Multisegment Foot Motion During Gait: Proof of Concept in Rheumatoid Arthritis

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ABSTRACT. ***Objective.*** To test a multisegment foot model for kinematic analysis during barefoot walking in patients with well established rheumatoid arthritis (RA) and foot impairments.

Methods. Five healthy adult subjects and 11 RA patients with advanced disease were studied. Foot impairments were assessed using standardized outcomes and clinical examination techniques. A 6-camera 60 Hz video-based motion analysis system was used to measure motion of the shank, rearfoot, forefoot, and hallux segments and the vertical displacement of the navicular. Face validity and estimates of repeatability were determined. Motion patterns were calculated and comparisons were made between healthy subjects and patients with RA. Relationships between clinical impairment and abnormal motion were determined through inspection of individual RA cases.

Results. Across the motion variables, the within-day and between-day coefficient of multiple correlation values ranged from 0.677 to 0.982 for the healthy subjects and 0.830 to 0.981 for RA patients. Based on previous studies, motion parameters for the healthy subjects showed excellent face validity. In RA patients, there was reduced range of motion across all segments and all planes of motion, which was consistent with joint stiffness. In the RA patients, rearfoot motion was shifted towards eversion and external rotation and peak values for these variables were increased, on average, by 7° and 11°, respectively. Forefoot range of motion was reduced in all 3 planes (between 31% and 53%), but the maximum and minimum angles were comparable to normal. The navicular height, during full foot contact, was on average 3 mm lower in the RA patients in comparison to normal. The hallux was less extended in the RA subjects in comparison to normal (21° vs 33°) during the terminal stance phase. Individual cases showed abnormal patterns of motion consistent with their clinical impairments, especially those with predominant forefoot pain or pes planovalgus.

Conclusion. In RA, multisegment foot models may provide a more complete description of foot motion abnormalities where pathology presents at multiple joints, leading to complex and varied patterns of impairment. This technique may be useful to evaluate functional changes in the foot and to help plan and assess logical, structurally based corrective interventions. (J Rheumatol 2004; 31:1918–27)

Key Indexing Terms:
MULTISEGMENT FOOT KINEMATICS RHEUMATOID ARTHRITIS FOOT IMPAIRMENTS

Existing motion analysis techniques do not easily permit measurement of movement between the small joints of the foot during walking; however, by combining individual bones into larger and more accessible segments, functional units can be formed for the rearfoot, midfoot, forefoot, and great toe. Recently, a number of multisegment foot models have been developed to measure and describe normal motion in the foot[1-4], and these techniques appear to be reproducible and yield moderately consistent patterns of motion. There have been limited applications to diseases such as the arthritides, which are associated with clinically recognizable changes in foot joint motion. Nevertheless, preliminary studies are encouraging; for example, Rattanaprasert, *et al* presented a case showing abnormal motion in the rearfoot and the forefoot consistent with medial longitudinal arch instability caused by tibialis posterior dysfunction[2].

A multisegment approach to foot motion analysis is conceptually appealing in rheumatoid arthritis (RA), since this inflammatory disease causes progressive destruction of many synovial joints of the foot leading to well recognized clinical signs and symptoms associated with changes in joint motion and alignment[5-7]. A multisegmental approach will help decipher which impairments are associated with

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A UK Medical Research Council Clinician Scientist Fellowship award supported the work of Dr. Woodburn.

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Submitted December 15, 2003; revision accepted May 14, 2004.

common signs and symptoms and support better direct clinical intervention. Disease in the subtalar and midtarsal joints and tenosynovitis of the medial tendons are associated with acquired pes planovalgus[7,8]. In early disease, onset of deformity is precipitated by soft tissue laxity, while in chronic disease joint erosion and subluxation may lead to joint stiffness. In the forefoot, inflammation and destruction of the metatarsophalangeal (MTP) joints leads to hallux valgus and hammer and claw toe deformities[7,9-11], and these joints have a tendency towards subluxation, stiffness, and fixed deformities. Antalgic gait is also associated with the painful rheumatoid foot.

Since the foot is a weight-bearing structure, the understanding of normal and abnormal function can be greatly aided by gait analysis[1]. Abnormal function in RA has been described in the foot modeled as a single segment[5,11] and for the rearfoot modeled as a joint complex consisting of the ankle and subtalar joints[6,8,12,13]. In single-segment models prolonged dorsiflexion, loss of plantarflexion movement, and delayed heel lift during terminal stance are motion deficits that characterize loss of rocker function associated with forefoot impairments[5,11], while increased eversion movement typifies the mobile pronated foot[5]. The latter is a functional consequence of acquired pes planovalgus in RA, and detailed motion studies have consistently shown excessive and prolonged rearfoot eversion coupled with internal rotation of the leg in this foot type[6,8,12,13].

Analysis of foot motion in RA using a multisegment foot model is a logical extension to previous work. The proof-of-concept reported here provides a description of a multisegment foot model, initial verification of the consistency of the patterns of foot motion with existing knowledge, quantification of within- and between-day repeatability, and a preliminary comparison of foot motion between healthy adults and patients with RA.

MATERIALS AND METHODS

Patients. Eleven patients with RA (fulfilling the American College of Rheumatology criteria[14]) and clinical evidence of foot impairments were recruited from the Rehabilitation Medicine Department and the National Institute of Arthritis and Musculoskeletal and Skin Diseases (NIAMS) of the National Institutes of Health. Patients were eligible if they had one or more features of pain, deformity, or stiffness in the tibiotalar, rearfoot, or forefoot joints, and provided informed consent indicating their willingness to participate in this study. Five healthy adults with no recent history of musculoskeletal disease or injury to the lower limb or foot were similarly recruited for comparisons. These subjects were recruited on the basis that their foot motion parameters approximated normal values as reported[3,6].

