

Development and validation of a novel rating system for scoring standing foot posture: The Foot Posture Index

Anthony C. Redmond^{a,b,*}, Jack Crosbie^c, Robert A. Ouvrier^b

^a Academic Unit of Musculoskeletal Disease, Rheumatology, University of Leeds, Chapel Allerton Hospital, Harehills Lane, Leeds LS7 4SA, United Kingdom

^b Department of Paediatrics and Child health, Faculty of Medicine, University of Sydney, Sydney 2006, Australia

^c School of Physiotherapy, University of Sydney, Lidcombe 2141, Australia

Received 10 May 2005; accepted 2 August 2005

Abstract

Introduction. The limitations of clinical methods for appraising foot posture are well documented. A new measure, the Foot Posture Index is proposed, and its development and validation described.

Methods. A four-phase development process was used: (i) to derive a series of candidate measures, (ii) to define an appropriate scoring system, (iii) to evaluate the validity of components and modify the instrument as appropriate, and (iv) to investigate the predictive validity of the finalised instrument relative to static and dynamic kinematic models. Methods included initial concurrent validation using Rose's Valgus Index, determination of inter-item reliability, factor analysis, and benchmarking against three dimensional kinematic models derived from electromagnetic motion tracking of the lower limb.

Results. Thirty-six candidate components were reduced to six in the final instrument. The draft version of the instrument predicted 59% of the variance in concurrent Valgus Index scores and demonstrated good inter item reliability (Cronbach's $\alpha = 0.83$). The relevant variables from the motion tracking lower limb model predicted 58–80% of the variance in the six components retained in the final instrument. The finalised instrument predicted 64% of the variance in static standing posture, and 41% of the variance in midstance posture during normal walking.

Conclusion. The Foot Posture Index has been subjected to thorough evaluation in the course of its development and a final version is proposed comprising six component measures that performed satisfactorily during the validation process. The Foot Posture Index assessment is quick and simple to perform and allows a multiple segment, multiple plane evaluation that offers some advantages over existing clinical measures of foot posture.

© 2005 Elsevier Ltd. All rights reserved.

Keywords: Goniometric measurement; Electromagnetic motion tracking; Gait analysis

1. Introduction

There exists at present no universally accepted or adequately validated method for quantifying variation in foot posture in the clinical setting (Razeghi and Batt,

2002). Laboratory-based objective studies of lower limb function represent the gold-standard but require complex technology and lengthy examination, which is not practical in some settings. Many objective studies have also modelled the foot as a single rigid segment (Reischl et al., 1999), justifying any oversimplification on the basis of reduced error in these studies. Conversely, studies modelling the foot in more detail are often impaired by poor reliability and validity (Keenan and Bach, 1996; Reinschmidt et al., 1997).

* Corresponding author. Address: Academic Unit of Musculoskeletal Disease, Rheumatology, University of Leeds, Chapel Allerton Hospital, Harehills Lane, Leeds LS7 4SA, United Kingdom.

E-mail address: a.redmond@leeds.ac.uk (A.C. Redmond).

In recent years, organizations such as the Research Council of the American Orthopaedic Foot and Ankle Society (Saltzman et al., 1997), the Foot and Ankle Special Interest Group of the American Physical Therapy Association (McClay, 2001) and others (Keenan, 1997; Kitaoka et al., 1997) have highlighted as a priority, the need for better measures of foot pathology and indicated some of the features required of a new instrument. Recommended features include reliability, simplicity in use, quantitative output reflecting the complexity of foot function, minimisation of subjectivity, and the ability to undertake measures without the use of sophisticated equipment.

The aim of this paper is to describe a series of studies in which an instrument for better assessing foot posture was developed and refined from these principles. A four phase process is presented detailing the derivation of the measures, development of a scoring system, component selection and reduction, and final validation. The result is a six criterion observational scoring system that provides valid quantification of standing foot posture we named the Foot Posture Index (FPI).

2. Methods

2.1. Phase one: derivation of measures suitable for inclusion

In a comprehensive review of the literature, 119 papers were identified as describing in adequate detail, the clinical evaluation of foot posture. From these, 36 discrete clinical measures were identified and were classified according to how each represented the foot. Five categories were identified: (1) direct measures of foot posture, (2) indirect measures of foot posture, (3) philosophies or approaches to foot classification, (4) pseudo dynamic tests, (5) supplementary tests. A matrix was constructed to map the candidate measures against the desirable features noted previously, and based on their capacity to measure postural changes in each of the three body planes, and according to the anatomical segment to be evaluated (hindfoot/midfoot/forefoot/multiple). Eight potential measures were selected for a draft version of the FPI (Supplementary data—Supplemental Table 1).

The instrument was designed to be used with the subject in quiet double limb standing because: (a) weight-bearing measures better represent foot function than non-weightbearing measures (McClay, 2001), (b) this position is well-known to practitioners and (c) the populations in which the new measure will be used includes patients with balance and postural control problems.

2.2. Phase two: defining the scoring system

A five point Likert-type scale was chosen for rapidity of data collection (Likert, 1952), and to constrain re-

sponses to set criteria. Five point scales provide a reasonable compromise between sensitivity, reliability and ease of use (Bennett et al., 2001). The scale was anchored such that the central response was zero, with the sign of the deviation from this central response indicating the direction of postural change. The central value allows symmetrical scores to be derived either side of a nominal 'neutral' or normal position. The specific scoring criteria are individualized to each of the component measures and described in an accompanying manual available online at: <http://www.leeds.ac.uk/medicine/FASTER/FPI/>. The resulting aggregate scores for the initial eight-item version of the FPI ranged from -16 (supinated characteristics) to +16 (pronated characteristics), and the aggregate scores for the finalised FPI six-item version range from -12 to +12.

