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Kinematic analysis of a multi-segment foot model for research and clinical applications: a repeatability analysis

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Abstract

An unbiased understanding of foot kinematics has been difficult to achieve due to the complexity of foot structure and motion. We have developed a protocol for evaluation of foot kinematics during barefoot walking based on a multi-segment foot model. Stereophotogrammetry was used to measure retroreflective markers on three segments of the foot plus the tibia. Repeatability was evaluated between-trial, between-day and between-tester using two subjects and two testers. Subtle patterns and ranges of motion between segments of the foot were consistently detected. We found that repeatability between different days or different testers is primarily subject to variability of marker placement more than inter-tester variability or skin movement. Differences between inter-segment angle curves primarily represent a shift in the absolute value of joint angles from one set of trials to another. In the hallux, variability was greater than desired due to vibration of the marker array used. The method permits objective foot measurement in gait analysis using skin-mounted markers. Quantitative and objective characterisation of the kinematics of the foot during activity is an important area of clinical and research evaluation. With this work we hope to have provided a firm basis for a common protocol for in vivo foot study.

Keywords: Foot kinematics; Gait analysis; Repeatability; Reliability; Stereophotogrammetry

1. Introduction

In gait analysis, the clinical biomechanical models usually represent the foot as a single rigid vector, permitting only foot progression angle and net dorsi/plantarflexion to be determined. In the research literature, there is no standard nor reliable method for dynamic in vivo measurement and it is recognised that this is very difficult to achieve due to the foot's complex structure. This paper describes a multi-segment approach to measuring foot kinematics during gait and a repeatability analysis on healthy feet.

In the last decade a few groups have presented multi-segment in vivo studies of the foot (DeLozier et al., 1991; D'Andrea et al., 1993; Kidder et al., 1996; Leardini et al., 1999), with others looking at the ankle/subtalar complex in vivo (Moseley et al., 1996; Liu et al., 1997). However, the means of marking and describing the segment fixed anatomical axes have varied between authors so that comparability of the results of these studies are limited (Leardini et al., 1999). There is a need for a standardised protocol which requires thorough testing and validation (Kidder et al., 1996). The objectives of the present study were:

(1) To develop a multi-segment foot model and measurement protocol applicable to gait analysis for clinical and research applications.
(2) To evaluate the reliability of the protocol and model.

2. Methods

2.1. Foot model

The foot model simplifies the complex anatomical structure of the 28 bones of the foot. We selected a three

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segment foot model (hindfoot, forefoot and hallux), plus a tibial segment (Fig. 1) based on rigid body assumptions. Here, interest in the mid-foot focussed on its role as a mechanism transmitting motion between the hindfoot and forefoot. Relative motion is described without inter-segment constraints, that is with six possible degrees of freedom between any pair of segments.

2.2. Subjects and strategy

The method was based on results of preliminary trials involving the assessment of 15 healthy feet and 4 club feet. A marker set and anatomical axes definitions were refined to give good qualitative accuracy according to existing knowledge of foot kinematics (Kapandji, 1987; Jahss, 1991) as well as good repeatability. It was important that the protocol developed was applicable to the assessment of both healthy and deformed feet in the clinical setting. Studies on patients will be reported elsewhere.

This paper reports the results of a repeatability analysis which was performed once the method and protocol had been refined. Sixteen test sessions were completed with two testers assessing each of two healthy subjects independently over four days separated by a minimum of one week. One male (age 24, height 170 cm, weight 71 kg) and one female (age 29, height 162 cm, weight 61.5 kg) were assessed. We instructed the subjects to walk at a self-selected speed for all trials. All subjects were volunteers and participated with informed consent.

2.3. Data collection

Two testers, experienced in marker placement during routine clinical gait analysis, adhered to a written protocol. Data were collected using a VICON 370 motion capture system with 6 cameras. A small fixed calibration volume was used ($400 \times 350 \times 500\,mm^3$). Three static standing trials were collected both before and after walking trials. In a static trial, the tibia was aligned in the vertical position with a jig (Fig. 2), to mimic the standard position of a standing X-ray of the foot (Long and Rafert, 1995). With a sub-set of markers (Figs. 3 and 4), a minimum of 10 barefoot walking trials were collected from a 7 m walkway, to achieve at least 6 trials yielding complete data sets (visibility of at least three markers per segment). The stance phase of one gait cycle was collected for each walking trial with an initial contact and toe-off determined from force plate data.

