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ORIGINAL ARTICLE

Foot and Ankle Kinematics in Rheumatoid Arthritis: Influence of Foot and Ankle Joint and Leg Tendon Pathologies

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Objective. **From early onset of the disease, patients with rheumatoid arthritis (RA) experience walking impairments. Pathologic effects of RA on foot and ankle structures have been studied clinically, but little is known as to how they relate to kinematic changes during gait. The aim of this study was to explore the relationship between clinically observed pathologies of foot and ankle joints and leg tendons and the corresponding gait kinematics.**

Methods. **The gait of 25 subjects with varying stages of RA was recorded and foot and ankle kinematics were assessed. Magnetic resonance imaging was performed for each subject: first metatarsophalangeal (MTP) joint, midfoot, and hindfoot synovitis, erosion scores, and leg tendon involvement were determined. The joint alignment and motion score represented daily clinical assessment. The 95% confidence intervals of the Spearman's correlation coefficient tests were used to explore the relationships between the clinical and kinematic parameters.**

Results. **Maximum first MTP joint dorsiflexion at preswing was related to reduced first MTP joint passive motion, first MTP joint synovitis and erosion, midfoot synovitis and erosion, and hindfoot erosion. Midfoot pronation range of motion during single stance was related to subtalar alignment and Achilles tendon involvement. Hindfoot eversion range of motion during single stance was related to subtalar alignment and peroneus longus tendon involvement. Involvement of the tibialis posterior tendon could not be identified as an independent factor influencing foot or ankle kinematics.**

Conclusion. **Our findings suggest moderate to strong relationships between foot and ankle gait kinematics and structural pathologies.**

INTRODUCTION

At the onset of rheumatoid arthritis (RA), 60% of the patients experience walking impairments; this percentage decreases to 40% later in the disease course (1). These impairments have been related to the effects of RA on, among other factors, walking speed and foot and ankle structures. Metatarsal pain, global foot pain, disease activity, foot swollen joint count, and hindfoot deformity all affect and impair walking at some point during the disease process (2–5). Several studies have analyzed foot and ankle joint kinematics in subjects with RA during walking at comfortable speed to attain insight in gait differences compared to healthy subjects (6–9). However, little is known about the effects of local structural pathologies on foot and ankle joint kinematics in RA subjects.

Turner and Woodburn analyzed the effects of predominantly forefoot, hindfoot, or combined deformation in RA subjects on foot and ankle kinematics and observed changes in both forefoot and hindfoot kinematics (10). Laroche et al studied the effect of metatarsophalangeal (MTP) joint stiffness on gait parameters in RA subjects (11). MTP joint stiffness was significantly related to walking speed, knee flexion, and foot angle at toe-off, although the effects on foot and ankle joint kinematics were not analyzed. The effects on foot and ankle kinematics of other frequently reported structural impairments, such as tibialis posterior tendon involvement and ankle arthritis, have been studied, but not in an RA population (12–15).

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Significance & Innovations

- The results of this study are the first to demonstrate moderate to strong relationships between local foot and ankle joint pathologies and maximum first metatarsophalangeal (MTP) joint dorsiflexion during gait of rheumatoid arthritis (RA) subjects. These insights may be used in future treatment and analysis.
- Our findings suggest that subtalar alignment and first MTP joint stiffness, both subscale scores of the Joint Alignment and Motion score and easily assessable in daily clinical practice, are at least moderately related to pathologic foot and ankle joint kinematics. Individual monitoring of these simple clinical assessments may provide insight into foot and ankle function of RA patients during gait.
- Pathologic changes to the Achilles and peroneus longus tendon may have a moderate to strong influence on midfoot pronation and hindfoot eversion motion during the stance phase of gait, respectively. The established hypothesis of the relationships between tibialis posterior tendon pathology and midfoot and hindfoot frontal plane kinematics during gait could not be confirmed. Our findings suggest a more important relationship between the hindfoot alignment and the midfoot and hindfoot frontal plane kinematics.

A better general understanding of the effects of foot and ankle structural pathologies on foot and ankle kinematics during gait may support clinical decisions in both conservative and surgical treatment for this complex disease (10,15–17). In addition, for daily clinical practice, a better general understanding of the relationship between easily accessible clinical scores and gait kinematics, if existing, would be of use. Assessment of structural pathologies usually requires technologies such as radiography or magnetic resonance imaging (MRI), but a clinical score, such as the joint alignment of motion (JAM) (18), can be easily, quickly, and frequently determined and has already been related to foot function impairments (2,19).

The aim of this study was to explore the relationship between clinical foot and ankle assessment (JAM), structural inflammation and damage, and joint kinematics of the foot and ankle during the gait of subjects with varying degrees of RA.

PATIENTS AND METHODS

Patients. Twenty-five RA patients (outpatient clinic, 3 male and 22 female) with varying foot and ankle impairments and disease duration participated in this cross-sectional observational study. Subjects were eligible for this study when they met the 1987 American College of Rheumatology criteria for RA (20), were at least age ≥17 years, and had not undergone orthopedic surgery on their feet and ankles. Exclusion criteria for gait analysis were the following: not being able to walk without a walking aid, walking at such a low speed that losing balance was an issue, and severe mobility restriction at the knee or hip joints.

The following demographic characteristics and clinical scores were collected: age, disease duration, rheumatoid factor, RA-related drug use, Disease Activity Score in 28 joints, visual analog scale (VAS) for foot and ankle pain, the Foot Function Index 5, the Larsen score, and the Sharp/van der Heijde score. The subjects were recruited consecutively, and informed consent was obtained from all subjects prior to participation. This study received ethical approval from the local medical ethics committee.