Clinical data. The age, sex, disease duration, and current disease modifying antirheumatic drug (DMARD) were recorded for each patient. Body height and mass were measured. A standard clinical examination of the feet was undertaken to determine the sites and severity of swollen and tender joints, soft tissue pathologies including tenosynovitis and bursitis, and range of motion (ROM). Fore and rearfoot deformities were quantified using the Structural Index (SI) score[15], and ambulation was quantified on the ambulation subscale of the Sickness Impact Profile[16]. The varus/valgus alignment of the heel — the Relaxed Standing Foot Posture (RSFP) — was measured using a goniometer[17].

Motion analysis. A 6-camera 60 Hz video-based motion analysis system (Vicon 370, Oxford Metrics Group, Oxford, UK) was used to track the motion of reflective targets placed on the shank and foot. The targets consisted of a combination of 19 mm diameter spherical and 10 mm diameter hemispherical reflective markers attached either directly to the skin using double-sided tape (Figure 1A) or as an array mounted on lightweight thermoplastic moulded plates for the lateral shank (Figure 1B) and rearfoot (Figure 1C). Visual3D software (C-motion, Inc., Rockville, MD, USA) was used to build models for each segment based on the coordinates of the markers placed over specific anatomical landmarks during static calibration. Marker placement and segment models were based on those described by Carson, *et al*[3]. From the walking trials segmental and joint kinematics were calculated that defined motion between the rearfoot and shank as dorsiflexion(+)/plantarflexion(–), inversion(+)/eversion(–), and internal(+)/external(–) rotation. Motion between the forefoot and rearfoot was defined as dorsiflexion(+)/plantarflexion(–), inversion(+)/eversion(–), and adduction(+)/abduction(–). Navicular height was calculated from the vertical component of the trajectory of a single marker placed over the tuberosity of the navicular. This measures the location of the navicular above the floor and reflects deformation of the medial longitudinal arch. The measure is most useful when the foot is flat on the floor, since in early and late stance it is influenced predominantly by ankle dorsi/plantar flexion. Finally, extension(+)/flexion(–) of the hallux was calculated from the angle formed between the hallux (defined by markers on the distal phalanx of the hallux and the head of the 1st metatarsal) and the horizontal plane of the forefoot coordinate system.

To identify the period of foot contact, a single force platform (Advanced Mechanical Technology Inc., Watertown, MA, USA) sampling at 240 Hz was used. This allowed normalization of the joint kinematics in the time domain, expressed as a percentage of the stance period, from heel-contact to toe-off. Walking speed was recorded using a gait timing device. One standing calibration trial and 5 satisfactory walking trials were recorded for right and left limbs with patients walking at natural cadence.

Repeatability measures. The within- and between-day repeatability was estimated from 5 trials of the right limb from the 5 healthy adult volunteers taken on 2 separate days, 48 hours apart. Patients with RA attended one gait analysis session; therefore only within-day repeatability was estimated from 5 suitable trials.

Statistical analyses. Each intersegmental pattern of motion was summarized as a group ensemble average and displayed as a time-series graph. The metric for repeatability (R) was the coefficient of multiple correlation (CMC), which is a measure of similarity for a group of curves[18]. In this study, greater similarity in the motion-time curves tends to result in an R value closer to 1.0[18]. In previous studies R values > 0.8 indicate acceptable repeatability for motion recorded in the joints of the foot[6,12].

Joint angles (maximum or peak values) are affected by target placement, whereas ROM is less sensitive to these errors. In this exploratory study both variables were compared; however, the small sample size did not permit formal hypothesis testing. Therefore, the mean between-group difference (± 95% confidence interval) was derived for each kinematic variable.

RESULTS

Demographic and clinical characteristics. Nine female and 2 male patients with median disease duration of 14 years were recruited to the study (Table 1). All patients were taking DMARD and were moderately disabled according to their Sickness Impact Profile scores. On examination, swollen and tender joints were found in the forefoot, midfoot, rearfoot, and ankle regions in a variety of combinations along with inflammation of tendons and bursae and plantar heel pain. Foot and ankle deformities were present

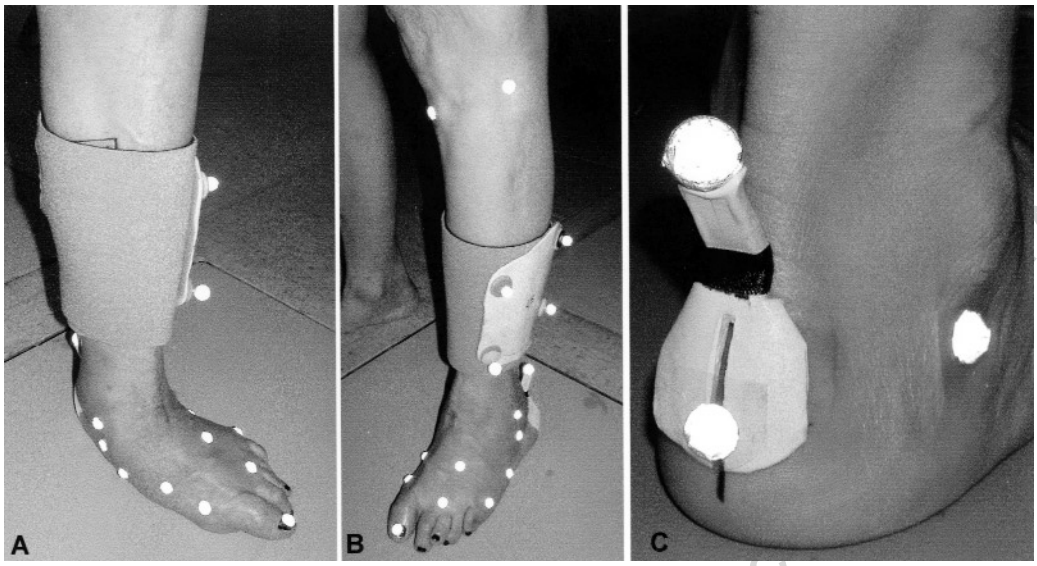

Figure 1. Marker placement on the shank and foot: (A) anteromedial view, (B) anterolateral view, and (C) close-up of heel wand system for tracking rearfoot segment. After Carson, *et al*[3].

in all subjects including lesser toe deformities, hallux valgus, tailor's bunion, splaying of the forefoot, and pes planovalgus. Seven patients reported joint stiffness in the feet, while ROM was restricted in 13 feet from 7 patients at various joint sites. The median SI was 4 for the forefoot and 2 for the rearfoot. The RSFP was valgus in 16 feet, neutral in one foot, and varus in 3 feet.