2.3. Phase three: component evaluation and reduction

An informal proof of concept evaluation, not reported here, demonstrated that the draft instrument had adequate clinical utility. The third phase examined the validity of the components and informed the reduction of components to create a final version of the instrument. The eight-item FPI scores were compared to concurrently derived Valgus Index scores (Rose, 1991) and in a second stage, a three-dimensional static lower limb model was reconstructed from data obtained from an electromagnetic motion tracking (EMT) system. Ordinal regression modelling was used to quantify the strength of the relationship between the EMT variables and each of the FPI components. Phase three, part one was approved by the research ethics committee of the University of Western Sydney of Sydney and part two by the research ethics committees of both the University of Western Sydney and the University of Sydney.

2.3.1. Phase three, part one: concurrent validity—field study

Foot Posture Index scores and Rose's Valgus Index were derived concurrently in a preliminary field trial. The Valgus Index was employed as it is objective and adequately valid (Thomson, 1994), and because it allowed for rapid collection of foot posture data from a large sample in the same non-laboratory setting for which the FPI was intended. FPI ratings were undertaken for each of 131 subjects while they stood on a 'pedograph', ink and paper mat. The Valgus Index was calculated later from the inked footprint. An ordinal regression model was constructed to evaluate the capacity of the total FPI eight-item score to predict the Valgus Index scores, and the inter-item reliability for each of the eight components was evaluated using Cronbach's α coefficient. A principal components analysis was also conducted to identify latent factors that were not apparent a priori, and to explore the uni-dimensionality of the measure.

The sample for this phase comprised 91(69.5%) male and 40(30.5%) female club athletes aged 18–65 (Mean = 33.7 years). The Valgus Index scores for the group ranged from -3.6 to 33.61 (Mean = 10.28, SD = 6.52), values in close agreement with normal values described previously (Rose, 1991; Thomson, 1994). FPI scores ranged from -7.0 to 15.0 (Mean = 4.9, SD = 3.9) and data from one limb only (decided by coin toss) were included in the inferential analyses. The ordinal regression model entered the FPI total score as the predictor (independent) variable, and Valgus Index score as the dependent variable. The linearity of the relationship was confirmed prior to undertaking the regressions. The ordinal regression modelling indicated that the FPI eight-item total scores predicted 59% of the variance in Valgus Index values (Cox and Snell $R^2 = 0.590$, $B = 0.551$, $P < 0.001$, $n = 131$).

The inter-item reliability is presented in Table 1. For the eight-item set, Cronbach's α was 0.834, indicating good inter-item reliability. The individual coefficients were high or very high for six of the eight FPI components. The components measuring Helbing's sign and the congruence of the lateral border of the foot showed poor inter-item reliability (Cronbach's $\alpha < 0.40$).

A principal components analysis with varimax rotation, was performed with extraction of factors with Eigenvalues greater than 0.9. The first factor extracted explained 49% of the variance in the FPI score (Supplementary data—Supplemental Table 2). This factor included seven of the FPI items. A second factor, explaining 12% of the variance, was primarily a function of the congruence of the lateral border of the foot (loading = 0.91), suggesting that a separate subgroup with variation in foot position independent of the lateral foot contour might be evident.

2.3.2. Phase three, part two: concurrent validity—laboratory study

To measure FPI ratings concurrently with a detailed objective measure of static foot posture, a Fastrak™

system was used to reconstruct a three-dimensional lower limb model for the right leg of 20 healthy volunteers (M = 9, F = 11, age range 21–45) in each of three positions. Two capture channels fed into a single motion capture unit sampling at 60 Hz. Channel one (c_1) collected data from a reference sensor fixed to the medial border of the tibia, while channel two (c_2) recorded the position and orientation of a sensor attached to a stylus, which was used to derive the Cartesian coordinates of 17 anatomical landmarks on the lower leg (Fig. 1). Rigid models of the shank, hindfoot and forefoot in each of three postures were reconstructed in software. The root mean square error of the protocol used to measure the landmark coordinates was between 0.87 mm and 2.54 mm. The intraclass correlation coefficient for the repeatability of segment definition using this protocol was 0.999.

Subjects were manipulated, according to a pre-determined randomisation protocol, into each of three positions: (i) a functionally neutral position corresponding to a '0' score using the FPI; (ii) a pronated stance position corresponding to the point of maximal internal tibial rotation and rearfoot eversion; (iii) a supinated stance position corresponding to the point of maximal external tibial rotation and rearfoot inversion.

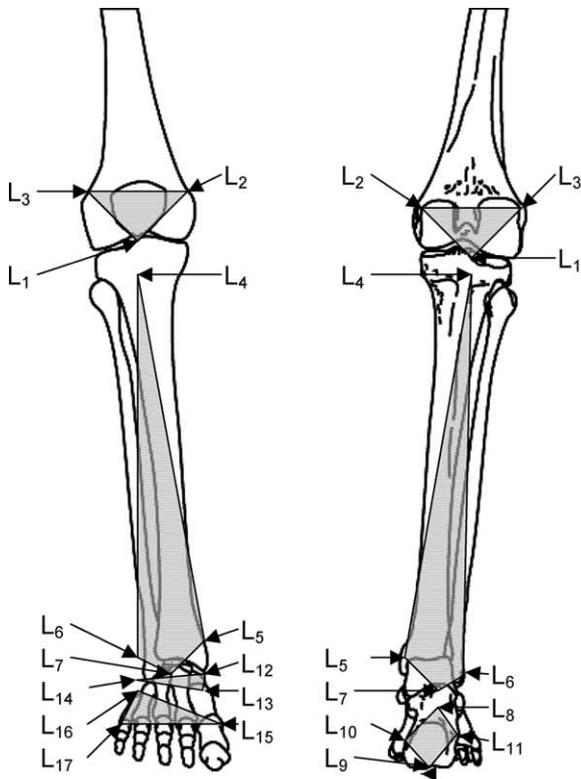
Postural variations in all three planes were calculated for five joint complexes:

Tibia (L ₄ –L ₇) to calcaneus (L ₈ –L ₁₁)	Designation	TC _{α,β,γ}
Tibia (L ₄ –L ₇) to forefoot (L ₁₅ –L ₁₇)	Designation	TF _{α,β,γ}
Calcaneus (L ₈ –L ₁₁) to forefoot (L ₁₅ –L ₁₇)	Designation	CF _{α,β,γ}
Calcaneus (L ₈ –L ₁₁) to midfoot (L ₁₂ –L ₁₄)	Designation	CM _{α,β,γ}
Midfoot (L ₁₂ –L ₁₄) to forefoot (L ₁₅ –L ₁₇)	Designation	MF _{α,β,γ}

Table 1
Cronbach's α for the eight components of the FPI-8

	Scale mean if item deleted	Scale variance if item deleted	Corrected item-total correlation	α if item deleted
Talar head palpation	4.1908	11.2633	0.6392	0.8042
Supra and infra lateral malleolar curvature	4.5573	12.1871	0.6353	0.8076
Helbing's sign	4.4809	12.0516	0.3635	0.8524
Prominence of the TNJ	4.4046	12.1966	0.6518	0.8062
Congruence of the medial longitudinal arch	4.5573	10.6179	0.7184	0.7917
Congruence of the lateral border of the foot	4.8397	14.2280	0.1987	0.8512
Abduction/adduction of the forefoot	4.5344	12.2661	0.6536	0.8066
Inversion/eversion of the calcaneus	4.3969	11.2412	0.7533	0.7895

Reliability coefficients: N of cases = 131; N of items = 8; $\alpha = 0.834$.



Legend

Segment	Landmark definition	Anatomical definition
Femur	L ₁	Base of patella
	L ₂	Medial femoral condyle
	L ₃	Lateral femoral condyle
Tibia	L ₄	Tibial tubercle
	L ₅	Medial malleolus
	L ₆	Lateral malleolus
	L ₇	Mid-point Achilles tendon
Calcaneus (hindfoot)	L ₈	Insertion of TA into calc
	L ₉	Lower calc
	L ₁₀	Medial heel
	L ₁₁	Lateral heel
Midfoot	L ₁₂	Navicular tuberosity
	L ₁₃	Navicular /cuneiform joint line
	L ₁₄	Cuboid notch
	Forefoot	L ₁₅
L ₁₆		5 th metatarsal base
L ₁₇		5 th metatarsal head

Fig. 1. Anatomical landmarks and segment definitions.

In addition, the frontal plane angle between markers L₇ (mid-point Achilles tendon), L₈ (insertion of Achilles tendon into calcaneus) and L₉ (lower calcaneus), was calculated to give an angle (AA)—the Achilles angle. Finally the true vertical height (*V*) of L₁₂ (the tuberosity of the navicular) was determined through triangulation from the positions and orientations of L₉, L₁₀, L₁₅ and L₁₇.

Each of the eight FPI components was entered in turn as the dependent variable into a series of ordinal regression models (Walters et al., 2001), and the contribution of the EMT measures to the explanation of variance in each FPI component score was established. The first iteration of each ordinal regression model entered all EMT variables, and subsequent iterations removed EMT variables not contributing to the model or demonstrating asymptotic correlation of covariates (colinearity or redundancy). The full model is presented as supplementary data (Supplementary data—Supplemental Table 3).

Six components demonstrated validity but two components caused concern. Firstly the FPI component measuring lateral border congruence did not fit the ordinal regression model, and so concurrent validity could not be established. Secondly, while the presence of Helbing’s sign was predicted moderately well ($R^2 = 0.73$) by a combination of four EMT variables, it was a concern that the EMT derived measure of ‘Achilles angle’—directly analogous to Helbing’s sign—was not retained in the final model.

2.3.3. Phase three, part three: component reduction

The performance of each of the eight components over the course of the previous phases of instrument development was used to inform the composition of the final draft of the instrument (Table 2).

The FPI component measuring lateral border congruence demonstrated poor fit to the regression model in the EMT study (no evidence of concurrent validity), loading onto a separate factor in the factor analysis (poor construct validity), and had a low inter-item

Table 2
Summary of the performance of the eight candidate components

	Item total correlation (Cronbach’s α)	Factor analysis (factor loading)	Concurrent validity vs EMT model (R^2)	Comments
Talar head palpation	0.64	Factor 1	0.70	Palpation of bony relationship
Malleolar curvature	0.66	Factor 1	0.69	Direct observation of bony segments
Helbing’s sign	0.36	Factor 1	0.74	Direct observation of soft tissue
Calcaneal angle	0.75	Factor 1	0.80	Direct observation of bony segment
TNJ congruence	0.65	Factor 1	0.72	Direct observation of composite bony segments
MLA congruence	0.72	Factor 1	0.58	Direct observation of composite bony segments
Lateral border congruence	0.20	Factor 2	N/A	Direct observation of composite bony segments
Abduction/adduction	0.65	Factor 1	0.64	Indirect observation of composite bony segments

correlation of $\alpha = 0.20$ (poor content validity). Furthermore, the theoretical overlap with the component measuring forefoot abduction/adduction, introduced some redundancy (poor construct validity) and so the lateral border congruence component was deleted from the final draft of the new instrument.

The FPI measure of medial arch congruence was also among the poorer performing measures in the EMT concurrent validity study, but had shown good inter-item correlation of $\alpha = 0.72$ (adequate content validity). This measure was considered to have low redundancy, being the only measure of sagittal plane foot posture and the medial arch measure was therefore retained.