Protocol. Gait analysis was performed, with subjects walking at a comfortable walking speed, using a motion analysis system comprised of 6 infrared video cameras (1.3 megapixels, 100 Hz; Vicon Nexus, Vicon Motion Systems). Nineteen infrared reflective markers were attached to the lower extremities of the subject according to the method described by Simon et al (21) (Figure 1). Both feet were measured according to the above protocol, but only the foot causing the most discomfort was used in the analysis. During each session, 8 to 10 trials were recorded to obtain sufficient usable steps in the analysis.

Data analysis. The temporal parameters (walking speed, step length, stride length, stride width, stride time, and double stance phase) were assessed for each subject from the marker coordinate recordings in a special LabVIEW script (version 7.2, National Instruments). This script was also used to normalize the data to the stance phase using the specified initial contact and toe-off indications in

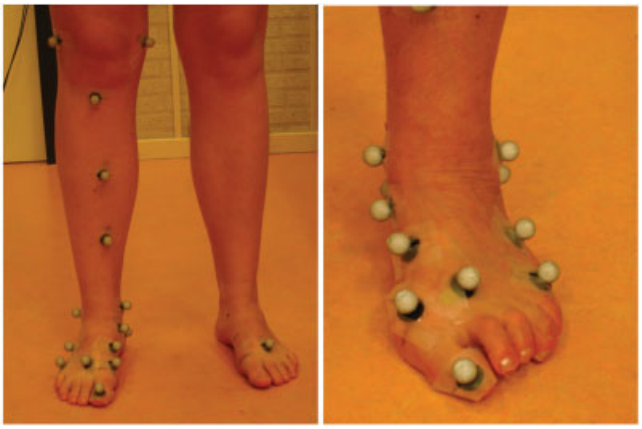

Figure 1. A, Leg, foot, and ankle marker placement according to Simon et al (21) and **B,** foot and ankle marker placement on a more severe deformed foot.

Table 1. Overview of demographic, clinical, and gait characteristics*

	Scoring range	Minimum	Maximum	Mean ± SD
Age, years		23.0	78.0	51.3 ± 15.8
Disease duration, months		6.0	276.0	113.0 ± 82.5
Rheumatoid factor		0.0	2,600.0	215.8 ± 549.8
DAS28	0–9.4	1.1	6.7	3.4 ± 1.3
Visual analog scale pain score, %	0–100	3.0	93.0	41.3 ± 25.4
Foot Function Index pain	0–126	0.0	75.0	30.0 ± 19.4
Foot Function Index disability	0–126	6.0	67.0	29.8 ± 16.4
Larsen score	0–15	0.0	5.0	1.4 ± 1.7
Sharp/van der Heijde score	0–64	0.0	39.0	12.7 ± 10.8
Joint alignment and motion				
Subtalar motion	0–4	0.0	4.0	2.0 ± 1.3
First MTP joint motion	0–4	0.0	4.0	1.9 ± 1.3
Subtalar alignment	0–4	0.0	3.0	0.6 ± 1.0
First MTP joint alignment	0–4	0.0	3.0	0.8 ± 1.1
Magnetic resonance imaging				
Synovitis first MTP joint	0–3	0.0	3.0	2.0 ± 1.3
Erosion first MTP joint	0–20	0.0	20.0	5.8 ± 5.1
Synovitis midfoot	0–6	0.0	6.0	2.3 ± 2.3
Erosion midfoot	0–100	0.0	73.0	15.8 ± 20.4
Synovitis hindfoot	0–12	0.0	12.0	4.0 ± 4.1
Erosion hindfoot	0–20	0.0	13.0	3.3 ± 4.2
Tibialis posterior tendon	0–5	0.0	5.0	1.8 ± 1.9
Flexor hallucis longus tendon	0–5	0.0	5.0	0.6 ± 1.2
Peroneus tendon	0–5	0.0	5.0	1.2 ± 1.6
Achilles tendon	0–5	0.0	3.0	0.3 ± 0.7
Gait characteristics, RA patients				
Walking speed, meters/second		0.44	1.00	0.77 ± 0.14
Individual variability walking speed, meters/second		0.02	0.15	0.61
Stride length, meters		0.59	1.35	0.99 ± 0.14
Individual variability stride length, meters		0.02	0.08	0.05
Maximum first MTP joint dorsiflexion toe-off, degrees		16.1	55.3	34.1 ± 10.2
Midfoot pronation ROM at single stance, degrees		1.7	9.8	4.8 ± 2.0
Hindfoot eversion ROM at single stance, degrees		1.0	5.5	2.6 ± 1.0
Gait characteristics, reference values of healthy subjects				
Walking speed, meters/second				1.25 ± 0.11
Individual variability walking speed, meters/second				0.03
Stride length, meters				1.32 ± 0.08
Individual variability stride length, meters				0.02
Maximum first MTP joint dorsiflexion toe-off, degrees				51.1 ± 5.1
Midfoot pronation ROM at single stance, degrees				8.6 ± 3.5
Hindfoot eversion ROM at single stance, degrees				3.7 ± 1.2

* DAS28 = Disease Activity Score in 28 joints; MTP = metatarsophalangeal; RA = rheumatoid arthritis; ROM = range of motion.