Gait analysis. Data were collected for one foot only from 2 RA patients who found walking barefoot too uncomfortable. RA patients generally walked slower with a median walking speed of 0.88 m/s (range 0.33 to 1.23) in comparison with 1.26 m/s (range 1.24 to 1.29) for the healthy subjects.

Intersegment model development. In the rearfoot segment, across the 3 directions of motion, within-day CMC values ranged from 0.912 to 0.977 for normal subjects and 0.847 to 0.981 for RA patients. Between-day CMC values in the normal subjects in the rearfoot were > 0.9 except for internal/external rotation (CMC 0.677). In the forefoot, across the 3 directions of motion, within-day CMC values ranged from 0.913 to 0.957 for normal subjects and 0.830 to 0.919 for RA patients. Between-day CMC values in the normal subjects in the forefoot were > 0.85 (range 0.853-0.895). Navicular height was highly repeatable both within-day (CMC 0.982) and between-day (CMC 0.981) for normal subjects and within-day for RA patients (CMC 0.956). Similar findings were noted for the hallux, where the within-day and between-day CMC for the normal subjects were 0.965 and 0.939, respectively, and the within-day CMC for the RA patients was 0.951.

Rearfoot motion. Rearfoot motion is summarized in Table 2. Peak dorsiflexion, peak plantarflexion, and ROM were similar for both groups. The most notable difference occurred in the pre-swing period, where plantarflexion was both delayed and failed to pass neutral in the RA patients in comparison with normal, with an absolute difference in position of 11.6° at toe-off. Rearfoot motion in the direction of inversion/eversion was markedly different between the groups; the RA patients demonstrated moderately restricted rearfoot motion typically about an everted range throughout stance (Table 2, Figure 2A). Inversion was observed during terminal stance in the RA patients, but was insufficient to move the rearfoot through neutral into the inverted position adopted by the normal subjects. When expressed in the shank coordinate system, the rearfoot in RA patients functioned about an excessively externally rotated position, and this motion was highly variable in comparison with normal subjects. Subsequently, the average peak internal and external rotation and the ROM were markedly different between the groups (Table 2).

Forefoot motion. Forefoot motion is summarized in Table 2. The ROM was reduced for all 3 planes of rotation, suggesting that the forefoot tended to be stiffer in the RA patients. In the sagittal plane, dorsiflexion, plantarflexion, and total ROM were reduced in the RA patients. As in the rearfoot, forefoot plantarflexion during pre-swing was reduced (by 3.8°) in the RA patients compared with normal subjects. In the frontal plane, peak inversion was reduced and peak eversion increased, with an overall reduction in the total ROM in the RA patients compared to normal subjects (Figure 2B). In the transverse plane, peak adduction in the RA patients was reduced, peak abduction the same, and total ROM reduced in the RA patients in comparison with normal subjects.

Navicular height. During full-foot contact the vertical posi-

Table 1. Demographic and clinical data, ambulation, impairment, and function scores for the feet of 11 patients with RA.