The FPI measure of Helbing’s sign had demonstrated a low inter-item correlation (Cronbach’s $\alpha = 0.36$) which again indicated poor content validity. The absence of any significant relationship with EMT measured Achilles angle indicated poor concurrent and construct validity. Helbing’s sign was the only FPI component to rely on observation of soft tissue relationships, and was one of three measures of estimating rearfoot position in the frontal plane, indicating some redundancy. The measure describing Helbing’s sign was therefore deleted from the final FPI draft also. The remaining five components were retained. A sample datasheet for the finalised six-item version of the instrument (FPI-6) is presented in Table 3.

2.4. Phase four: concurrent and predictive validity of the finalised FPI-six item version

The aims of the fourth phase were to:

- (i) Evaluate the concurrent validity of finalised FPI-6 scores against a validated static EMT model of the ankle joint complex (AJC).
- (ii) Determine the extent to which static FPI-6 scores predict systematic variations in AJC position during normal walking.

Comparison of FPI measures (six-item version) with contemporaneous static and dynamic EMT data derived from surface mounted sensor data, using a six degrees of freedom ankle joint complex model. Ethical approval was provided by the local research ethics committee of the University of Sydney.

Ankle joint complex positions and motions were captured using a Fastrak™ electromagnetic motion tracking system (Polhemus Inc., Colchester VT., USA), employing a long range transmitter and capturing at 30 Hz. Within the capture volume used in this study of 800 mm (X direction) by 1300 mm (Y direction) by 600 mm (Z direction), the root mean square error associated with angular rotation were determined for our setup to be 0.8° for α rotations, 0.6° for β rotations, and 0.4° for γ rotations. In the dynamic studies, the participants

Table 3
 Datasheet for the six-item Foot Posture Index

Foot Posture Index (6-item) Datasheet

<i>Patient name</i>		<i>ID number</i>					
COMPONENT	PLANE	SCORE 1		SCORE 2		SCORE 3	
		Date _____	Comment _____	Date _____	Comment _____	Date _____	Comment _____
		Left (-2 to +2)	Right (-2 to +2)	Left (-2 to +2)	Right (-2 to +2)	Left (-2 to +2)	Right (-2 to +2)
Rearfoot	Talar head palpation	Transverse					
	Curves above and below lateral malleoli.	Frontal/ trans					
	Inversion/eversion of the calcaneus	Frontal					
Forefoot	Bulge in the region of the TNJ	Transverse					
	Congruence of the medial longitudinal arch	Sagittal					
	Abduction/adduction of the forefoot on the rear foot (too-many-toes).	Transverse					
TOTAL							

started walking at one end of a 9 m walkway and passed uninterrupted through the calibrated capture volume at a self-selected walking pace, continuing to the far end of the walkway. Stance phase events were appended using force sensing resistors (Interlink Electronics Inc, Santa Barbara CA, USA), taped to the hallux and heel. Sensor data were filtered and synchronised by the 6D ResearchTM motion analysis software package (Skill Technologies Inc., Phoenix, AZ, USA) as described in detail previously (Woodburn et al., 1999).

Using the ankle joint coordinate system defined by Wu et al. (2002), segmental models were constructed for three planes, although only motions for AJC inversion/eversion (AJC_β) are reported here.

Fifteen healthy volunteers were recruited from the staff and postgraduate students of the Rheumatology and Rehabilitation Research Unit, at the University of Leeds (Male = 10, Female = 5, age range 18–57). Both limbs were instrumented on each participant, with the sensors measuring AJC motions placed according to a protocol described previously (Cornwall and McPoil, 1999).

Participants undertook the walking trials (and related static measures) in each of three conditions in random order:

- (i) A control condition representing the participants' natural standing or walking position/motion.
- (ii) An everted position induced by the application of a preformed 450 kg/m³, high density 10° ethylene vinyl acetate wedge under the heel, oriented with the thick edge parallel with the lateral border of the heel (the lateral wedge condition).
- (iii) An inverted position induced by the application of a 10° ethylene vinyl acetate wedge under the heel, with the thick edge of the wedge parallel to the medial border of the heel (the medial wedge condition).

The EMT system was calibrated to zero prior to data collection with the subject standing on a spot marked in the centre of the capture volume. While standing on this spot, the participant was manipulated into a position equating a zero score for the FPI-6, with the ankle at 90° and the knee straight. This position subsequently acted as a reference for all future measures.

After the two familiarisation passes of the 9 m walkway, participants returned to the centre of the capture volume and five seconds of static data were recorded along with contemporaneous derivation of FPI scores. Participants then returned to the end of the walkway to undertake the walking trials at a self selected speed. One full gait cycle was obtained for each pass, with five good gait cycles recorded for each of the barefoot and wedged conditions. Angular rotation data from the walking trials were post-processed to 100 centiles of the gait cycle using Cornwall's '6DNorm' software as described by Wood-

burn et al. (Woodburn et al., 1999) and coefficients of multiple correlation (CMCs) were calculated as described by Kadaba et al. (Kadaba et al., 1989).

2.5. Analysis

Descriptive outputs such as the motion time curves were based on pooled data from both limbs ($n = 30$), but inferential analyses (Table 4) were performed on data from the right limb only to avoid breaching the assumption of independence in the dataset (Menz, 2004). Concurrent validity was investigated using linear regression modeling because the large number of levels (25) in the FPI total score represent an underlying scale that is effectively continuous and therefore suitable for parametric analysis (Cohen, 2001; Walters et al., 2001). Prior to constructing linear regression models all data were scatterplotted to check for linearity in the relationships, and Levene's test was used to test for homogeneity of variances.

3. Results

3.1. Static condition

Static positional data for one participant were found to be unusable at post-processing, and static data relate to 14 participants (five female and nine male). A linear regression model was constructed with static AJC_β entered as the dependent variable and FPI-6 total score entered as the independent variable. The FPI-6 scores predicted 64% of the variation in the static AJC_β position during quiet double limb standing (adjusted $R^2 = 0.64$, $F = 73.529$, $P < 0.001$, $n = 14$).