Vicon Nexus. The method developed by Simon et al was applied to assess foot and ankle kinematics (21). This model is able to assess the kinematics of 5 foot and ankle segments, i.e., hallux, forefoot, midfoot, hindfoot, and leg, and has been developed specifically for subjects with more or less severe foot deformities for which the axes of intersegmental motion may not conform to the standard anatomic planes.

For each subject, the mean value of the joint angles motion, as function of the percent stance phase, was assessed using 6 to 7 trials. The stance phase was subdivided into 3 parts: foot loading, single stance, and preswing. Foot loading was defined from initial heel contact to opposite foot toe-off (first double stance); single stance was defined from opposite foot toe-off to opposite foot heel contact; and preswing was defined from opposite foot heel contact to foot toe-off (second double stance). For each subject, the maximum, the minimum, and the range of motion (ROM) values were calculated for each joint and for each part of the stance phase. ROM was defined as the maximum angle minus the minimum angle (21,22). Simon and colleagues analyzed the reliability of the kinematic measures by means of the coefficient of multiple correlations (CMCs) (21). Several of the minimum and maximum kinematic measures, especially those of the midfoot, were sensitive to an offset in the data. But for all ROM values, as well as for the maximum ankle and first MTP joint dorsiflexion, the CMCs were >0.94. In this

Table 2. Results of Spearman's correlation coefficient tests between clinical and kinematic parameters*

Spearman's correlation test	First MTP joint maximum dorsiflexion at toe-off		Midfoot pronation ROM at single stance		Hindfoot eversion ROM at single stance	
	Lower CI	Upper CI	Lower CI	Upper CI	Lower CI	Upper CI
Subtalar motion, JAM score	−0.65	0.05	−0.57	0.19	−0.55	0.21
First MTP joint motion, JAM score	−0.75	−0.13	−0.57	0.18	−0.59	0.15
Subtalar alignment, JAM score	−0.67	0.02	−0.75	−0.14	−0.78	−0.20
Synovitis first MTP joint, MRI	−0.82	−0.30	−0.41	0.39	−0.67	0.05
Erosion first MTP joint, MRI	−0.86	−0.40	−0.65	0.07	−0.57	0.20
Synovitis midfoot, MRI	−0.69	0.00	−0.57	0.21	−0.40	0.40
Erosion midfoot, MRI	−0.77	−0.17	−0.62	0.13	−0.55	0.23
Synovitis hindfoot, MRI	−0.63	0.11	−0.68	0.03	−0.34	0.46
Erosion hindfoot, MRI	−0.69	0.00	−0.63	0.12	−0.51	0.29
Tibialis posterior tendon involvement, MRI	−0.42	0.38	−0.32	0.48	−0.45	0.36
Flexor hallucis longus tendon involvement, MRI	−0.50	0.30	−0.31	0.49	−0.34	0.47
Peroneus tendon involvement, MRI	−0.55	0.23	−0.59	0.17	−0.70	−0.01
Achilles tendon involvement, MRI	−0.43	0.37	0.02	0.70	−0.28	0.51

* MTP = metatarsophalangeal; ROM = range of motion; CI = confidence interval; JAM = joint alignment and motion; MRI = magnetic resonance imaging.

study, only the maximum first MTP joint dorsiflexion at preswing, the midfoot supination–pronation ROM at single stance, and the subtalar eversion–inversion ROM at single stance were evaluated. These foot motions were identified as being influenced by RA as an independent factor in addition to the corresponding, often reduced, walking speed (22).

The 3 kinematic parameters being influenced by RA as an independent factor were correlated with clinical parameters assessed by an experienced radiologist and rheumatologist. Synovitis and bone erosions of the first MTP joint, the midfoot, and the hindfoot were assessed by means of MRI (16,23). The exact MRI protocol and reliability of the method have been described previously (24). Bone erosion was scored from 0–10 and synovitis from 0–3. The MRI bone erosions of the proximal and distal part of the first MTP joint were combined as the first MTP joint erosion. Midfoot erosion was defined as the sum of the MRI bone erosion scores of the proximal metatarsals, the cuneiform, the cuboid, and the navicular bone. Hindfoot erosion was defined as the sum of the MRI bone erosion scores of the calcaneal and talar bone. First MTP joint synovitis was obtained directly from the MRI synovitis score for the first MTP joint. The MRI joint synovitis of the tarsometatarsal and cuneonavicular joint formed the midfoot synovitis. The MRI joint synovitis of the tibiotalar, talo(calcaneo)navicular, calcaneotalar, and calcanealcuboid joints formed the hindfoot synovitis. Furthermore, involvement of the tibialis posterior, peronei, triceps surae, and flexor hallucis longus tendons were assessed from MRI. The tendon involvement scores were calculated by adding the MRI tendon scores (0–1) for signal inhomogeneity, fluid (collection), thickening, enhanced signal intensity, and tearing, as a sign of tenosynovitis or damage of the tendons, resulting in an ordinal scale. The JAM (18) was assessed, and the subscores for subtalar alignment and passive motion and first MTP joint passive motion were analyzed as individual parameters. Involvement of the second through fifth MTP joints and flexor digitorum longus was not taken into account as the second through fifth MTP joints were not represented in the computer model.