Patient/ Age/ Sex	Disease Dur (yrs)	DMARD	Body mass (kg)	Height (m)	SIP Amb (0-100)	Foot (L/ R)	Impairments: Foot & ankle pain	Foot & ankle deformity	Self-report stiffness	↓ROM	SI FF (0-12)	SI RF (0-7)	RSFP (deg)
1/57/F	33	MTX, PRD	89.2	1.71	21	L	Retro-calcaneal bursitis, plantar heel pain	Splay FF, less toe def	TTJ	NAD	4	3	0° neut
						R	S/T MTPJs	Less toe def	NAD	NAD	6	3	1° valgus
2/39/F	14	LEF,AZ, PRD	63.1	1.70	29	L	S/T MTPJs	Pes plvalgus, hal valg, tailors bun, less toe def	NAD	MTPJ1	3	0	6° valgus
						R	S/T MTPJs, MTJ, TTJ; TPTS	Pes plvalgus, hal valg, tailors bun	MTJ	MTJ, MTPJ1	2	0	3° varus
3/55/F	5	MTX, PRD	82.8	1.54	47	L	-	-	-	-	-	-	-
						R	S/T MTPJ, MTJ, STJ, TTJ; TPTS	Pes plvalgus, less toe def	TTJ, MTJ	NAD	4	4	6° valgus
4/60/M	35	MTX,LEF, PRD	69.0	1.81	22	L	S/T MTPJs; T MTJ, STJ, TTJ; TPTS, PTS	Splay FF, hal valgus, less toe def	NAD	STJ, MTPJ1	9	2	6° valgus
						R	T MTPJs, MTJ; S/T STJ TTJ	Hal valgus, less toe def	TTJ, STJ	TTJ, STJ, MTPJ1	4	3	4° valgus
5/62/F	13	MTX,LEF, PRD	73.1	1.64	24	L	-	-	-	-	-	-	-
						R	S/T MTJ, STJ; S TTJ ; PTTS, FHLTS	Splay FF, MTPJ callus	NAD	TTJ, STJ, MTJ, MTPJ1	0	3	9° valgus
6/69/F	18	TNFα, MTX,PRD	44.0	1.61	18	L	S TNJ, TTJ	Splay FF, pes plvalg, less toe def	NAD	TTJ, STJ, MTJ, MTPJ1	2	5	15° valgus
						R	S TNJ, TTJ	Splay FF, pes plvalg	NAD	TTJ, STJ, MTJ, MTPJ1	1	4	10° valgus
7/56/M	19	TNFα, MTX,PRD	68.4	1.77	27	L	S/T MTPJs, CCJ	Splay FF, less toe def	MTPJs	TTJ, MTJ, MTPJ1	8	2	4° varus
						R	S/T MTPJs, CCJ	Splay FF, less toe def	MTPJs	TTJ, MTJ, MTPJ1	8	2	4° varus
8/54/F	27	HCQ, PRD	64.5	1.67	19	L	S/T STJ, TTJ; plantar heel pain	Splay FF, less toe arthroplasties, pes plvalgus	TTJ	TTJ,STJ, MTJ, MTPJ1	9	5	6° valgus
						R	T MTPJs; retro-calcaneal bursitis	Splay FF, less toe def, pes plvalgus	TTJ	TTJ,STJ, MTJ, MTPJ1	6	5	5° valgus
9/77/F	11	MTX, PRD	62.7	1.52	15	L	T MTJs, STJ; plantar heel pain	Splay FF, less toe def, hal valg	NAD	NAD	8	1	5° valgus
						R	T MTPJs, CCJ; plantar heel pain	Splay FF, less toe def, hal valg	NAD	NAD	8	0	4° valgus
10/63/F	14	MTX, PRD	58.2	1.57	0	L	S/T MTPJs, STJ, TPTS	Splay FF, less toe def, hal valg, pes plvalgus	NAD	NAD	8	2	5° valgus
						R	S/T MTPJs; T MTJ, STJ	Splay FF, hal valg, pes plvalgus	MTPJs	NAD	1	2	5° valgus
11/58/F	6	MTX, HCQ	82.7	1.57	12	L	S/T MTPJs, STJ, TTJ ; TPTS	Splay FF, hal valg, tailors bun, pes plvalgus	NAD	TTJ, MTPJ1	2	2	10° valgus
						R	S/T MTPJs, STJ, TTJ; TPTS; Ach Tend	Splay FF, hal valg, tailors bun	NAD	TTJ, MTPJ1	2	0	4° valgus
Median	14		68.4	1.64	21						4	2	5° valgus

DMARD: disease modifying antirheumatic drug; TNFα: tumor necrosis factor-α blockade; MTX: methotrexate; HCQ: hydroxychloroquine; LEF: leflunomide; PRD: prednisone; AZ: azathioprine; SIP: Sickness Impact Profile ambulation subscale; S: joint swelling; T: joint tenderness; TTJ: tibiotalar joint; STJ: subtalar joint; TNJ: talonavicular joint; CCJ: calcaneocuboid joint; MTJ: midtarsal joint; MTPJ: metatarsophalangeal joint; TPTS: tibialis posterior tenosynovitis; PTS: peronei tenosynovitis; FHLTS: flexor hallucis longus tenosynovitis; Ach Tend: Achilles tendonitis; FF: forefoot; RF: rearfoot; tailors bun: tailors bunion; less toe def: lesser toe deformities; pes plvalgus: pes planovalgus; NAD: no abnormality reported or detected; SI: structural index; RSFP: relaxed standing foot posture.

Table 2. Motion variables (mean with SD in parentheses) summarized by segment and plane of rotation for patients with RA and normal subjects.

Segment	Variable	RA	Normal	Mean Difference	95% CI Difference
Rearfoot	Peak dorsiflexion, + deg	15.1 (5.1)	14.0 (2.6)	1.0	(–2.5, 4.5)
	Peak plantarflexion, – deg	–2.2 (4.6)	–5.1 (2.9)	2.9	(–0.8, 6.5)
	ROM, deg	17.3 (3.0)	19.1 (2.1)	–1.8	(–4.5, 0.8)
	Peak inversion, + deg	–0.2 (4.7)	11.3 (5.6)	–11.4	(–18.3, –4.6)
	Peak eversion, – deg	–8.2 (4.4)	–1.3 (4.9)	–7.0	(–12.9, –1.1)
	ROM, deg	8.1 (3.4)	12.5 (2.8)	–4.5	(–8.0, –1.0)
	Peak internal rotation, + deg	–6.1 (8.8)	12.6 (2.8)	18.7	(13.7, 23.8)
	Peak external rotation, – deg	–11.7 (8.5)	–0.3 (3.5)	–11.3	(–16.5, –6.1)
	ROM, deg	5.5 (2.4)	12.9 (2.6)	–7.4	(–10.6, –4.3)
Forefoot	Peak dorsiflexion, + deg	4.8 (3.4)	6.4 (1.7)	–1.5	(–3.9, 0.8)
	Peak plantarflexion, – deg	–3.6 (4.3)	–5.9 (3.1)	2.3	(–1.5, 6.1)
	ROM, deg	8.5 (3.5)	12.3 (2.0)	–3.8	(–6.4, –1.2)
	Peak inversion, + deg	0.3 (3.4)	4.4 (2.5)	–4.1	(–7.8, –0.5)
	Peak eversion, – deg	–7.4 (5.1)	–5.6 (4.1)	–1.8	(–7.9, 4.3)
	ROM, deg	7.7 (4.1)	10.0 (4.5)	–2.4	(–9.1, 4.4)
	Peak adduction, + deg	1.0 (9.9)	3.5 (6.4)	–2.6	(–10.7, 5.6)
	Peak abduction, – deg	–3.7 (8.8)	–3.7 (3.8)	–0.1	(–5.6, 5.4)
	ROM, deg	4.7 (3.0)	7.2 (3.8)	–2.5	(–7.1, 2.1)
Navicular	Minimum height, mm	35.5 (13.6)	38.3 (4.6)	–2.8	(–10.4, 4.9)
	Maximum height, mm	87.1 (21.2)	116.0 (10.3)	–28.9	(–43.1, –14.6)
	Displacement, mm	51.6 (18.9)	77.7 (7.3)	–26.1	(–37.3, –14.9)
Hallux	Peak extension, + deg	21.0 (10.3)	33.1 (4.8)	–12.1	(–18.8, –5.4)
	Peak flexion, – deg	–2.6 (8.5)	–5.6 (1.9)	3.0	(–1.3, 7.4)
	ROM, deg	23.6 (11.5)	38.7 (4.1)	–15.1	(–21.7, –8.5)