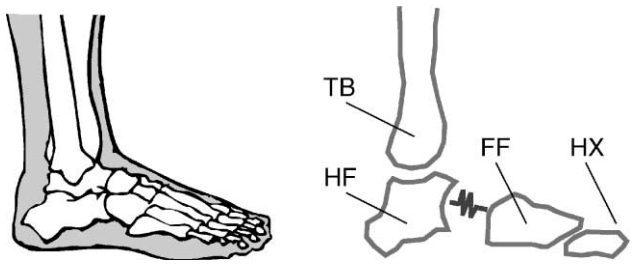

Fig. 1. Schematic of the three segment foot model with tibia: TB-Tibial segment (tibia and fibula), HF-Hindfoot (calcaneus and talus), FF-Forefoot (five metatarsals), HX-Hallux (hallux proximal phalanx).

2.4. Model segment identification

The analysis protocol included identification of segment-embedded co-ordinate frames based on anatomical landmarks identified by marker positions in the static trials. The planes corresponded to the anatomical sagittal, transverse and frontal planes of each segment. Since these are mutually orthogonal, they could be defined by at least two perpendicular planes (Figs. 3 and 4).

2.5. Data analysis, repeatability trials

We evaluated inter-segment angles between segment pairs, including global motion, (i.e. with respect to the floor, FL). Of these 5 'segments' (FL, TB, HF, FF, HX), we examined the 4 inter-segment pairs:

- TB/FL: tibia with respect to the floor.
- HF/TB: hindfoot with respect to the tibia.
- FF/HF: forefoot with respect to the hindfoot.
- HX/FF: hallux with respect to the forefoot.

The inter-segment angles were calculated according to the method proposed by Grood and Suntay (1991) and

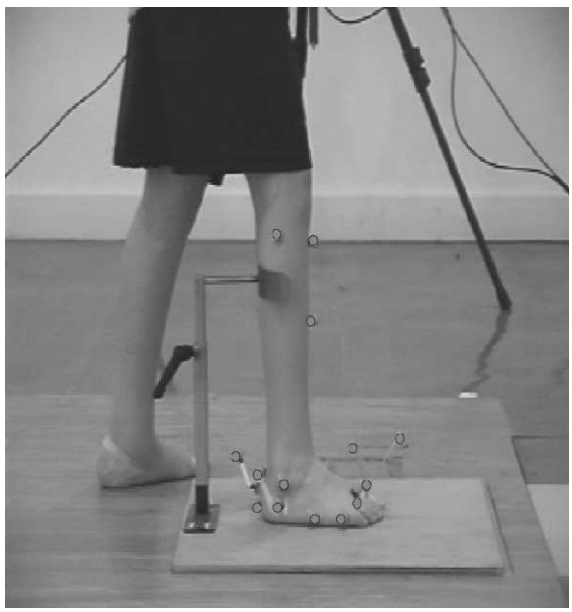

Fig. 2. Static trial tibia alignment jig.

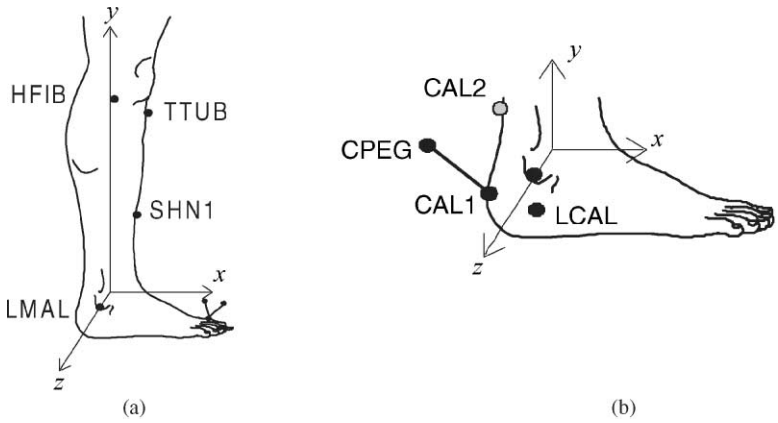

Fig. 3. Tibial (TB) and Hindfoot (HF) segment axes description. (a) TB: Frontal plane through the malleoli (MMAL, LMAL) and fibula head (HFIB); sagittal plane through the tibial tuberosity (TTUB) and midpoint between the two malleolar markers (MMAL, LMAL). SHN1 = additional marker. MMAL removed for dynamic trials. (b) HF: Sagittal plane aligned with markers along the vertical axis of the calcaneus posteriorly (CAL1, CAL2) and the static malleolar midpoint; transverse plane is taken parallel to the floor (from the static calibration). LCAL, STAL additional markers on lateral and medial calcaneus, respectively. CAL2 removed for dynamic trials.

