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Concurrent repeatability and reproducibility analyses of four marker placement protocols for the foot-ankle complex

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ABSTRACT

Multi-segment models of the foot have been proposed in the past years to overcome limitations imposed by oversimplified traditional approaches used to describe foot kinematics, but they have been only partially validated and never compared. This paper presents a unique comparative assessment of the four most widely adopted foot kinematic models and aims to provide a guidance for the clinical interpretation of their results.

Sensitivity of the models to differences between treadmill and overground walking was tested in nine young healthy adults using a 1D paired *t*-test. Repeatability was assessed by investigating the joint kinematics obtained when the same operator placed the markers on thirteen young healthy adults in two occasions. Reproducibility was then assessed using data from three randomly selected participants, asking three operators to repeat the marker placement three times. The analyses were performed on sagittal kinematics using curve similarity and correlation indices (Linear Fit Method) and absolute differences between selected points.

Differences between treadmill and overground gait were highlighted by all the investigated models. The two most repeatable and reproducible investigated models had average correlations higher than 0.70, with the lowest values (0.56) obtained for the midfoot. Averaged correlations were always higher than 0.74 for the former and 0.70 for the latter, with the lowest obtained for the midfoot (0.64 and 0.51). For all investigated models, foot kinematics generally showed low repeatability: normative bands must be adopted with caution when used for comparison with patient data.

1. Introduction

The observation of the foot-ankle complex is of clinical interest for various pathologies, including foot drop or deformities. Clinical decision-making might benefit of objective measurements of foot kinematics to isolate the causes of altered movements.

In gait analysis the foot is typically considered as a rigid segment linked to the tibia. This simplification, justifiable for some clinical applications, might be unsuitable for problems where the multi-segmental anatomy of the foot is needed. In the past two decades several multi-segment models of the foot-ankle complex have been proposed and reviewed (Deschamps et al., 2011; Saraswat et al., 2012; Sawacha et al., 2009; Theologis and Stebbins, 2010). Nowadays, the most popular models used either for research or clinical applications are those illustrated by Leardini et al. (2007), Saraswat et al. (2012), Sawacha et al. (2009) and Stebbins et al. (2006). The major differences are in the number and definition of the segments to be tracked, as well as in the identification of the associated anatomical landmarks. The validation of these models is limited (Arnold et al., 2013; Caravaggi et al., 2011; Curtis et al., 2009; Deschamps et al., 2012a) and their clinical feasibility and utility has been previously questioned (Baker and Robb, 2006). Moreover, their repeatability (i.e. their precision when applied on same or similar subjects by the same operator (JCGM, 2012)) and reproducibility (i.e. their precision when applied on the same, or similar, subjects by different operators (JCGM, 2012)) are still unclear (Deschamps et al., 2011).

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Nomenclature

a_0	shift coefficient yielded by the LFM;
a_1	scaling factor yielded by the LFM;
FF	metatarsus and forefoot;
Foot	foot modelled as a rigid element;
Hal	hallux;
HF	hindfoot and calcaneus;
IC	Initial Contact;
Knee	Knee;
LFM	Linear Fit Method;
M1	model proposed by Stebbins et al. (2006);
M2	model proposed by Leardini et al. (2007);
M3	model proposed by Sawacha et al. (2009);
M4	model proposed by Saraswat et al. (2012);
MAD	Median Absolute Deviation;
MD	Maximum Difference;
MF	midfoot;
R^2	coefficient of determination yielded by LFM;
ROM	Range Of Motion;
SD_{a0}	standard deviation for a_0;
SD_{a1}	standard deviation for a_1;
SPM	Statistical Parametric Mapping;
Tib	tibia and fibula;
TO	Toe-Off;

This paper aims at: quantifying the within- and between-subject repeatability, and between-operator reproducibility of the data obtained from the four mentioned models for overground and treadmill walking and at assessing their ability to highlight changes imposed by these two walking conditions.

2. Materials and methods

2.1. Subjects

Thirteen healthy subjects were recruited (ten males, age: 27.0 ± 1.9 years, height: 1.83 ± 0.08 m, foot length: 28.5 ± 1.0 cm). Exclusion criteria were self-reported musculoskeletal pain or impairments. Ethical approval was granted by the University of Sheffield. Prior to the data collection, all subjects read and signed a consent form. The sample size was calculated using a power analysis with significance $\alpha=0.05$ and power $\beta=0.80$, based on the data from the sagittal kinematics of the first two subjects.

2.2. Data collection and processing

Each subject was instrumented with the marker set obtained merging those proposed by Stebbins et al. (2006) (M1, modified version of the Carson et al. (2001) model), Leardini et al. (2007) (M2), Sawacha et al. (2009) (M3), Saraswat et al. (2012) (M4), and Plug-in-Gait (commercial version of Davis et al. (1991)) (Fig. 1 and supplementary material). This choice allowed avoiding the effect of the between-stride variability associated to placing each marker-set once per time. The merged set of 39 markers was obtained respecting the anatomical landmark locations and the positioning critical alignments described in each paper: 4 on the pelvis, 2 on the thighs, 2 on the lateral femoral condyles; plus, on the right side, 6 markers on the shank, 7 on the hindfoot, 2 on the mid-foot, 12 on the forefoot, and 4 on the hallux. Spherical markers (diameter: 9.5 mm) were used for pelvis, thighs and shank segments, whereas hemispherical markers (diameter: 4 mm) were used for the foot.