ROM: range of motion. +/– deg: +/– degrees.

tion of the navicular was lower in the RA patients compared to normal (Table 2); however, the observed difference in the peak height, observed at the start of terminal stance, was typically < 5 mm (Figure 2C). Navicular height was more variable in the RA patients, and during terminal stance the maximum vertical displacement was lower in comparison with normal.

Hallux extension/flexion. Hallux flexion during the loading response and through midstance to pre-swing was reduced in comparison with normal values (Figure 2D). Hallux extension was reduced in the RA patients during pre-swing, and the observed peak angle for extension and the ROM were much smaller in the patient cohort in comparison with normal (Table 2).

Case studies. Case studies providing individual motion patterns are presented for 3 RA patients with different foot impairments. The first case (Table 1, Patient 6, left foot) illustrates the relationship between the rearfoot, forefoot, and medial longitudinal arch (navicular height). During walking the rearfoot was excessively everted, and this was consistent with the clinical measurement of 15° RSFP, indicating a valgus heel position (Figure 3). During rearfoot eversion, the floor forces the forefoot into inversion and in this case, since the rearfoot motion was abnormal, the forefoot was excessively inverted relative to the rearfoot throughout stance. This motion was accompanied by dorsiflexion of the forefoot on the rearfoot, with a corresponding lowering of the navicular height. Indeed, the patient showed a very low navicular height throughout the period of full-foot contact. Further, the motion patterns showed small ranges of motion about these misaligned foot segments and these findings are related to joint swelling and stiffness around the tibiotalar, subtalar, and midtarsal joints as detected from the clinical examination.

Case 2 (Table 1, Patient 2, right foot) presented with markedly swollen and tender MTP joints in the forefoot with a stiff 1st MTP joint and severe hallux valgus deformity. The motion analysis recorded both the position (~30° extended) and the stiffness (~5° of motion) of the hallux during walking (Figure 4). Two features of rearfoot motion were also important; first, the heel position was mostly inverted during stance with a small ROM (corresponding to the 3° varus heel position captured clinically with the RSFP measurement), and second, during terminal stance, there was limited rearfoot plantarflexion. Both motion patterns may be compensation mechanisms to protect painful forefoot joints. Maintaining an inverted heel position offloads the medial forefoot, where in this case notable tenderness and deformity were observed, while reduced terminal stance plantarflexion is related to reduced ankle plantarflexor moments and decreased pushoff, which lessen forefoot loads[11].