3.2. Dynamic condition

Ankle joint complex kinematic data were obtained from all 15 participants for five passes of the walkway in each condition. The within-subject coefficient of multiple correlation for for AJC_α was 0.93 and a systematic shift was evident between the conditions (Table 4, Fig. 2).

It has been suggested previously that the midstance instant of the stance phase is related theoretically to the position assumed by the foot in static stance (McPoil and Hunt, 1995). The relationships between the static EMT position and the dynamic EMT data were investigated at various discrete points (Table 5), and midstance was confirmed as the point at which the static and dynamic AJC_β rotations are most closely related ($R = 0.864$). The instant of midstance was entered therefore, as the dependent variable for exploration in the predictive regression modelling, with the FPI-6 total score entered as the sole independent variable. The data were plotted, demonstrating a suitably linear relation-

Table 4
Mean ($\pm 95\%$ CI) AJC_{β} angular rotation at key stance events

	Lateral wedge (95% CI)	Control (95% CI)	Medial wedge (95% CI)	ANOVA model	Significance of relationships ($N = 15$)
Max	-1.3 (-2.4 to -0.1)	-0.7 (-1.8 to -0.3)	+2.1 (+1.0 to +3.3)	$F = 47.42$ ($P < 0.001$)	Lat-Con, $P = 0.592$ Con-Med, $P < 0.001$ Lat-Med, $P < 0.001$
Min	-8.3 (-9.3 to -7.1)	-8.5 (-9.5 to -7.6)	-5.8 (-6.9 to -4.7)	$F = 52.47$ ($P < 0.001$)	Lat-Con, $P = 1.00$ Con-Med, $P < 0.001$ Lat-Med, $P < 0.001$
HS	-2.3 (-3.5 to -1.1)	-3.1 (-4.1 to -2.1)	-1.9 (-3.1 to -0.8)	$F = 2.247$ ($P < 0.145$)	N/A
FF	-3.4 (-4.5 to -2.3)	-2.5 (-3.4 to -1.6)	+0.9 (-0.2 to +2.1)	$F = 12.58$ ($P = 0.001$)	Lat-Con, $P = 0.102$ Con-Med, $P < 0.001$ Lat-Med, $P < 0.001$
MS	-6.6 (-7.6 to -5.7)	-5.6 (-6.4 to -4.7)	-1.5 (-2.5 to -0.4)	$F = 135.9$ ($P < 0.001$)	Lat-Con, $P = 0.104$ Con-Med, $P < 0.001$ Lat-Med, $P < 0.001$
HL	-7.8 (-8.9 to -6.7)	-7.9 (-8.8 to -7.1)	-4.6 (-5.6 to -3.6)	$F = 250.78$ ($P < 0.001$)	Lat-Con, $P = 1.00$ Con-Med, $P < 0.001$ Lat-Med, $P < 0.001$
TO	-2.7 (-4.2 to -1.3)	-2.6 (-4.0 to -1.1)	-1.7 (-3.2 to -0.2)	$F = 11.45$ ($P = 0.002$)	Lat-Con, $P = 1.00$ Con-Med, $P = 0.047$ Lat-Med, $P = 0.006$
Integral	-336.2 (-397.3 to -275.4)	-303.8 (-354.1 to -253.6)	-108.1 (-167.8 to -48.4)	$F = 98.83$ ($P < 0.001$)	Lat-Con, $P = < 0.538$ Con-Med, $P < 0.001$ Lat-Med, $P < 0.001$

Lat = laterally wedged condition; Con = control condition (the no wedged condition); Med = medially wedged condition. All values are angles in degrees except for the integral, which represents the area under the curve. For β rotations, positive values represent inversion, and negative values eversion. Significance of individual relationships (contrasts) was only calculated and itemised in Column 6 where the overall ANOVA model reached statistical significance.

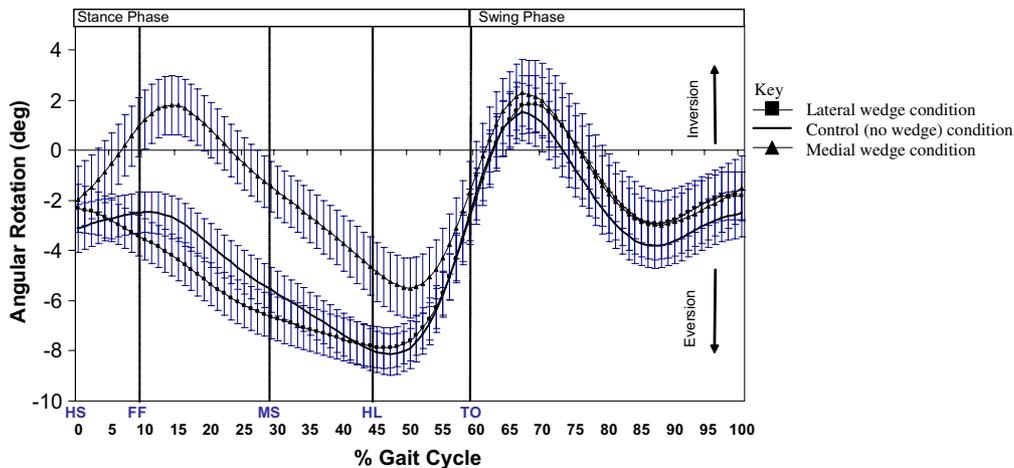


Fig. 2. Motion time curves for AJC_{β} ($N = 30$, Mean $\pm 95\%$ CI).

ship, and the homogeneity of variance was again checked with Levene’s statistic. The resulting linear regression model ($n = 15$) yielded an adjusted R^2 of 0.41 ($F = 31.786$, $P < 0.001$) indicating that the FPI total score predicted 41% of the dynamic variation in midstance foot position.