Statistical analysis. Statistical analysis was performed using SPSS, version 16.0. The minimum, maximum, and mean values and corresponding SDs of the demographic characteristics, clinical scores, and kinematic parameters were assessed. The kinematic and clinical parameters were not normally distributed. Furthermore, we anticipated that several clinical scores are interrelated due to temporal effects, chronological effects, or the effects of local joint damage on joint stiffness. Hence, Spearman's correlation tests were performed between the clinical parameters and also between the kinematic parameters. The 95% confidence interval (95% CI) of the correlation coefficient was assessed and used to evaluate possible clinical parameter relationships. As it is not the aim of this study to analyze the relationships between the clinical parameters, the results will be reported, but will only be discussed in reference to the kinematic parameters.

The relationships between the kinematic and clinical parameters were evaluated with the lower and upper values of the 95% CI of the Spearman's correlation coefficients. All clinical parameters were included in the correlation with kinematic parameters as, at this stage, it is not clear what relationships exist between the clinical scores. As suggested by Cohen, relationships with a correlation coefficient larger than 0.3 or 0.5 are defined as moderate or strong, respectively (25).

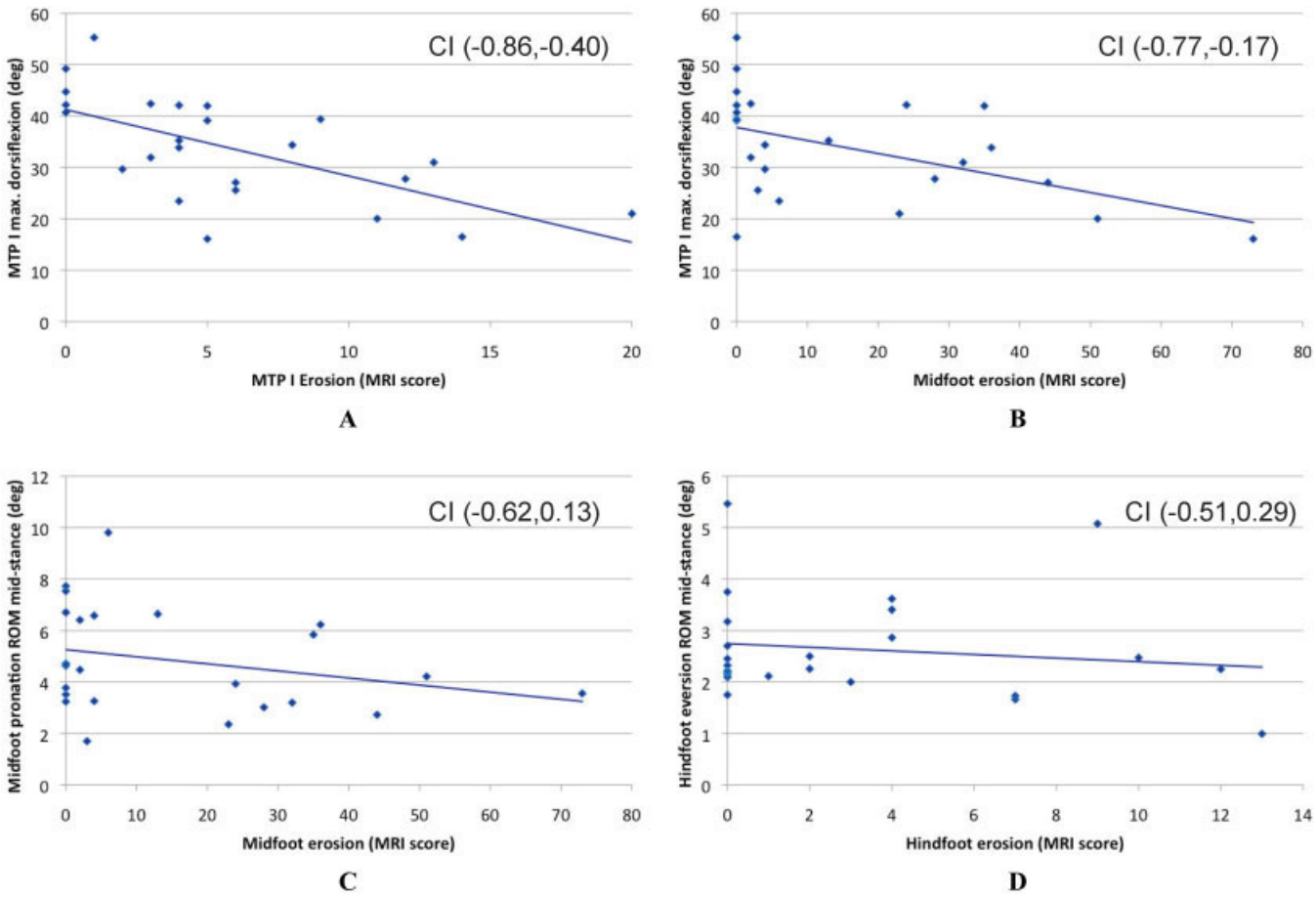

Figure 2. Individual effects of joint erosion on joint motion with corresponding linear regression line and the confidence interval (CI; lower value, upper value) of the Spearman's correlation coefficient. Maximum first metatarsophalangeal (MTP I) joint dorsiflexion as function of MTP I erosion (**A**) and midfoot erosion (**B**). Midfoot pronation range of motion (ROM) as function of midfoot erosion (**C**) and hindfoot eversion ROM as function of hindfoot erosion (**D**). MRI = magnetic resonance imaging. Color figure can be viewed in the online issue, which is available at http://onlinelibrary.wiley.com/doi/10.1002/acr.21852/abstract.