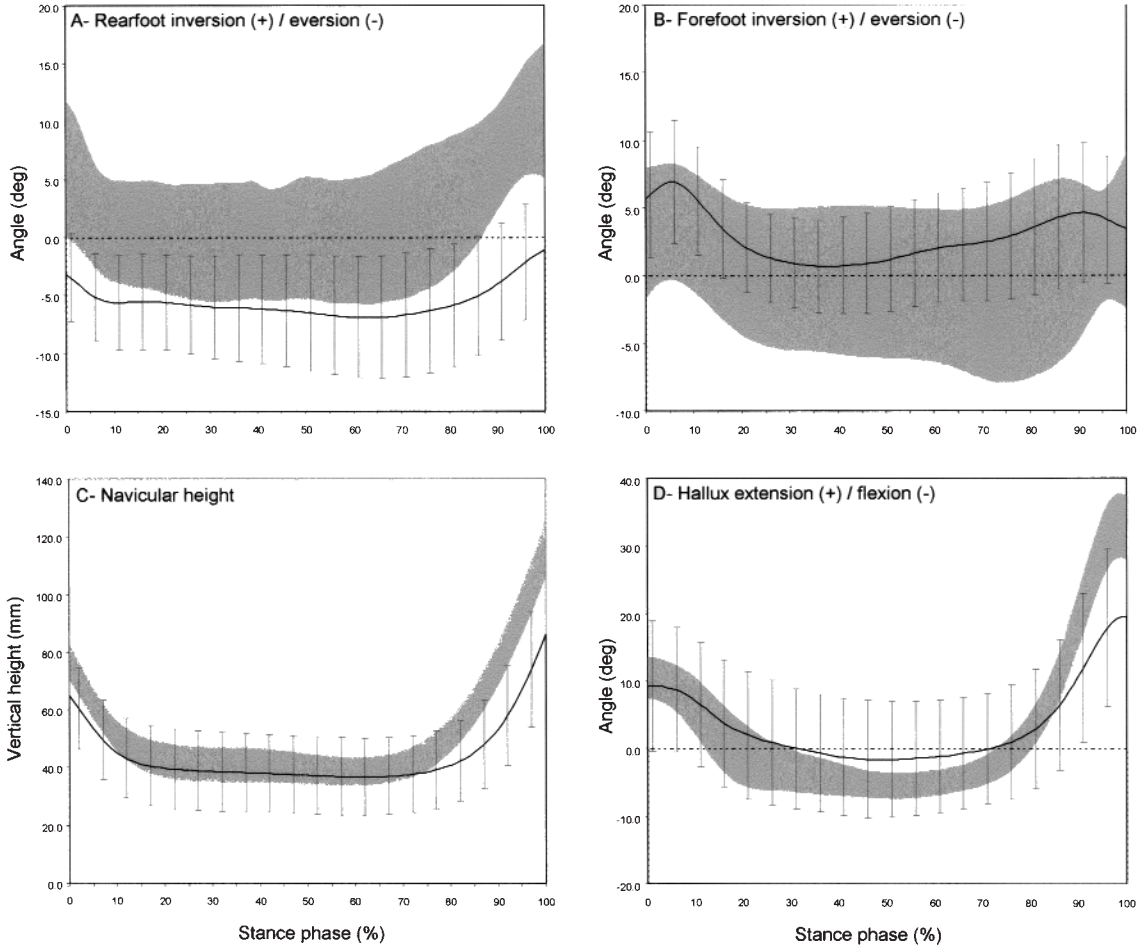

Figure 2. Motion summarized for (A) rearfoot inversion/eversion; (B) forefoot inversion/eversion; (C) navicular height; and (D) hallux extension/flexion. The shaded band represents the mean ± 1 SD for the normal subjects; solid line is the mean ± 1 SD error bars for patients with RA. Each graph is individually scaled.

The third case (Table 1, Patient 8, left foot) was an RA patient with long-standing disease, severe foot deformity (SI forefoot 9/12, SI rearfoot 5/7), joint tenderness and stiffness, and a history of forefoot arthroplasty surgery. Rearfoot motion was abnormal and showed excessive dorsiflexion, eversion, and external rotation (Figure 5A). The motion description rules for the rearfoot are such that with the heel in floor contact, external rotation is measured through internal shank rotation. This motion tends to be coupled with rearfoot eversion, as observed here, and notably, both are abnormal. The forefoot was excessively dorsiflexed, inverted, and severely abducted relative to the rearfoot and the navicular arch height was low (Figure 5B). These abnormal motion patterns are highly consistent with a planovalgus foot type. Further, in accord with the observed ranges of motion captured in gait, joint stiffness and reduced ROM in the rear- and midfoot joints were strong clinical features. Similarly, in the forefoot, peak hallux extension was ~15°, confirming the stiffness observed at the 1st MTP joint clinically (Figure 5C).

DISCUSSION

The purpose of this study was to assess the feasibility of developing a reliable multisegment foot model, using video-based motion analysis, to quantify joint motion abnormalities associated with foot impairments in RA. The proposed model was developed to track the shank, rearfoot, and forefoot segments in 3 dimensions, and the hallux and navicular in one dimension. When applied in otherwise healthy adults, repeatable and valid estimates (based on current understanding of foot function) of foot motion were achieved[1,3,4,19]. In a cohort of 11 RA patients with long-standing disease, abnormal foot motion was detected and, on a per-case basis, found to be closely associated with clinical impairments including pain, stiffness, and deformity.

There are no other multisegment foot motion studies in RA with which to compare the results of this study. We previously conducted studies where the foot was modeled as a single segment[5] or where rearfoot-to-shank motion only was measured[6]. One definition of joint instability is excessive range of motion in one direction; thus both studies con-

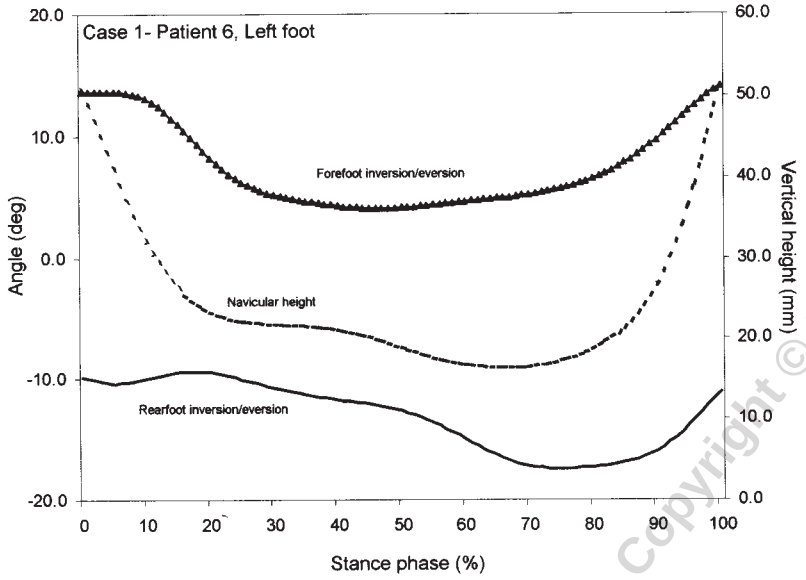

Figure 3. Abnormal multisegment foot motion patterns in RA. The primary y-axis denotes joint angle (degrees) and the secondary y-axis denotes vertical height (mm) for the navicular height plot.