4. Discussion

A variety of measures exist for quantifying foot posture and function, including radiographic techniques, direct anatomical measures, footprint evaluations, and dynamic laboratory analyses (Brosh and Arcan, 1994;

Table 5

Correlations (Pearson's R) between AJC_{β} motion data at key gait cycle events, and measures obtained during quiet standing (AJC_{β} static and FPI-6 score)

	Dynamic AJC_{β} at key stance phase events							
	Minimum	Maximum	Heel strike	Foot flat	Midstance	Heel lift	Toe-off	Integral
Static AJC_{β} ($n = 14$)	$R = 0.705$ ($P < 0.001$)	$R = 0.724$ ($P < 0.001$)	$R = 0.428$ ($P = 0.005$)	$R = 0.713$ ($P = 0.001$)	$R = 0.864$ ($P = 0.001$)	$R = 0.815$ ($P < 0.001$)	$R = 0.414$ ($P = 0.006$)	$R = 0.828$ ($P < 0.001$)
FPI-6 score ($n = 15$)	$R = -0.458$ ($P < 0.001$)	$R = -0.520$ ($P < 0.001$)	$R = -0.060$ ($P = 0.694$)	$R = -0.474$ ($P = 0.001$)	$R = -0.652$ ($P < 0.001$)	$R = -0.544$ ($P < 0.001$)	$R = -0.222$ ($P = 0.142$)	$R = -0.565$ ($P < 0.001$)

Cavanagh et al., 1997; Williams and McClay, 2000). Laboratory gait analysis remains the gold-standard, but the facilities to produce high-quality objective data are expensive, and the process of acquiring the data can be overly time-consuming for routine patient assessment. Radiographic imaging is similarly demanding and cannot be justified for routine screening because of the risks associated with exposing subjects to ionising radiation. As an objective clinical alternative, measures based on footprints are sometimes used, and while these have proven relatively reliable (Cavanagh and Rodgers, 1987; Freychat et al., 1996), the relationship between these measures and dynamic function is variable (Cavanagh and Rodgers, 1987; Hawes et al., 1992; Weiner-Ogilvie and Rome, 1998).

The most common approach to assessing the foot in routine clinical practice remains direct measurement of the angles and positions of anatomical landmarks. The most commonly reported measures are the angular relationship of the calcaneus, either relative to the leg or the floor, and measures of arch height. Estimates of the reliability of the techniques vary greatly (Jonson and Gross, 1997), but the majority of accounts suggest limited reliability (LaPointe et al., 2001; Weiner-Ogilvie and Rome, 1998; Williams et al., 1999). Direct measurement of the height of medial arch of the standing foot appears to be more reliable than most other measures (Saltzman et al., 1995; Williams and McClay, 2000) and relative measures such as navicular drop have also been reported to be reliable (Mueller et al., 1993; Weiner-Ogilvie and Rome, 1998). The application of such measures remains limited however, because only one aspect of foot posture is measured.

The application of a common scoring system across the component measures represents a novel approach, and is potentially the most important aspect of the new instrument. By introducing a dimensionless index system to replace a range of measures in millimetres, degrees and other units, the FPI component scores can be aggregated to cover multiple planes and anatomical segments. The five-point Likert system is observational, but adherence to clearly defined criteria introduces objective boundaries and minimises the subjectivity.

It is a strength of the FPI that aggregate scores may be interpreted as they relate to the separate hindfoot and

forefoot segments or according to the three body planes (Table 3). As a consequence, one potential weakness of the composite measure, i.e. the potential for the same total scores to reflect varying combinations of component scores, can be turned to the user's advantage. Simple review of total score may be useful for within-subject comparisons or for providing threshold values while disaggregated scores may provide more detailed information for between-subject comparisons or for clinical decision making. This richness of information yielded by review of segment or planar scores exceeds that available from widely-used single plane measures such as calcaneal angle or arch height.

The 59% of variance in the Valgus Index scores predicted by the original FPI eight-item draft was higher than many accounts of agreement between clinical measures noted in the literature (Hawes et al., 1992; Mueller et al., 1993) and was considered acceptable for the first draft of the new measure.

Early drafts of the FPI were shared with independent research groups and reports of the reliability and validity of the FPI eight-item version have appeared in the literature (Evans et al., 2003; Payne et al., 2003; Scharf-billig et al., 2004; Yates and White, 2004).

The reported inter-tester reliability of the eight item FPI has ranged from 0.62 to 0.91, depending on population, and intra-tester reliability ranges from 0.81 to 0.91 (Evans et al., 2003; Payne et al., 2003; Yates and White, 2004). A previous study of component validity (Scharf-billig et al., 2004), which included the first author (ACR) employed radiography as the gold-standard but was unable to substantiate the validity of the FPI component scores. The strength of any inference that can be drawn from the radiographic study are limited however by methodological shortcomings such as between-day variations in the protocol, and poor systematic change in radiographic measure with change in clinical position. This led to concerns over the 'gold-standard' radiographic variables against which FPI component scores were being compared. These shortcomings have been largely addressed by the protocol detailed in phase three, part two in which the use of a stylus-based EMT system allowed accurate and repeatable definition of anatomical segments and the systematic shift seen in Table 4. This provided for the

construction of a more robust and detailed model than had been achievable previously.

The finalised FPI-6 demonstrated adequate concurrent validity when compared to a skin-mounted-sensor defined static model, which indicates that the constrained, criterion-based observational scoring system reflects adequately, the variations in posture detected simultaneously by the EMT measure. More important however is the capacity of the static clinical measure to predict dynamic positions.

Validated models for measurement of kinematics at the ankle joint complex using EMT have been reported (Woodburn et al., 1999), and the approach was appropriate for capturing small motions to a high degree of accuracy, and within a confined capture volume. Issues over the constraints imposed by the tethered nature of the EMT sensor setup, low sampling frequency and the sensitivity to ferro-magnetic interference have been noted previously (Poulin and Amiot, 2002) but these issues were less relevant to the controlled laboratory environment used in this study. The protocol we used provided acceptable accuracy in our laboratory measurement of low velocity AJC motions, yielding a root mean square error of less than 0.8° angular rotation. The dynamic EMT data obtained in this study appear to represent an adequate benchmark, as they are in close accord with previous data for both the absolute values observed, and the reliability coefficients of the measures (Cornwall and McPoil, 1999; Nester et al., 2003; Pierrynowski and Smith, 1996).