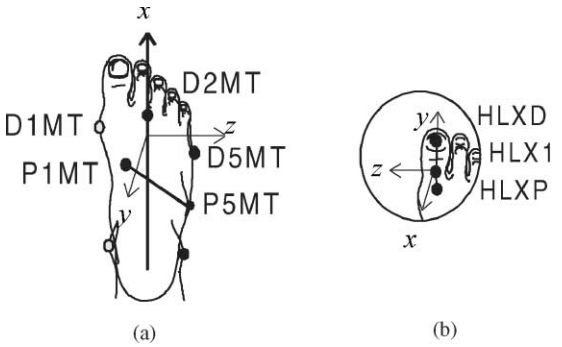

Fig. 4. Forefoot (FF) and Hallux (HX) segment axes description. (a) FF: Transverse plane through the distal medial side 1st MT (D1MT) and proximal and lateral side 5th MT markers (P5MT, D5MT); sagittal plane through the mid-2nd/3rd MT head marker (D2MT) and one third the distance from the dorsal, proximal end 1st MT (P1MT) and P5MT. D1MT removed for dynamic trials. (b) HX: Sagittal plane perpendicular to the floor (from static calibration) and through the stick markers (HLXP, HLXD) aligned with its long axis; transverse plane parallel to the floor (from static calibration).

the angular motion was examined in the three anatomical planes. Since terminology used to describe foot motion can be ambiguous due to different axes definitions and usage in the literature (Liu et al., 1997; Leardini et al., 1999), we chose to use terms with clinical relevance (AAOS, 1966) and have defined them below:

HF/TB:

- Plantar/dorsiflexion about the mediolateral axis of the tibia, z, Fig. 3a.
- Inversion/eversion about the posterior / anterior axis of the hindfoot, x, Fig. 3b.
- Internal/external rotation about the common perpendicular axis.

FF/HF:

- Plantar/dorsiflexion about the mediolateral axis of the hindfoot, z, Fig. 3b.
- Supination/pronation about the posterior / anterior axis of the forefoot, x, Fig. 4a.
- Ab/adduction about the common perpendicular axis.

HX/FF:

- Plantar/dorsiflexion about the mediolateral axis of the forefoot, z, Fig. 4a.
- Ab/adduction about the plantar dorsal axis of the hallux, x, Fig. 4b.
- Axial rotation about the common perpendicular axis.

The median of all inter-segment angles for each subject was taken to be the representative trial and used for discussion and presentation of results. A median rather than a mean was used to avoid smoothing effects of averaging so that peaks and trends remain apparent (Gage et al., 1997). The median trial was identified as follows. For each trial from one test session (one day, one tester, one subject), the average of each inter-segment angle was calculated over the whole stance phase. The median of each average was identified and subtracted from every average. The sum of these differences over all inter-segment angles was determined for each trial and the trial with the smallest sum was the median trial for that test session. This was repeated over all eight sessions for each subject irrespective of the tester.

2.6. Repeatability analysis

Four components of variability were assessed:

- systematic variability,
- between-trial variability,
- between-day variability and
- between-tester variability.

Results were presented in the following form:

${}^{TSD}\theta_{ij}(\tau)$,

where $\theta(\tau)$ = inter-segment angle at percent stance time, τ

The left hand side subscripts describe the test session:

T (=1,2)	references the tester,	n_T (=2) number of testers.
S (=1,2)	references the subject,	n_S (=2) number of subjects.
D (=1,4)	references the day,	n_D (=4) number of days.

The right hand subscripts describe the session details:

i (=1,6)	references the trial,	${}^{TSD}n$ (=5,6) number of trials in session TSD.
j (=1,12)	references the inter-segment angle.	

The systematic variability of the stereophotogrammetric system was quantified for any new calibration and was defined by the commercial software as camera calibration residuals. A rigid bar, with two markers at 130 mm apart, was also measured in different static positions and in dynamic trials of random movement through the calibration volume.

The between-trial variability was assessed for each inter-segment angle relationship by examining both the standard deviation over all trials, σ_j, and the session standard deviation for one subject and one tester, ${}^{TSD}\sigma_j$, as follows:

$$\sigma_j = \frac{\sum_{S=1}^{n_S}\sum_{T=1}^{n_T}\sum_{D=1}^{n_D} {}^{TSD}\sigma_j}{n_S \times n_D \times n_T}, \tag{1}$$

$${}^{TSD}\sigma_j = \frac{\sum_{\tau=1}^{100} {}^{TSD}\sigma_j(\tau)}{100}, \tag{2}$$

where

$${}^{TSD}\sigma_j(\tau) = \frac{\sum_{i=1}^{{}^{TSD}n} ({}^{TSD}\theta_{ij}(\tau) - {}^{TSD}\bar{\theta}_{ij}(\tau))^2}{{}^{TSD}n} \tag{3}$$

and

$${}^{TSD}\bar{\theta}_j(\tau) = \frac{\sum_{i=1}^{{}^{TSD}n} {}^{TSD}\bar{\theta}_{ij}(\tau)}{{}^{TSD}n}. \tag{4}$$

Between-day variability was analysed by examining repeated measurements for each inter-segment angle over four different days on the same subject by the same tester. The variability of kinematic behaviour for one subject over many trials was assumed to exhibit a normal distribution. For a given tester, T_1, T_2, and a given subject, S_1, S_2, the mean inter-segment angle measurements were calculated from six trials on each of two different days for each joint angle relationship and each percentage of stance phase.