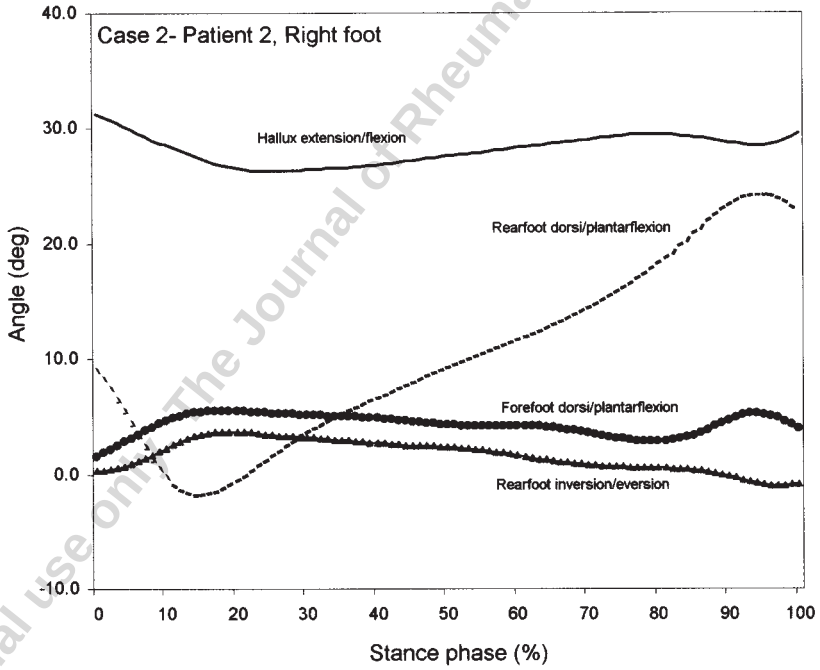

Figure 4. Abnormal multisegment foot motion patterns in RA.

clude that the rearfoot in RA is unstable in the direction of eversion. The same observation is made here, and the coupling between the rearfoot and shank was also found to be abnormal (by convention, external rotation of the rearfoot can also be expressed as internal leg rotation when the rearfoot is used as the reference coordinate system). These findings may be explained by the fact that half the feet studied had clinical evidence of pes planovalgus associated with a high prevalence of tarsal arthritis. Further, among this cohort the rearfoot tended towards valgus in the frontal plane according to the static rearfoot alignment, which showed 80% of feet to be in valgus. Such consistency of information from different patient populations measured using different motion analysis systems provides strong

evidence that these motion changes are important functional deficits associated with the persistent inflammation and soft tissue and joint pathology in the rearfoot. This also agrees with other studies that employed clinical goniometry[20] and 2-dimensional motion analysis[8] to measure valgus heel deformity under static and walking conditions.

Our current study adds new evidence to suggest that in RA, abnormal motion is seldom found in only one segment of the foot. This is plausible, since interdependency between rearfoot and forefoot motion has been reported in normal adults in previous 3-dimensional gait studies[1,3,4]. Furthermore, motion between these segments largely occurs through the talonavicular and calcaneocuboid joints, which are sites for joint pathology in RA, so a biological explanation exists[7,9]. Inspection of individual cases was necessary to detect these differences since forefoot motion was within normal limits for this small cohort of patients. Again, the predominant finding was abnormal frontal plane motion (eversion in the rearfoot and inversion in the forefoot-midfoot "twisting") among those cases with pes planovalgus. The multisegment approach gives a more complete description of this foot type since alongside midfoot "twisting," excessive forefoot dorsiflexion and abduction and low navicular height were also detected; both are motion and structural features that are in accord with the clinical description of this complex deformity.

Joint stiffness in the foot would be a useful functional impairment to detect using 3-dimensional motion analysis. This has been described previously in the RA foot from walking studies, but only for the rearfoot[13]. The current cohort all had long-standing disease and clinical evidence of stiffness as detected by passive ROM testing, and this was evident in our gait results. Of interest was the suggestion of an association between the magnitude of deformity and stiffness, since the largest relative loss of ROM was observed for inversion/eversion in both the forefoot and rearfoot. Further, a strong association was found between deformity, stiffness, and reduced ROM in walking at the 1st MTP joint, which was expected for this patient cohort given the high prevalence of pathology at this site.

Patients with RA with isolated rear- and forefoot impairments have shown distinctly different relationships between pain, deformity, disability, and functional gait limitations[5,6,8,11,15]. In particular, the deformed and painful forefoot leads to avoidance of weight-bearing in this region and is characterized by smaller ankle plantarflexor moments and decreased pushoff leading to slow walking speed and moderate disability[11]. In practice, these isolated foot impairments are difficult to find; indeed in the present cohort, 5 of 11 patients had predominant forefoot impairments but all had swollen or tender joints in the rearfoot or midfoot, or soft tissue involvement in the form of tenosynovitis, bursitis, or enthesitis, making comparisons more challenging. Nevertheless, we found evidence of forefoot weight-bearing avoidance through motion indicators that included delayed onset and reduced magnitude of rearfoot plantarflexion during pre-swing and lower than normal maximum vertical displacement of the navicular during pre-swing — both indicating a loss of forefoot rocker function. Future models incorporating joint kinetics may provide more complete information to help explain functional deficit and gait compensations associated with foot impairments.

Despite these encouraging findings several problems were encountered with the model in its present format. Accurate definition of an anatomically based coordinate system requires accurate palpation of anatomical landmarks on which to place surface markers, usually at sites with minimal adipose tissue. In some RA cases, localized swelling obscured otherwise palpable landmarks, especially over the medial and lateral surfaces of the calcaneus. The resultant errors were not quantified here, but future models may require modifications or additional measures to yield offsets to correct for soft tissue swelling. Anatomically based models are preferred since deformity and stiffness may not allow the use of alignment jigs to obtain standard calibration postures. Additionally, correction angles, such as those for valgus misalignment in the rearfoot, are difficult to measure in the foot. Finally, barefooted gait protocols may not be appropriate for some RA patients who experience worsening of symptoms when walking on unfamiliar hard surfaces[5]. Practical issues such as these are seldom reported and require greater consideration in future protocols.

This study describes the application of a valid and repeatable multisegmental foot model for a more complete description of complex foot deformities associated with RA. Some aspects of foot motion in the RA cases were abnormal and associated with foot impairments such as pain and deformity. Simple measurement of navicular displacement provides a repeatable measure of medial longitudinal arch height, and this is useful since this structure frequently collapses in RA. More distally, the destructive and deforming action of inflammation on 1st metatarsophalangeal joint function was demonstrated by changes in flexion-extension motion of the hallux. Future work will refine and develop the model, but this approach may be useful for assessing functional impairment in RA and to assist the planning and evaluation of rehabilitation programs for the foot.