Once the variability introduced by dynamic function is included in the regression modelling, the strength of the relationship between the FPI-6 as a static clinical measure and the EMT data is weaker than for the concurrent static measures, in common with previous studies (Cavanagh et al., 1997; McPoil and Cornwall, 1996a). Nevertheless the FPI-6 score predicted over 40% of the variance in dynamic AJC_β , a stronger association than in most reports in the literature for pairs of static and dynamic measures (Cashmere et al., 1999; McPoil and Cornwall, 1996b). In common with previous studies of composite measures (Cavanagh et al., 1997), this suggests that the composite nature of the FPI, accounting for variation in all three body planes, may provide a more complete description of foot posture than most currently used static clinical measures.

5. Conclusion

The FPI has been developed to address a need for a valid clinical tool that measures foot posture in multiple planes and anatomical segments. It is not intended to replace dynamic studies, which remain the ideal, but to provide a more valid alternative to existing static clinical measures when laboratory studies are not feasible. The

development of the FPI-6 has been undertaken in a structured and formal manner, informed by the literature and the instrument has been adapted to ensure appropriate component validity and clinical utility.

The FPI, in both its draft version and the final six-item version, has been subjected to a thorough validation process. In a number of independent evaluations of reliability, the FPI has proven adequately reliable in varied clinical settings (Intraclass correlation coefficients = 0.62–0.91) (Evans et al., 2003; Noakes and Payne, 2003; Yates and White, 2004). The strength of the association between the FPI scores and static EMT data seen in the current study further supports the validity of the FPI-6. The ability of the static measure to predict variance in AJC kinematics obtained during walking was higher than for other clinical measures reported in the literature. The final six-item version of the FPI includes only those components that passed a thorough validation process and it is recommended that use of the FPI eight-item version reported previously, is discontinued.

Acknowledgements

This work was supported financially by the UK Arthritis Research Campaign and a Moore Fellowship from the Charcot-Marie-Tooth Association of the United States.

The authors are also grateful for the support of many of the staff at the Children's Hospital Westmead and the Universities of Sydney, South Australia, Western Sydney and Leeds for their assistance in the validation process, with Joshua Burns, Elizabeth Barr, Dr. Jim Woodburn and Dr. Jenny Peat warranting particular mention.

Supplementary data

Supplementary data associated with this article can be found, in the online version at [doi:10.1016/j.clinbiomech.2005.08.002](https://doi.org/10.1016/j.clinbiomech.2005.08.002).

References

- Bennett, M.E., Tulloch, J.F., Vig, K.W., Phillips, C.L., 2001. Measuring orthodontic treatment satisfaction: questionnaire development and preliminary validation. *Journal of Public Health Dentistry* 61 (3), 155–160.
- Brosh, T., Arcan, M., 1994. Toward early detection of the tendency to stress fractures. *Clinical Biomechanics* 9 (2), 111–116.
- Cashmere, T., Smith, R., Hunt, A., 1999. Medial longitudinal arch of the foot: stationary versus walking measures. *Foot & Ankle International* 20 (2), 112–118.
- Cavanagh, P.R., Rodgers, M.M., 1987. The arch index: a useful measure from footprints. *Journal of Biomechanics* 20 (5), 547–551.