RESULTS

An overview of the demographic characteristics, clinical scores, and kinematic parameters is given in Table 1. The subjects represent all ages and disease durations, with a mean age of 51 years (range 23–78 years) and mean disease duration of 9 years (range 0.5–23 years). Eight (32%) subjects used 2 disease-modifying antirheumatic drugs (DMARDs), 15 (60%) subjects used 1 DMARD, and 2 (8%) subjects used no RA-related drugs.

The Spearman's correlation test demonstrated that the 3 kinematic parameters were independent. The subscales of the JAM were all interrelated (95% CI 0.0, 0.7) and related to MRI scores. The subtalar motion score was related to midfoot erosion (95% CI 0.1, 0.7), hindfoot erosion (95% CI 0.5, 0.9), and synovitis (95% CI 0.1, 0.8), as well as to tibialis posterior tendon (95% CI 0.1, 0.7) and flexor hallucis longus tendon (95% CI 0.2, 0.8) degeneration. The subtalar alignment score was related to hindfoot erosion (95% CI 0.2, 0.8), synovitis (95% CI 0.0, 0.7), and peroneus tendon degeneration (95% CI 0.1, 0.8). For each joint, MRI erosion and synovitis scores were strongly interrelated (95% CI 0.5, 0.8). Erosion and synovitis of the hindfoot were related to erosion of the midfoot (95% CI 0.2, 0.8), degeneration of the peroneus tendon (95% CI 0.1, 0.7), and flexor hallucis longus tendon (95% CI 0.1, 0.8).

The maximum first MTP joint dorsiflexion at preswing was significantly related to local pathologies of the first MTP joint: a moderate to strong negative correlation coefficient (95% CI −0.8, −0.3) was found for the correlation with synovitis and erosion of the first MTP joint, respectively. A negative correlation coefficient indicates that more first MTP joint erosion and inflammation resulted in less first MTP joint dorsiflexion at preswing. Furthermore, erosions of the midfoot and hindfoot, as well as the first MTP joint passive motion, measured clinically in the JAM, were moderately related to first MTP joint dorsiflexion at preswing (95% CI −0.7, −0.1) (Table 2 and Figure 2).

Midfoot pronation and hindfoot eversion ROM during single stance were not significantly related to local erosions or inflammations. However, a more everted alignment of the subtalar joint was related to less midfoot pronation and hindfoot eversion ROM (95% CI −0.8,