The between-day variability analyses were repeated for all of the four possible combinations of two different testers and two different subjects. These were quantified by determining the 95% confidence intervals (CI), expressed in degrees and given by:

$$d - \mathrm{se}\times t \quad to \quad d + \mathrm{se}\times t, \tag{5}$$

where d is the difference between mean inter-segment angles from any two days, se the standard error of the difference, and t the Student's t-test value for $P = 0.05$, and also a function of the degrees of freedom (dof) of the comparison.

The dof are calculated as $({}^{TSD}n - 1)$ for a test session defined by T, S and D. A typical comparison of two test days would have ${}^{TSD}n = 6$ for each day, and 10 dof overall.

The difference between comparing two days and several days was accounted for by the standard error (se) calculation. se is a function of pooled within-group standard deviation or residual standard deviation, s_{res}, where 'group' refers to the group of all days under consideration, holding S and T constant:

$$s_{\mathrm{res}}(\tau)_j = \sqrt{\frac{\sum_{i=1}^{{}^{TS1}n} ({}^{TS1}\theta_{ij}(\tau) - {}^{TS1}\bar{\theta}_j(\tau))^2 + \cdots + \sum_{i=1}^{{}^{TS4}n} ({}^{TS4}\theta_{ij}(\tau) - {}^{TS4}\bar{\theta}_j(\tau))^2}{({}^{TS1}n - 1) + \cdots + ({}^{TS4}n - 1)}}. \tag{6}$$

The standard error, comparing days 1 and 2 for example, is then:

$$\mathrm{se}(\tau)_j = s_{\mathrm{res}}(\tau)_j \times \sqrt{\frac{1}{{}^{TS1}n} + \frac{1}{{}^{TS2}n}}. \tag{7}$$

The 95% CI for each pair of days was calculated. We chose the 'worst case' result by taking the upper limit of the interval, $d + \mathrm{se} \times t$, based on the absolute value of the difference between any two days. For each inter-segment angle, the largest value from all between-day comparisons was selected to define the between-day 95% CI.

The between-testers variability was evaluated by considering the 95% CI of the mean difference between results from two testers. The between-tester analysis compares the mean inter-segment angle values for four different days from each of two different testers and each subject. Again the 95% CI is given by Eq. (5) above. However, the difference between means, d is now given by,

$$d = {}^{ST1}\bar{\theta}_j(\tau) - {}^{ST2}\bar{\theta}_j(\tau)$$

and the standard error is:

$$\mathrm{se}(\tau)_j = s_{\mathrm{p}}(\tau)_j \times \sqrt{\frac{1}{{}^{S1}n_D} + \frac{1}{{}^{S2}n_D}}, \tag{8}$$

where s_{p} estimates population standard deviation from small sample sizes, given by

$$s_{\mathrm{p}}(\tau)_j^2 = \frac{({}^{S1}n_D - 1) \times {}^{S1}\sigma_j(\tau)^2 + ({}^{S2}n_D - 1) \times {}^{S2}\sigma_j(\tau)^2}{{}^{S1}n_D + {}^{S2}n_D - 2} \tag{9}$$

and ${}^{S1}\sigma_j(\tau)$ and ${}^{S1}\sigma_j(\tau)$ are the standard deviation of results for each tester, 1 and 2.

The dof reflect the number of days, $(n_D - 1) = 3$. This construction is an unpaired t-test since each parallel group, tester 1 and tester 2, are independent.

3. Results

3.1. Inter-segment motion

Twelve inter-segment angles plotted against stance time for every test run, $\theta(\tau)$, show distinct patterns of motion. Fig. 5 gives one example of the median result from one subject. The hindfoot dorsiflexes with respect to the tibia through mid-stance and plantar flexes at push off (Fig. 5d). It also progresses into inversion and internal rotation in late stance (Figs. 5e and f), a movement known to occur mostly in the subtalar joint complex (Perry, 1992). The forefoot dorsiflexes with respect to the hindfoot in mid-stance as the longitudinal arch of the foot flattens (Fig. 5g). In terminal stance, restoration of the arch is characterised by forefoot plantarflexion, supination and adduction (Figs. 5g–i). The hallux, as expected, dorsiflexes with respect to the forefoot as the heel comes off the ground (Fig. 5j) and it remains at near neutral ab/adduction (Fig. 5l).