- Cavanagh, P.R., Morag, E., Boulton, A.J., Young, M.J., Definer, K.T., Pammer, S.E., 1997. The relationship of static foot structure to dynamic foot function. *Journal of Biomechanics* 30 (3), 243–250.
- Cohen, M.E., 2001. Analysis of ordinal dental data: evaluation of conflicting recommendations. *Journal of Dental Research* 80 (1), 309–313.
- Cornwall, M.W., McPoil, T.G., 1999. Three dimensional movement of the foot during the stance phase of gait. *Journal of the American Podiatric Medical Association* 89 (2), 56–66.
- Evans, A.M., Copper, A.W., Scharfbillig, R.W., Scutter, S.D., Williams, M.T., 2003. The reliability of the foot posture index and traditional measures of foot position. *Journal of the American Podiatric Medical Association* 93 (3), 203–213.
- Freychat, P., Belli, A., Carret, J.P., Lacour, J.R., 1996. Relationship between rearfoot and forefoot orientation and ground reaction forces during running. *Medicine & Science in Sports & Exercise* 28 (2), 225–232.
- Hawes, M.R., Nachbauer, W., Sovak, D., Nigg, B.M., 1992. Footprint parameters as a measure of arch height. *Foot & Ankle* 13 (1), 22–26.
- Jonson, S.R., Gross, M.T., 1997. Intraexaminer reliability, interexaminer reliability, and mean values for nine lower extremity skeletal measures in healthy naval midshipmen. *Journal of Orthopaedic & Sports Physical Therapy* 25 (4), 253–263.
- Kadaba, M., Ramakrishnan, H., Wootten, M.E., Gainey, J., Gorton, G., Cochran, G.V., 1989. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research* 7 (6), 849–860.
- Keenan, A.-M., 1997. A clinician's guide to the practical implications of the recent controversy of foot function. *Australasian Journal of Podiatric Medicine* 31 (3), 87–93.
- Keenan, A., Bach, T.M., 1996. Video assessment of rearfoot movements during walking: a reliability study. *Archives of Physical Medicine & Rehabilitation* 77 (7), 651–655.
- Kitaoka, H.B., Zong Ping, L., An, K.N., 1997. Effect of the posterior tibial tendon on the arch of the foot during simulated weightbearing: Biomechanical analysis. *Foot & Ankle International* 18 (1), 43–46.
- LaPointe, S.J., Peebles, C., Nakra, A., Hillstrom, H., 2001. The reliability of clinical and caliper-based calcaneal bisection measurements. *Journal of the American Podiatric Medical Association* 91 (3), 121–126.
- Likert, R.A., 1952. A technique for the development of attitude scales. *Educational and psychological measurement* 12, 313–315.
- McClay, I.S., 2001. Report of "Static and dynamic classification of the foot" meeting, Annapolis, Maryland, May 2000. *Journal of Orthopaedic and Sports Physical Therapy* 31 (3), 158.
- McPoil, T.G., Hunt, G.C., 1995. Evaluation and management of foot and ankle disorders: present problems and future directions. *Journal of Orthopaedic & Sports Physical Therapy* 21 (6), 381–388.
- McPoil, T.G., Cornwall, M.W., 1996a. Relationship between three static angles of the rearfoot and the pattern of rearfoot motion during walking. *Journal of Orthopaedic & Sports Physical Therapy* 23 (6), 370–375.
- McPoil, T.G., Cornwall, M.W., 1996b. The relationship between static lower extremity measurements and rearfoot motion during walking. *Journal of Orthopaedic & Sports Physical Therapy* 24 (5), 309–314.
- Menz, H.B., 2004. Two feet, or one person? Problems associated with statistical analysis of paired data in foot and ankle medicine. *The Foot* 14 (1), 2–5.
- Mueller, M.J., Host, J.V., Norton, B.J., 1993. Navicular drop as a composite measure of excessive pronation. *Journal of the American Podiatric Medical Association* 83 (4), 198–202.
- Nester, C.J., van der Linden, M.L., Bowker, P., 2003. Effect of foot orthoses on the kinematics and kinetics of normal walking gait. *Gait & Posture* 17 (2), 180–187.
- Noakes, H., Payne, C., 2003. The reliability of the manual supination resistance test. *Journal of the American Podiatric Medical Association* 93 (3), 185–189.
- Payne, C., Oates, M., Noakes, H., 2003. Static stance response to different types of foot orthoses. *Journal of the American Podiatric Medical Association* 93 (6), 492–498.
- Pierrynowski, M.R., Smith, S.B., 1996. Rear foot inversion/eversion during gait relative to the subtalar joint neutral position. *Foot & Ankle International* 17 (7), 406–412.
- Poulin, F., Amiot, L.P., 2002. Interference during the use of an electromagnetic tracking system under OR conditions. *Journal of Biomechanics* 35 (6), 733–737.
- Razeghi, M., Batt, M.E., 2002. Foot type classification: a critical review of current methods. *Gait & Posture* 15, 282–291.
- Reinschmidt, C., Van den Bogert, A.J., Murphy, N., Lundberg, A., Nigg, B.M., 1997. Tibiocalcaneal motion during running, measured with external and bone markers. *Clinical Biomechanics* 12 (1), 8–16.
- Reischl, S.F., Powers, C.M., Rao, S., Perry, J., 1999. Relationship between foot pronation and rotation of the tibia and femur during walking. *Foot & Ankle International* 20 (8), 513–520.
- Rose, G.K., 1991. *Pes Planus*. In: Jahss, M. (Ed.), *Disorders of the Foot and Ankle: Medical and Surgical Management*, second ed. WB Saunders, Philadelphia, pp. 892–920.
- Saltzman, C.L., Nawoczenski, D.A., Talbot, K.D., 1995. Measurement of the medial longitudinal arch. *Archives of Physical Medicine & Rehabilitation* 76 (1), 45–49.
- Saltzman, C.L., Domsic, R.T., Baumhauer, J.F., Deland, J.T., Gill, L.H., Hurwitz, S.R., et al., 1997. Foot and ankle research priority: report from the Research Council of the American Orthopaedic Foot and Ankle Society. *Foot & Ankle International* 18 (7), 447–448.
- Scharfbillig, R., Evans, A.M., Copper, A.W., Williams, M., Scutter, S., Iasiello, H., Redmond, A., 2004. Criterion validation of four criteria of the foot posture index. *Journal of the American Podiatric Medical Association* 94 (1), 31–38.
- Thomson, C.E., 1994. An investigation into the reliability of the valgus index and its validity as a clinical measurement. *Foot* 4 (4), 191–197.
- Walters, S.J., Campbell, M.J., Lall, R., 2001. Design and analysis of trials with quality of life as an outcome: a practical guide. *Journal of Biopharmaceutical Statistics* 11 (3), 155–176.
- Weiner-Ogilvie, S., Rome, K., 1998. The reliability of three techniques for measuring foot position. *Journal of the American Podiatric Medical Association* 88 (8), 381–386.
- Williams, D., McClay, I., Laughton, C., 1999. A comparison of between day reliability of different types of lower extremity kinematic variables in runners. Paper presented to 23rd Annual Meeting of the American Society of Biomechanics, University of Pittsburgh, 21–23 October.
- Williams, D.S., McClay, I.S., 2000. Measurements used to characterize the foot and the medial longitudinal arch: reliability and validity. *Physical Therapy* 80 (9), 864–871.
- Woodburn, J., Turner, D.E., Helliwell, P.S., Barker, S., 1999. A preliminary study determining the feasibility of electromagnetic tracking for kinematics at the ankle joint complex. *Rheumatology* 38 (12), 1260–1268.
- Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M., D'Lima, D.D., Cristofolini, L., Witte, H., Schmid, O., Stormont, D.M., 2002. ISB recommendation on definition of joint coordinate system of various joints for the reporting of human joint motion—part I: ankle, hip and spine. *Journal of Biomechanics* 35, 543–548.
- Yates, B., White, S., 2004. The incidence and risk factors in the development of medial tibial stress syndrome among naval recruits. *American Journal of Sports Medicine* 32 (3), 772–780.