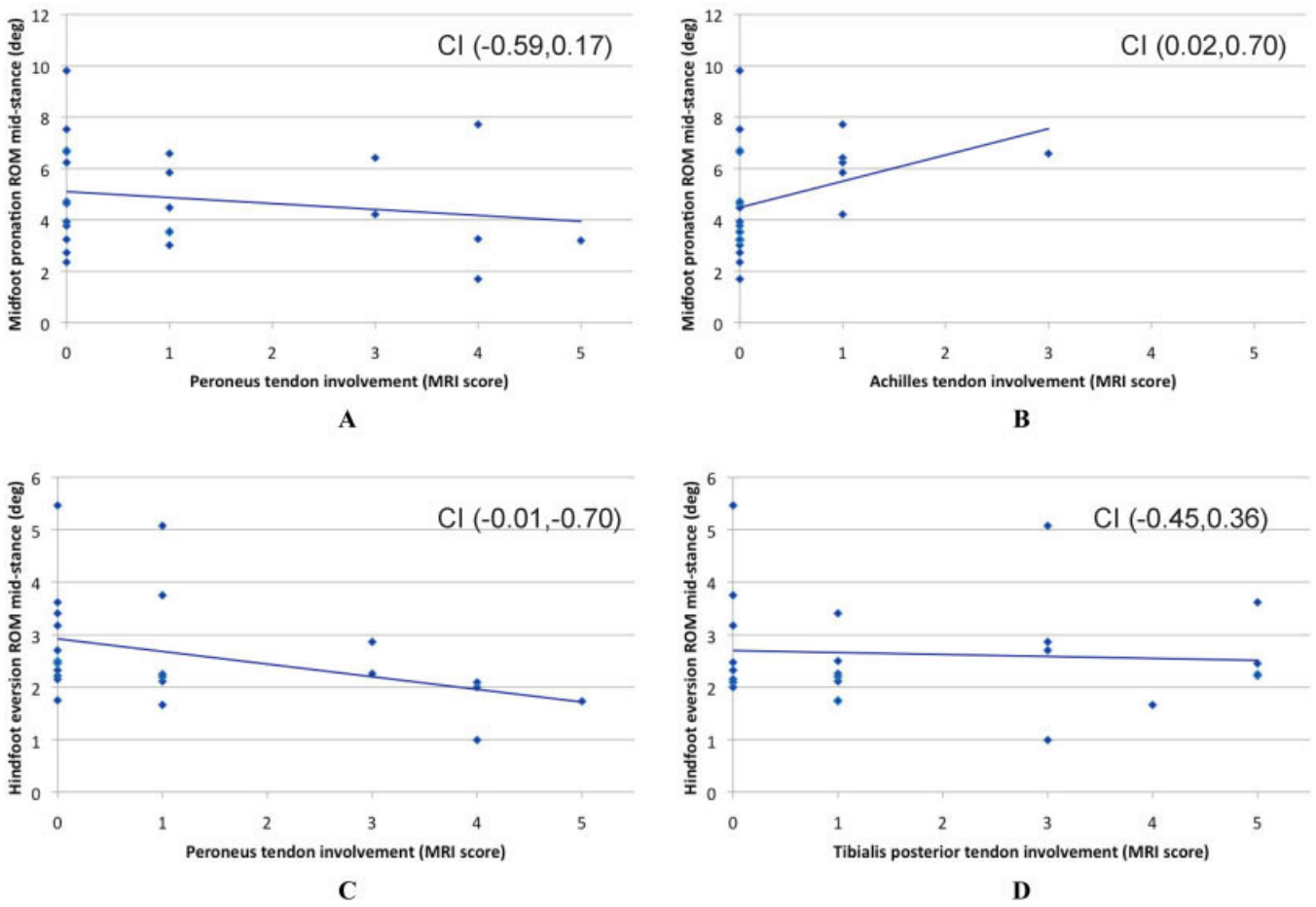

Figure 3. Individual effects on midfoot (**A** and **B**) and hindfoot (**C** and **D**) kinematics with corresponding linear regression line and the confidence interval (CI) of Spearman's correlation coefficient. ROM = range of motion; MRI = magnetic resonance imaging. Color figure can be viewed in the online issue, which is available at http://onlinelibrary.wiley.com/doi/10.1002/acr.21852/abstract.

−0.2). Furthermore, the results suggest a moderate relationship between midfoot pronation motion and pathologic changes of the Achilles tendon (95% CI −0.7, −0.0). More severe Achilles tendon involvement was related to more midfoot pronation motion. More severe involvement of the peroneus longus tendon was related to less hindfoot eversion motion at single stance (95% CI −0.7, −0.0). No significant relationship was observed for involvement of the tibialis posterior tendon on midfoot or hindfoot motion (Table 2 and Figure 3).

DISCUSSION

The aim of this study was to explore the relationship between clinically observed pathologic changes in the joints and tendons of the foot in RA patients and their corresponding first MTP joint, midfoot, and hindfoot motion during gait. In addition, the relationship between subscores of the JAM and joint kinematics were analyzed. The cross-sectional cohort consisted of RA subjects with more or less severe disease activity, pain, and structural damage, and they represented a broad range of RA patients. The mean kinematic data were comparable to findings in more or less severe RA populations (5,6,10,22). Although RA is a complex disease with multiple impairments to the foot and ankle, relationships between clinical and kinematic parameters were found in our cross-sectional cohort

Regarding joint involvement, the maximum first MTP joint dorsiflexion at preswing was moderately to strongly related to first MTP joint mobility and by joint pathologies in the whole foot and ankle. Synovitis and erosion of the first MTP joint result in pain and/or stiffness of the joint. First MTP joint pain may result in the desire to unload the pressure applied to the forefoot and reduce the range of first MTP joint motion during gait. This can be achieved, among other ways, by reducing stride length, which was observed in our RA subjects with pain (VAS), and which has already been observed in RA subjects with forefoot pain (4). In healthy subjects, lower walking speed resulted in lower peak pressures under the first MTP joint (26), required less first MTP joint dorsiflexion and ankle range of motion at preswing (27), which were both related to peak pressure under first MTP joint and hallux (28). To

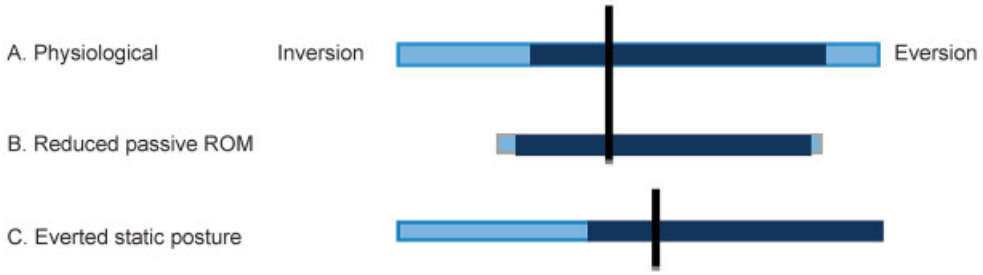

Figure 4. Hindfoot inversion and eversion motion with active range of motion (ROM) (dark blue) required during gait, available passive ROM (light blue), and posture of the hindfoot in the frontal plane (black line). Physiological situation: the active ROM required during gait is less than the available ROM (**A**). The required ROM during gait is still possible even though the available ROM is reduced as a consequence of joint stiffness (**B**). Due to an initial everted hindfoot posture, the joint reaches its maximum eversion value during the required active ROM (**C**). Color figure can be viewed in the online issue, which is available at http://onlinelibrary.wiley.com/doi/10.1002/acr.21852/abstract.

further unload their first MTP joint, RA subjects increase their cadence and reduce their stride length (29) so that, for similar walking speeds, an even lower first MTP joint dorsiflexion at preswing can be achieved. Nevertheless, in RA subjects, an increased peak pressure under the first MTP joint was observed compared to healthy subjects and was related to damage to the forefoot in RA subjects (30). Also in our study, lower maximum first MTP joint dorsiflexion at preswing was related to smaller stride lengths. First MTP joint stiffness directly limits the maximum attainable first MTP joint dorsiflexion during gait. Canseco et al reported a significant reduction of first MTP joint maximum dorsiflexion in subjects with hallux rigidus compared to healthy subjects (31) and furthermore, in RA subjects, first MTP joint stiffness was related to walking speed (11). Joint erosions of the midfoot and hindfoot seem to relate to less first MTP joint dorsiflexion at preswing. These hindfoot findings confirm earlier studies that observed effects of hindfoot osteoarthritis (in a general population) (14) or hindfoot deformities (in a RA population) (4,10) on first MTP joint motion preswing and stride length. No studies were found that studied the effects of midfoot erosion on gait parameters.