The coupling of FF plantar flexion and HX dorsiflexion in late stance is also observed in Fig. 5g and j where dorsiflexion of the hallux is observed to begin slightly before FF plantarflexion. This is a recognised combined motion due to tightening of the flexor hallucis longus tendon (Rose et al., 1986).

The contribution of the FF and HF motions to overall supination/pronation of the foot can be distinguished as well. The change from eversion to inversion motion of the HF with respect to the tibia occurs at about 20% of the stance phase (Fig. 5f). The FF mimics this motion with a change from pronation to supination motion at about 30% of the stance phase (Fig. 5i). These values were calculated from the data.

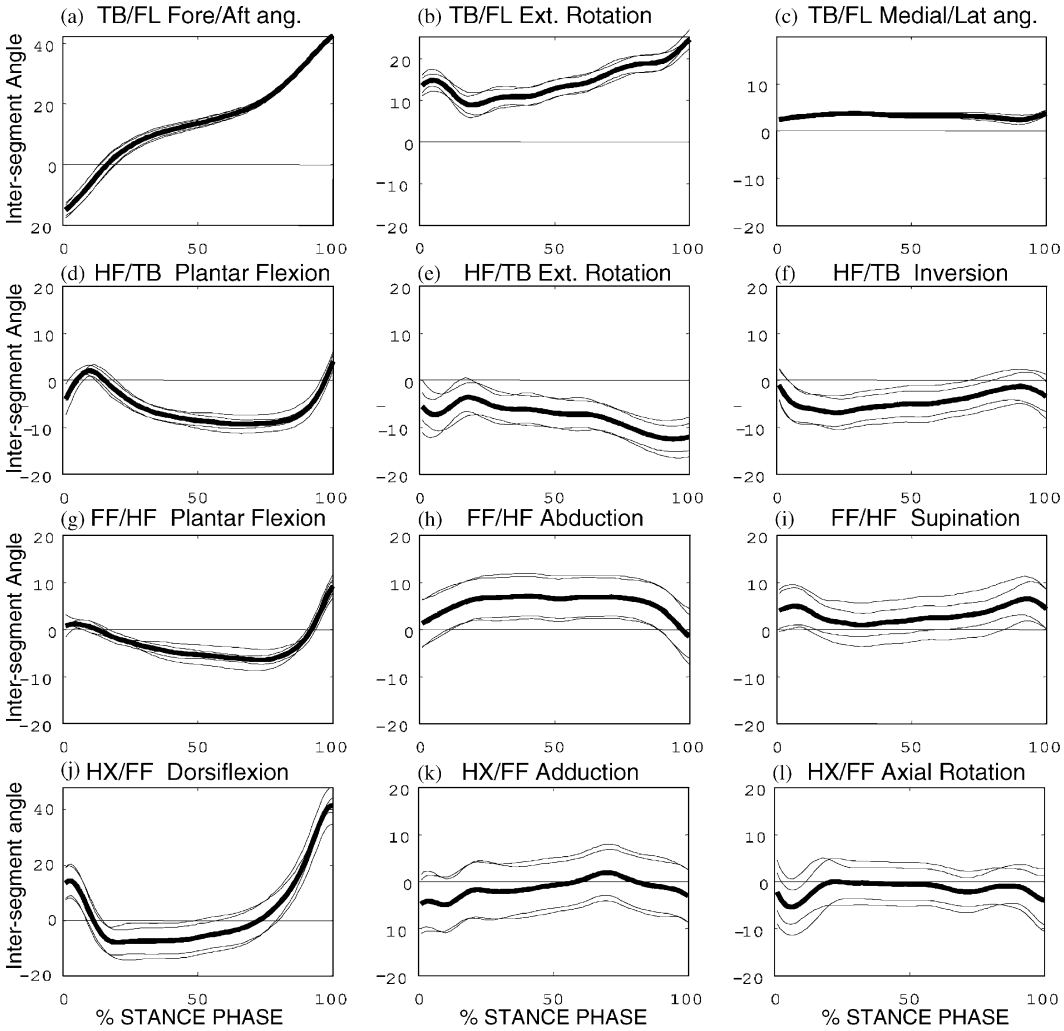

Fig. 5. Overall median trial for subject 1 with between-day 95% confidence intervals for each tester.

3.2. Repeatability analysis

The systematic accuracy of the system was quantified by the mean camera calibration residual for all test days of 0.66 ± 0.12 mm and a standard deviation of 0.6 mm for calculation of distance between two fixed distance markers from rigid bar tests.

The between-trial standard deviation calculated for each inter-segment angle from each test session and averaged over all test sessions and all inter-segment angles was less than $\pm 1^\circ$. The results for each inter-segment angle are shown in Table 1. Both the HF/TB inter-segment angles and the FF/HF inter-segment angles had inter-trial standard deviations of less than $\pm 0.7^\circ$. A further breakdown of the overall standard deviations for each test session revealed that the variations were consistent for both subjects and both testers, with higher standard deviation values observed in TB/FL rotation ($\pm 1.5^\circ$) and the HX/FF flexion angle ($\pm 2.0^\circ$).

