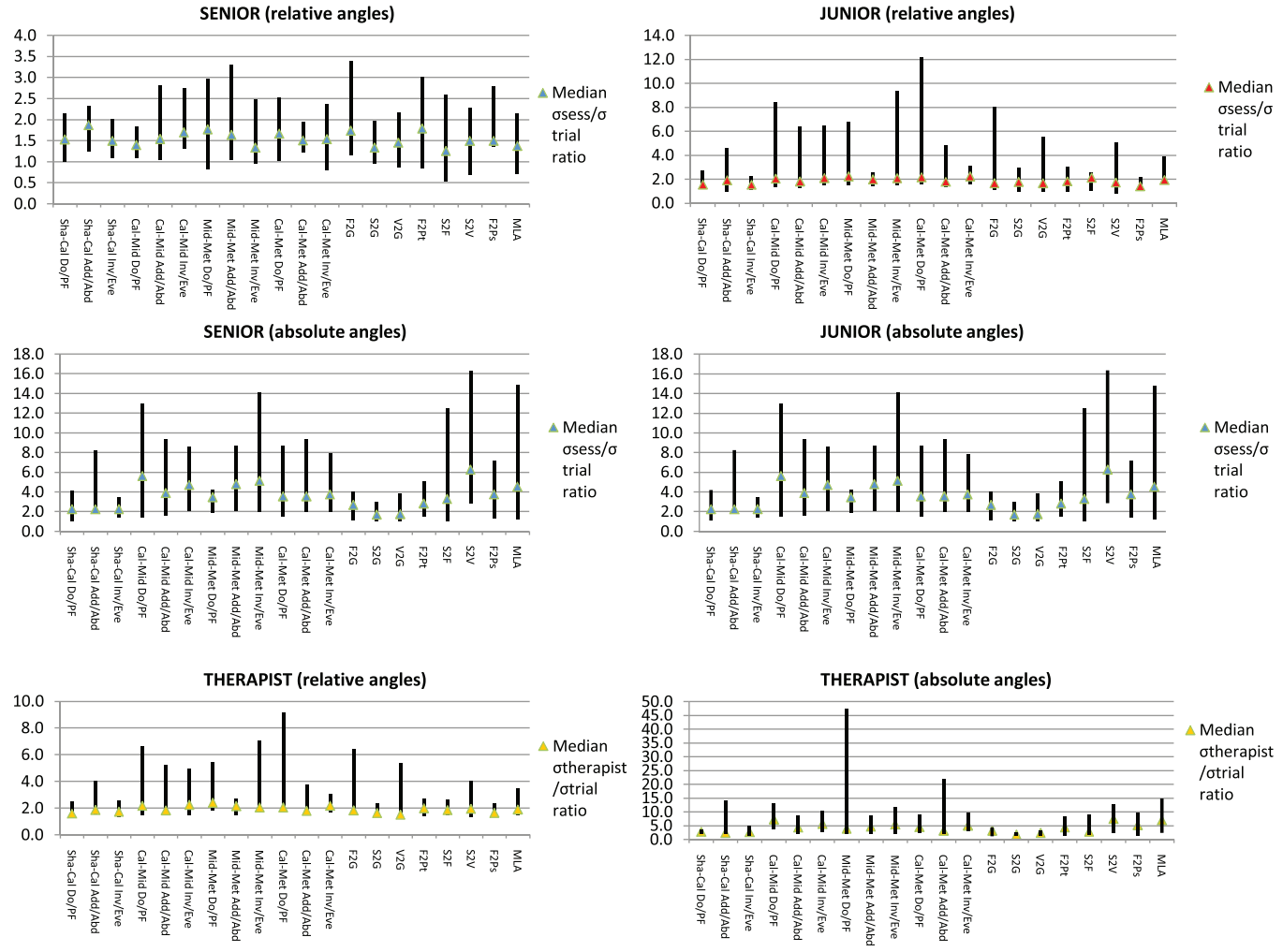

Fig. 1. The $\sigma^{session}/\sigma^{trial}$ and $\sigma^{therapist}/\sigma^{trial}$ ratios obtained for the relative and absolute 3D rotations and planar angles for both therapists (Schwartz et al., 2004). Ratio calculations were performed on patient-level and the median is represented together with the range.