Midfoot supination–pronation and hindfoot eversion–inversion motion during the single stance phase seem to be at least moderately related to hindfoot alignment, but not to midfoot or hindfoot erosion or synovitis. Reduced midfoot pronation and hindfoot eversion motion were observed in only the more severe cases of hindfoot erosion. The latter corresponds to similar findings reported by Turner and Woodburn, who only observed significant changes in hindfoot and forefoot kinematics in a group of RA subjects with severe hindfoot deformations and not in a group with mostly forefoot deformations (10). Also in subjects with severe ankle osteoarthritis, changes in hindfoot kinematics were observed (14). This may be explained by the fact that during gait, only a limited amount of hindfoot motion is required in the frontal plane (Figure 4A). The data suggest that only a more advanced stage of hindfoot pathologies with severe stiffness may influence and impair midfoot and hindfoot kinematics (Figure 4B). Foot posture, however, shifts the required motion with regard to the available motion (Figure 4C). A pronated foot type has been related to increase in maximum hindfoot eversion during gait in healthy and in RA subjects (32,33). Therefore, in our study, the increased hindfoot alignment of RA subjects with a more everted static posture of the hindfoot may result in less available eversion motion during single stance.

Our findings suggest moderate to strong relationships between tendon involvements and midfoot and hindfoot motion during gait. Achilles tendon involvement was related to increased pronation motion of the midfoot. Four RA subjects were observed with MRI signal inhomogenities and 1 subject with thickening of the Achilles tendon, and for each of these subjects staining of the attachment of the plantar fascia was observed on MRI. The latter was not observed in RA subjects without Achilles tendon involvement. Several studies have reported that tensioning of the Achilles tendon results in reduced inclination of the calcaneus, flattening of the medial arch, and tensioning of the plantar fascia (34–37). Consequently, damage to the Achilles tendon or the plantar fascia may reduce the pretensioning capacity to the foot structures and result in more midfoot motion during single stance. The studies including Achilles tensioning did not report on its effect on midfoot and hindfoot motion in the frontal plane.

Moderate to strong relationships between pathologic changes of the peroneus longus tendon and reduced hindfoot eversion motion were observed during single stance. In this study, involvement of the peroneus longus tendon was strongly related to the subtalar alignment subscale score of the JAM (95% CI 0.1, 0.8) and to hindfoot synovitis (95% CI 0.1, 0.7). Hindfoot joint synovitis can lead to destruction of the ankle ligaments (38). Both have been associated with peroneus longus tendon involvement (39,40) and also with changes in passive ankle joint ROM and alignment (34,41,42). As subtalar alignment also significantly influences midfoot motion, it is not clear at present if the peroneus longus involvement and reduced midfoot motion have a causal relationship. As far as we know, there are no studies that report on the effects of local peroneus tendon pathologies on foot and ankle kinematics in subjects with or without a systemic disease. Our

findings demonstrate a need for further analysis of the effects of peroneus tendon and hindfoot ligament and alignment pathologies on foot and ankle kinematics.

Tibialis posterior tendon involvement was related to the subtalar passive motion subscore of the JAM (95% CI 0.1, 0.7), but did not influence the midfoot supination or the hindfoot eversion motion during single stance. Eight of our RA subjects did not have pathologic involvement of their tibialis posterior tendon, and another 7 subjects only had MRI signal inhomogeneities. However, also for those RA subjects with more severe involvement of the tibialis posterior tendon, no change in midfoot or hindfoot motion during single stance was observed in our study. Other studies did report a statistically significant relationship of tibialis posterior tendon dysfunction with forefoot and hindfoot kinematics in subjects with severe tibialis posterior tendon pathologies (13). It must be noted, however, that in these studies the subjects also had a flatfoot or significant hindfoot eversion posture, which was not always the case in our study. So possibly, the observed effects in the other studies might be attributed mostly to foot alignment. This is in agreement with the finding in our study, which demonstrates a moderate to strong relationship of the hindfoot alignment with hindfoot eversion and midfoot pronation motion. Furthermore, Imhauser et al (41) and Pisani (43) demonstrate and discuss that the tibialis posterior tendon can only control and support midfoot and hindfoot motion if the hindfoot joint is stable and the ligaments are intact. However, in RA subjects, the hindfoot ligaments are frequently involved in pathologies due to tarsitis (38). Although we did not assess the hindfoot ligaments, we did observe a relationship between tibialis posterior tendon involvement and the subtalar motion subscale score of the JAM.

We analyzed a cross-sectional cohort of RA subjects with various stages of the disease and corresponding pathologies. Due to the complexity of the disease, heterogeneity of the study population and for some clinical parameters, a limited number of subjects, the analysis of relationships between clinical and gait parameters resulted in large confidence intervals. In the future, it is suggested to study the effects of pathologies on kinematics in a more homogeneous study population and preferably, in a longitudinal study.

In this exploratory study, we have tried to explain several of our findings by means of other studies, which used, among others, plantar pressure and muscle strength analysis. These parameters were not measured in our study, but the suggested possible explanations might be used as starting points or hypotheses in future studies. Furthermore, due to limitations of the used foot and ankle model, the lateral forefoot (second through fifth MTP joints) was not taken into account in this study. As these structures are frequently impaired in RA subjects, future kinematic analysis studies should consider taking the motion of the second through fifth MTP joints or the lateral forefoot into account.