Table 1
Between-trial standard deviations (degrees) for each inter-segment angle over all of stance phase

	Sagittal plane	Transverse plane	Frontal plane
TB/FL	Fore/aft angle	Int/external rotation	Medial/lateral angle
	0.89	1.45	0.59
HF/TB	Plantar/dorsi flexion	Int/external rotation	Inversion/eversion
	0.66	0.70	0.68
FF/HF	Plantar/dorsi flexion	Abb/adduction	Supination/pronation
	0.69	0.57	0.59
HX/FF	Plantar/dorsi flexion	Abb/adduction	Axial rotation
	1.95	1.07	0.96

The 95% CI of repeated measures over four days are shown in Fig. 6 for each of the four between-day analyses. These intervals were also plotted previously in Fig. 5, with the inter-segment angle curves for subject 1. The expected difference between results from any two days (for the same tester) was found to be within $\pm 2.0^\circ$ for the global tibial position (TB/FL), $\pm 3.0^\circ$ for the ankle joint complex (HF/TB), $\pm 4.3^\circ$ for mid-foot motion (FF/HF), and $\pm 6.5^\circ$ for hallux motion (HX/FF).

The results from between-tester analysis were similar to those of the between-day analysis (Fig. 7). The between-tester result was never more than 1° greater that the between-day result.

4. Discussion

4.1. Kinematic analysis of a multi-segment foot model

Several previous multi-segment models have been presented (DeLozier et al., 1991; D'Andrea et al., 1993; Kidder et al., 1996; Liu et al., 1997; Leardini et al., 1999). The marker set described here is most similar to that of Kidder et al. (1996) although there are important differences. Two additional markers are introduced (CPEG, D2MT), the proximal first MT marker is attached to the dorsal side of the foot, and a reduction of the marker set is proposed between the static and dynamic measurements. For example, the first MT head marker was removed for dynamic trials because significant skin motion was expected at this position.

Our acquisition protocol is non-invasive and not dependent upon X-ray information, unlike most previous studies. However, it is recognised that a modification of the hindfoot axes based on X-ray would be necessary in the presence of hindfoot deformity affecting

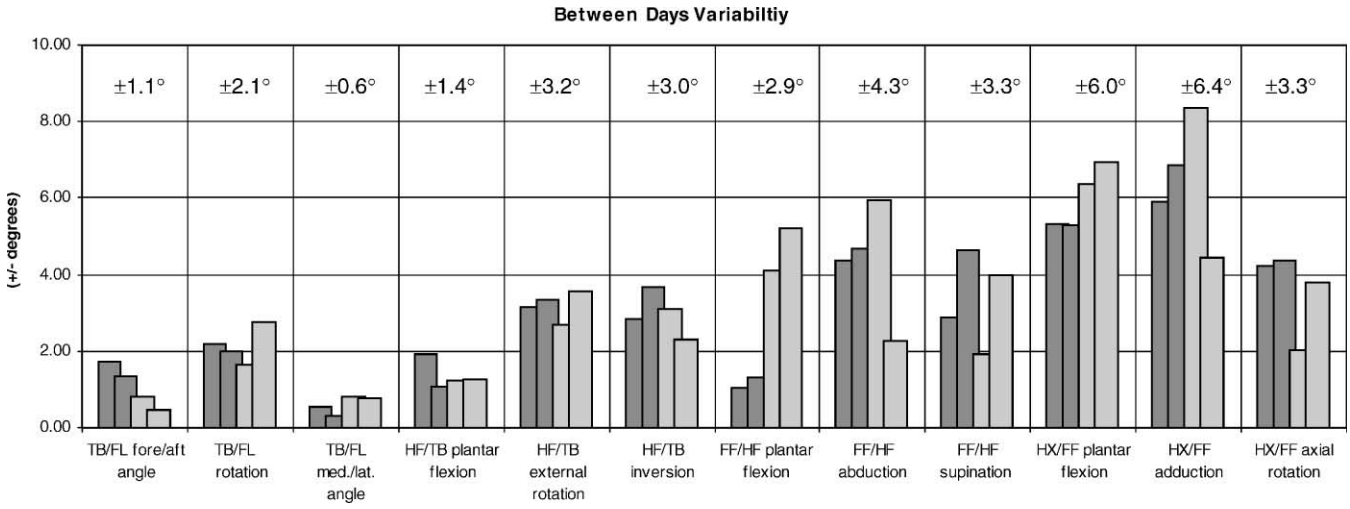

Fig. 6. Between days variability for each joint angle averaged over time, showing ■ subject 1 with each tester and □ subject 2 with each tester.