Table 2
Mean range of motion calculations (degrees) for 3D rotations and planar angles obtained for each participant.

	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7	Subject 8
Sha-Cal Do/PF	15.4	29.5	8.6	25.7	21.5	28.7	23.1	33.7
Sha-Cal Add/Abd	7.6	24.5	6.4	15.3	9.2	24.0	11.7	13.4
Sha-Cal Inv/Eve	11.6	21.0	6.9	8.0	16.2	23.1	13.8	24.1
Cal-Mid Do/PF	11.0	18.6	4.8	12.0	18.1	9.6	7.9	7.0
Cal-Mid Add/Abd	8.3	7.9	3.9	6.7	12.8	14.1	6.6	11.7
Cal-Mid Inv/Eve	5.1	11.2	2.9	8.1	7.3	5.3	7.5	6.4
Mid-Met Do/PF	6.2	16.9	8.3	9.3	8.4	8.9	9.7	12.2
Mid-Met Add/Abd	3.7	10.1	4.5	2.5	4.0	1.7	4.0	6.9
Mid-Met Inv/Eve	12.6	18.8	4.7	9.0	9.0	5.0	10.9	4.3
Cal-Met Do/PF	7.9	21.4	10.6	20.4	23.6	6.1	11.8	15.9
Cal-Met Add/Abd	4.4	13.6	5.0	8.8	8.9	6.7	9.6	9.3
Cal-Met Inv/Eve	10.8	24.8	6.4	13.4	14.6	15.1	9.3	13.4
F2G angle	61.3	56.0	41.9	60.4	98.4	48.0	64.0	79.8
S2G angle	66.3	77.3	41.6	63.5	92.7	62.2	58.1	82.6
V2G angle	69.2	98.7	42.7	54.9	91.6	67.8	68.0	104.2
F2Pt angle	6.9	15.8	19.5	9.0	15.2	8.0	13.9	7.8
S2F angle	11.1	19.4	14.4	10.7	18.5	0.3	11.0	2.9
S2V angle	40.1	96.4	42.4	23.0	19.7	55.3	27.3	17.1
F2Ps angle	31.0	32.5	25.2	47.0	36.1	22.6	34.1	19.1
MLA	21.2	29.9	14.0	29.5	31.2	20.7	11.4	13.4

The mean was quantified by considering all range of motion values of all sessions of both therapists.

the relative parameters indicate that the decision making process can be done on the basis of pattern evaluation as well as on the basis of range of motion quantities. From Table 2 it can be observed that marker placement was done with lesser variation by the senior therapist. The absolute 3D rotations between the Sha-Cal and Cal-Met seem to have the lowest variability in both therapists. Contrarily, we observed a general trend towards higher $\sigma^{sess}/\sigma^{trial}$ ratios when the midfoot was involved. In certain subjects these ratios were considerably high, questioning the utility of these absolute waveforms in the decision making process. The *z*-scores