ACKNOWLEDGMENT

Dr. Woodburn attended the Rehabilitation Medicine Department at the National Institutes of Health as a Special Volunteer as part of the overseas component of a UK Medical Research Council Fellowship. The support of Dr. Gerber, Dr. Stanhope, Dr. Perry, Ms S. Bender, and the staff and patients of the Rehabilitation Medicine Department and the National Institute of Arthritis and Musculoskeletal and Skin Diseases at the NIH was greatly appreciated.

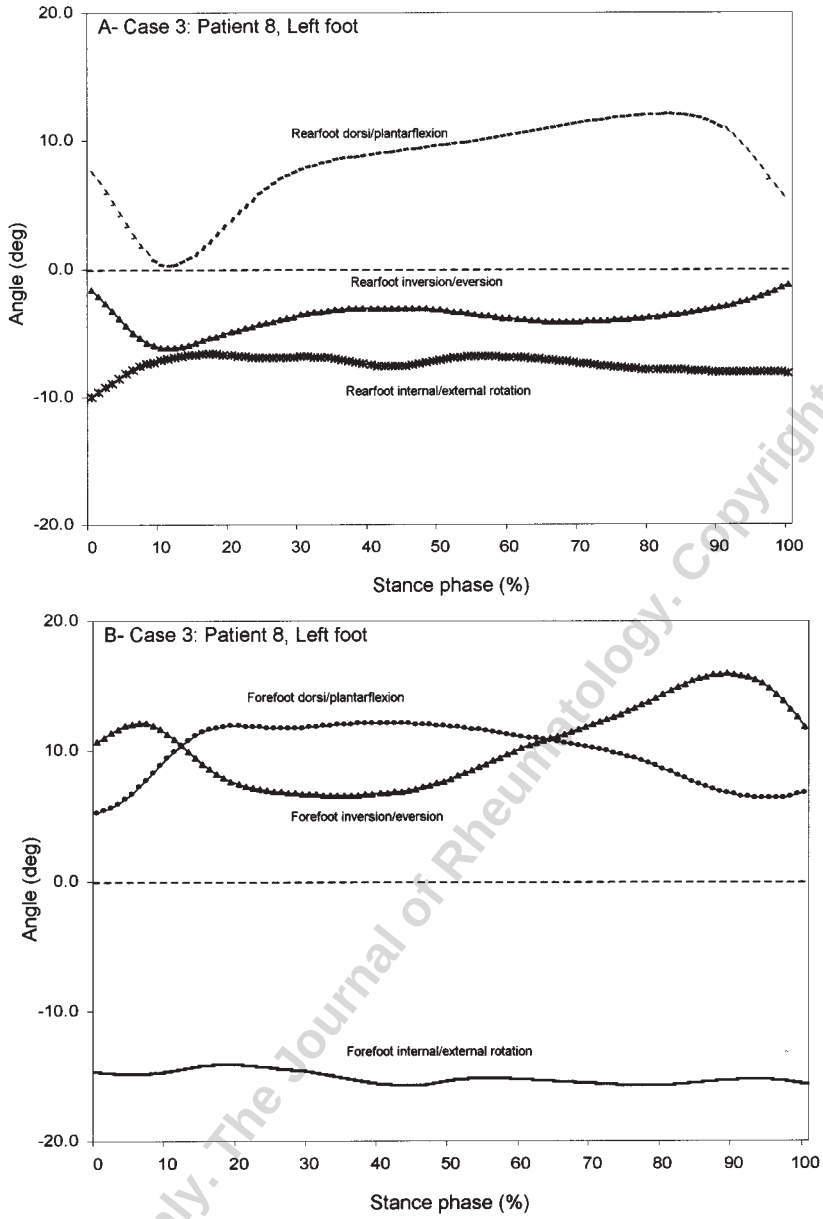

Figure 5. Abnormal multisegment foot motion patterns in RA. (A) Rearfoot motion; (B) forefoot motion; (C, opposite) hallux extension/flexion (primary y-axis) and navicular height (secondary y-axis).

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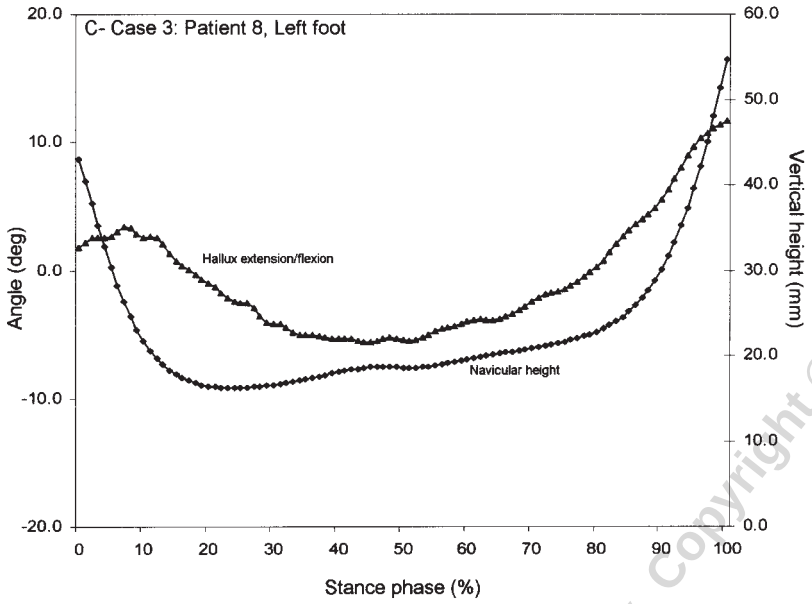

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