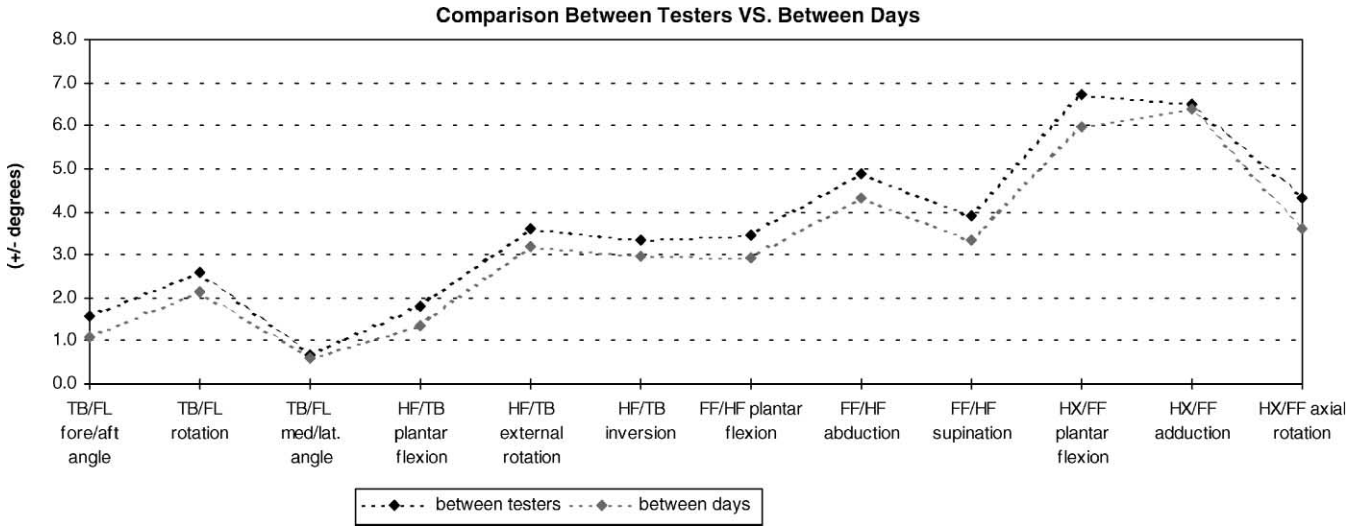

Fig. 7. Comparison of the overall difference between testers versus between days in 95% confidence interval analysis.

the inclination of the calcaneus in the sagittal plane. There may also be some hindfoot deformity where the current static malleolar midpoint will not be appropriate for the hindfoot definition.

A recent study by Leardini et al. (1999) used a different approach and reported patterns of motion within the foot similar to those described here. Quantitative comparison was not possible due to differences in anatomical reference axes definitions. Leardini et al. (1999) used rigid arrays of markers to define the foot segments whereas we favoured skin mounted markers, except for the hallux due to its limited surface area. A disadvantage of the array approach is the time required for landmark identification in a static trial. Additionally, skin motion artefact affects the array of markers in a uniform manner and is therefore impossible to filter mathematically. However, the use of arrays offers an advantage for systems with few cameras.

4.2. Repeatability analysis

A method with poor repeatability is unreliable and yet an appropriate repeatability analysis for measurement of in vivo foot kinematics was not found in the existing literature. Kadaba et al. (1989) introduced a statistical analysis of 'repeatability' between waveforms for lower limb gait analysis, which has been subsequently applied in other gait studies (Liu et al., 1997; Steinwender et al., 1999; Leardini et al., 1999). However, we have decided not to use this approach since the coefficient of multiple determination, R^2 (Neter et al., 1990; Winer et al., 1991), used in that work is based on a correlation analysis. We confirmed this decision by testing the Kadaba method using our own data and found the coefficient of multiple correlation, CMC $= R$ was higher (closer to unity) for an inter-segment angle with a greater range of motion, than one with a very small range of motion, despite wider confidence intervals (Fig. 8).

Repeatability analysis establishes whether there is agreement between repeated measures and to what degree. This is a problem of estimation about which most texts agree that '*…the best approach to analysing this type of data is to analyse the differences between the measurements…on each subject*.' (Altman, 1991).

We concluded that the foot study would be evaluated best using CI analysis to compare inter-segment angles. Despite its basic simplicity, it was the most appropriate statistical tool for quantifying the variability involved in the proposed method. Inter-tester comparison studies of continuous data are frequently described using a CI (Altman, 1991; Winer et al., 1991; Swinscow, 1996).