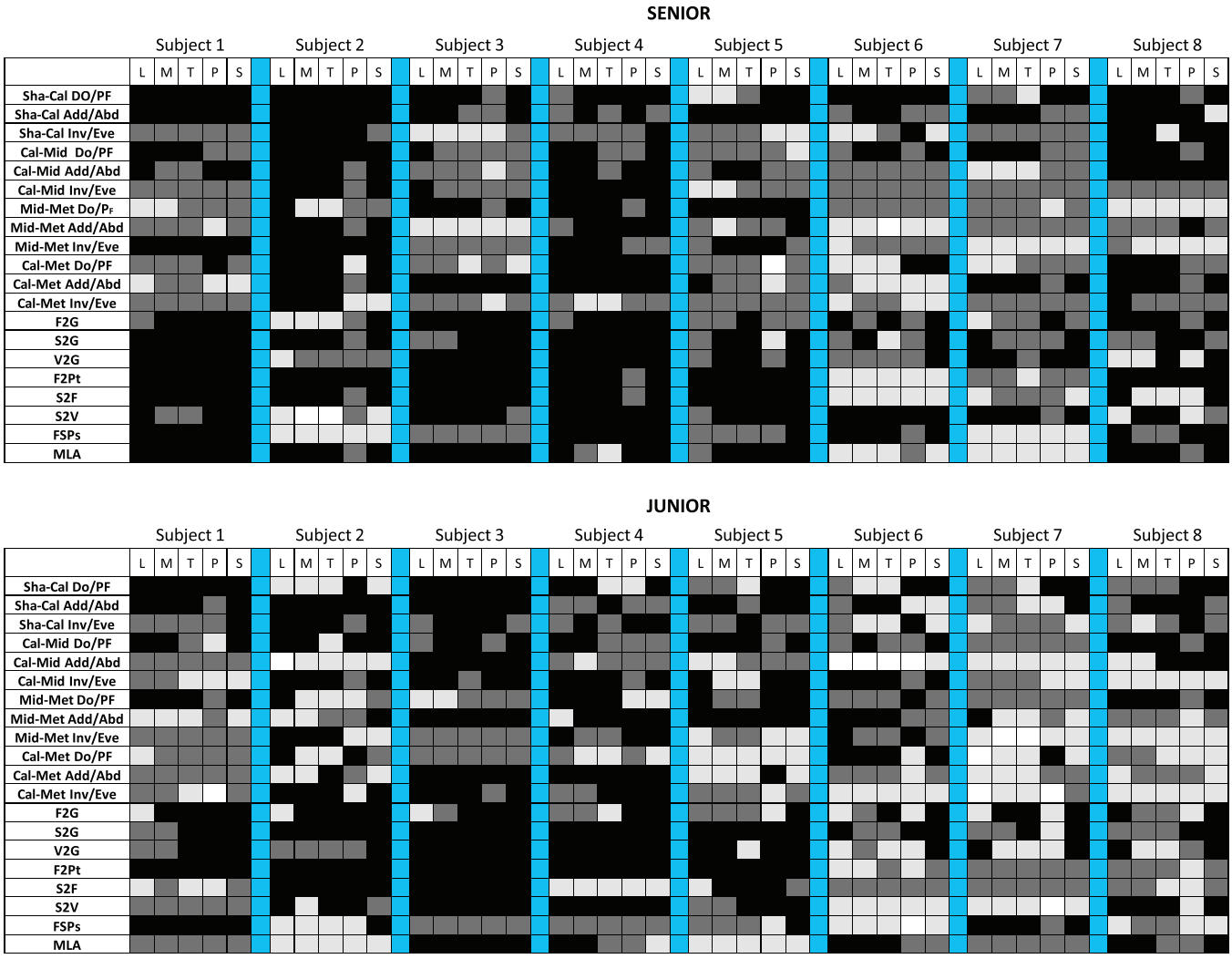

Fig. 2. Results of *z*-score based comparisons from the absolute parameters of both therapists. The current table illustrates the impact of the observed repeatability indices on the clinical decision making process throughout the different gait phases. ■ Indicates 100% agreement between the individual *z*-scores of the four sessions, ▩ Indicates 75% agreement between the individual *z*-scores of the four sessions, ▨ Indicates 50% agreement between the individual *z*-scores of the four sessions, □ Indicates no agreement between the individual *z*-scores of the four sessions.

based analyses on the absolute parameters illustrated not only the more consistent marker placement of the senior therapist but also the higher variability in the 3D rotations involving the midfoot.

The fact that only one senior and one junior clinician participated to the study can be considered as a limitation as it influences the inter-therapist variability. The selection of a heterogeneous group may have impeded the production of generalizable results; however, this was not the main objective of the study.

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Conflicts of interest statement

The authors declare that no financial and personal relationship exist which could have influence (bias) their work.

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