Marker trajectories were collected with a 10-camera stereophotogrammetric system (T-160, Vicon Motion System Ltd – Oxford, UK, 100 Hz, Vicon Nexus 1.8.5). Aperture, focus and position of the cameras were set to ensure good visibility and precise and accurate tracking of the smaller 4 mm markers (Di Marco et al., 2016; Windolf et al., 2008).

Labelling, manual cycle-events detection (from absolute vertical component of the heel marker, and 3D position of the foot), gap filling, and filtering (Woltring spline routine, size 30 (Woltring, 1986)) were conducted within Nexus and C3D files were then post-processed in MATLAB (R2015b, The MathWorks, Inc. – Natick, MA, USA). The local coordinate systems for each segment were defined according to the corresponding model, selecting the pertaining markers, and used to compute joint kinematics consistently with the definitions given in each paper. M1 was implemented according to its most repeatable configuration (option 5 in (Stebbins et al., 2006)), using static calibration and dynamic tracking of the hindfoot without considering the wand marker.

The following notations will be used to simplify the data reporting: hindfoot and calcaneus will both be indicated as HF, midfoot as MF, metatarsus and forefoot as FF, tibia and fibula as Tib, hallux as Hal, and finally, the foot modelled as a rigid segment as Foot. A left-side superscript will specify the model: e.g. the forefoot in M1 and the metatarsus in M2 will be noted as ^{M1}FF and ^{M2}FF, respectively. Fig. 2 summarises the flow of data collection and processing explained in the following sections.

2.3. Comparison between treadmill and overground walking

A treadmill (ADAL3D-F, TECMACHINE HEF Groupe – Andrezieux Bouthéon, France) was used to collect more than one stride per trial. A comparison between treadmill and overground walking conditions allowed to check whether the models were all sensitive enough to detect expected changes in the kinematic patterns, known to be different mainly due to the inherent different walking speeds (Alton et al., 1998; Sloot et al., 2014).

A trained operator placed the entire marker-set on the thirteen subjects, who were asked to walk barefoot at a self-selected speed on both the treadmill and overground. The observed walking speeds were 0.82 ± 0.15 m/s and 0.99 ± 0.11 m/s, respectively. A total of five right strides were retained from each session for the analysis.

Data from four subjects among the thirteen recruited were discarded due to poor marker visibility in the overground trials. For the remaining subjects, the ability of the models to discriminate between treadmill and overground walking was tested with the 1D paired t-test ($\alpha=0.05$) (Pataky, 2012). This test is based on the statistical parametric mapping (SPM) theory (Friston et al., 2007), which is used to analyse statistical differences among continuous curves, without reducing the test to summary metrics (maximum or minimum values). The analysis was performed using the SPM1D open-source package for MATLAB (spm1d.org) and generated: map of t-values (SPM{t}), t^* limit, and areas where differences were found with relevant p-values.

2.4. Within- and between-subjects analyses

Two sessions of data collection for the treadmill walking were carried out one month apart. In each session the same operator re-placed the markers on the same subject.

2.4.1. Waveform similarity

Waveform similarity was assessed both for overground and treadmill walking using the Linear Fit Method (LFM) (Iosa et al., 2014). This method was chosen rather than the Coefficient of Multiple Correlation (Kadaba et al., 1989) as it has been heavily questioned in the past (Ferrari et al., 2010; Røislien et al., 2012). The LFM yields three coefficients: a_1 is the scaling factor between the comparing curves and the similarity index (the closer to 1, the more similar the curves); a_0 measures the shift between the curves, quantifying the offset, when a_1 tends to 1; R^2 validates the linear relationship between the curves and measures their correlation (the closer to 1, the stronger the linear model).

For the within-subject analysis in treadmill walking, for each i-th subject the j-th kinematic curve at the k-th gait cycle was compared to the same kinematics averaged among the five strides and the two sessions of the i-th subject. As reported in (Iosa et al., 2014), a_1 and a_0 tend to their ideal values (i.e., 1 and 0, respectively) when comparing n curves with their averaged pattern. In this case, to have a measure of the variations, it is relevant to report and observe the standard deviations for both a_1 and a_0.

2.4.2. Repeatability

Models' repeatability was assessed considering the sagittal joint angles at Initial Contact (IC) and Toe-Off (TO) as summary metrics (Wilken et al., 2012). The Median Absolute Deviation (MAD) and the Maximum Difference (MD) were calculated. The former is a variability index reported to be robust to the outliers, the latter measures the differences obtained in the worst case (Benedetti et al., 2013).