An overall between-trial variability of less than $\pm 1.0^\circ$, and less than $\pm 0.7^\circ$ for HF/TB and FF/HF reflects the good systematic accuracy of the motion capture system and the repeatability of motion within the foot in normal gait. The TB/FL inter-segment angle between-trial variability was between $\pm 1^\circ$ and $\pm 2^\circ$. This angle defines the tibia with respect to the floor and reflects both skew in the subject's direction of progression and variability in motion of the segments proximal to the tibia.

The hallux inter-segment angles also exhibited a higher between-trial variation than the other joints, particularly in the sagittal plane ($\pm 2.0^\circ$). The hallux plots of $\theta(\tau)$ were examined and two events were observed. First, toe-strike resulted in a transient spike in hallux marker position measurements which could contribute to greater between-trial variation. Secondly, the hallux array bolt allowed slight relative movement of

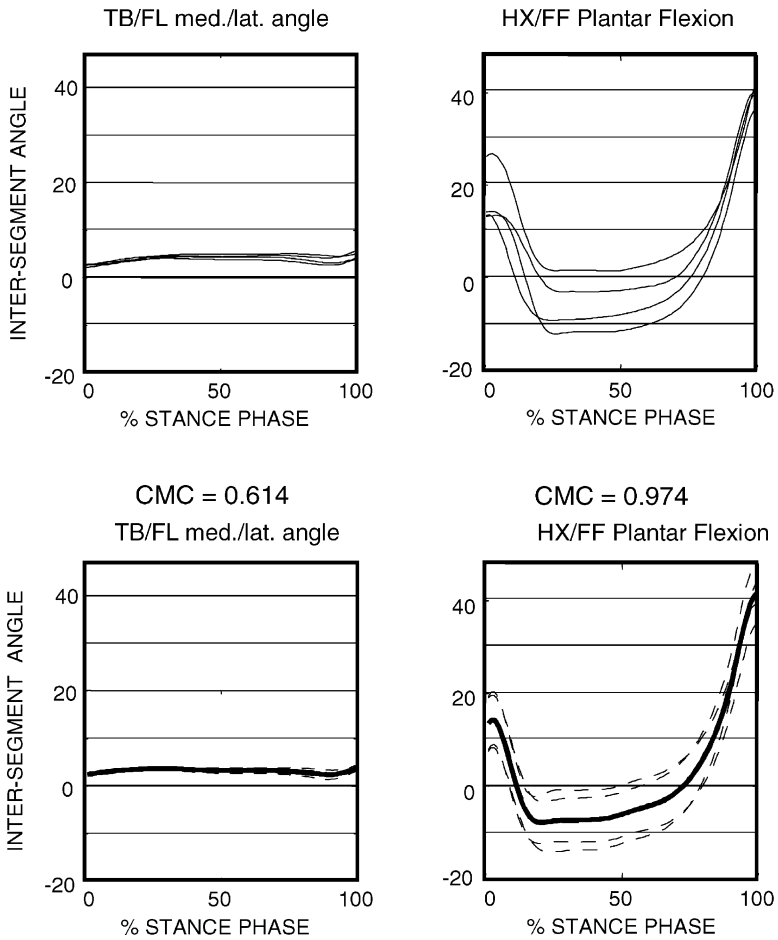

Fig. 8. Comparison of confidence intervals with coefficient of multiple-correlation for two sample inter-segment angle curves: (a) shows the mean joint angle curve for each of four days and (b) shows the 95% confidence intervals for between-day repeatability, along with the coefficient of multiple correlation, CMC (Kadaba et al., 1989), for each of the corresponding inter-segment angle curve.

the two stick markers during toe strike in early stance (at about 20% stance phase). Although less significant to the overall variation than toe-strike vibrations, the hallux array has since been reinforced to assure complete rigidity for future testing.

The good consistency seen here between trials implies that artifacts from skin movement are repeatable and systematic. We sort to minimise such artifacts by refining marker positions and assessing the results qualitatively based on known foot kinematics. A rigorous quantitative assessment of this requires simultaneous direct measurement of the motion of the underlying bones.

The CI that was calculated to quantify between-day and between-tester variability contains two components. These are the difference between the means of repeated measures and the standard error of the difference, which is a function of the standard deviations across each set of repeated measures. Since standard deviations between trials were low (Table 1), the standard error component of the CI is proportionately low. Thus the CI results primarily represent a shift in absolute value of the inter-segment angles, rather than differences in the shape of the curves. This shift is mainly due to variability of marker placement and could be reduced by subtracting a neutral position for joints from the static trial as others have proposed (Leardini et al., 1999). However, this would reduce the application of the model clinically.

The qualitative assessments within the present study from both method development and the repeatability analysis have detected subtle patterns of foot motion consistent with existing knowledge of foot kinematics. The overall level of repeatability was found to be acceptable, thus providing a basis for objective foot measurement in gait analysis for both research and clinical applications.

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