In this study, moderate to strong relationships of joint and tendon pathologies with foot and ankle kinematics were observed from the onset of the assessed joint and tendon pathologies. Even small changes in joint motion or alignment during the stance phase of gait may have functional implications such as loss of walking speed (22), compensation or overload in foot, knee, or hip joints (26–28,44), increased energy consumption (45), and consequently, reduced social participation (5,46). Deterioration of joint and tendon structures occurs from the beginning of RA and therefore should be monitored and treated carefully.

The JAM subscores, first MTP joint passive motion, and subtalar alignment are easily measured in daily clinical practice without burden to the patient. Our findings suggest a moderate to strong relationship between JAM subscale scores and foot and ankle kinematics, which might make the JAM suitable for quick assessment of foot and ankle function during gait. While large JAM subscore variability was observed between subjects, long-term individual monitoring may provide a good estimate for individual foot and ankle function during gait, as it already does for foot and ankle function during daily life (2,19).

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All authors were involved in drafting the article or revising it critically for important intellectual content, and all authors approved the final version to be submitted for publication. Ms Dubbeldam had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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REFERENCES

1. Van der Leeden M, Steultjens MP, Ursum J, Dahmen R, Roorda LD, Schaardenburg D, et al. Prevalence and course of forefoot impairments and walking disability in the first eight years of rheumatoid arthritis. Arthritis Rheum 2008;59:1596–602.
2. Baan H, Drossaers-Bakker W, Dubbeldam R, van de Laar MA. We should not forget the foot: relations between signs and symptoms, damage and function in rheumatoid arthritis. Clin Rheumatol 2011;11:1475–9.
3. Van der Leeden M, Steultjens MP, Ursem J, Dahmen R, Roorda LD, Schaardenburg D, et al. Prediction of walking disability by disease-related factors in patients with rheumatoid arthritis. J Rehab Med 2010;42:506–10.
4. Platto MJ, O'Connell PG, Hicks JE, Gerber LH. The relationship of pain and deformity of the rheumatoid foot to gait and an index of functional ambulation. J Rheumatol 1991;18:38–43.
5. Turner DE, Helliwell PS, Lohmann Siegel K, Woodburn J. Biomechanics of the foot in rheumatoid arthritis: identifying abnormal function and the factors associated with localised disease 'impact.' Clin Biomech 2008;23:93–100.
6. Khazzam M, Long JT, Marks RM, Harris GF. Kinematic changes of the foot and ankle in patients with systemic rheu-

matoid arthritis and forefoot deformity. J Orthop Res 2007;25:319–29.
7. Turner DE, Helliwell PS, Emery P, Woodburn J. The impact of rheumatoid arthritis on foot function in early stage of disease: a clinical case series. BMC Musculoskelet Disord 2006;7:102.
8. Weiss RJ, Wretenberg P, Stark A, Palmblad K, Larsson P, Grondal L, et al. Gait pattern in rheumatoid arthritis. Gait Posture 2008;28:229–34.
9. Woodburn J, Nelson KM, Lohman Siegel K, Kepple TM, Gerber LH. Multisegment foot motion during gait: proof of concept in rheumatoid arthritis. J Rheumatol 2004;31:1918–27.
10. Turner DE, Woodburn J. Characterising the clinical and biomechanical features of severely deformed feet in rheumatoid arthritis. Gait Posture 2008;28:574–80.
11. Laroche D, Ornetti P, Thomas E, Ballay Y, Maillefert JF, Pozzo T. Kinematic adaptation of locomotor pattern in rheumatoid arthritis patients with forefoot impairment. Exp Brain Res 2007;176:85–97.
12. Ness ME, Long J, Marks R, Harris G. Foot and ankle kinematics in patients with posterior tibial tendon dysfunction. Gait Posture 2008;27:331–9.
13. Tome J, Nawoczenski DA, Flemister A, Houck J. Comparison of foot kinematics between subjects with posterior tibialis tendon dysfunction and healthy controls. J Orthop Sports Phys Ther 2006;36:635–44.
14. Khazzam M, Long JT, Marks RM, Harris GF. Preoperative gait characterization of patients with ankle arthrosis. Gait Posture 2006;24:85–93.
15. Beeson P, Phillips C, Corr S, Ribbans WJ. Hallux rigidus: a cross-sectional study to evaluate clinical parameters. Foot (Edinb) 2009;19:80–92.
16. Conaghan P, Edmonds J, Emery P, Genant H, Gibbon W, Klarlund M, et al. Magnetic resonance imaging in rheumatoid arthritis: summary of OMERACT activities, current status, and plans. J Rheumatol 2001;28:1158–62.
17. Helliwell P, Woodburn J, Redmond A, Turner D, Davys H. The foot and ankle in rheumatoid arthritis. London: Churchill Livingstone; 2007.
18. Spiegel TM, Spiegel JS, Paulus HE. The joint alignment and motion scale: a simple measure of deformity in patients with rheumatoid arthritis. J Rheumatol 1987;14:887–92.
19. Bal A, Aydog E, Aydog ST, Cakci A. Foot deformities in rheumatoid arthritis and relevance of foot function index. Clin Rheumatol 2006;25:671–5.
20. Arnett FC, Edworthy SM, Bloch DA, McShane DJ, Fries JF, Cooper NS, et al. The American Rheumatism Association 1987 revised criteria for the classification of rheumatoid arthritis. Arthritis Rheum 1988;31:315–24.
21. Simon J, Doederlein AS, McIntosh AS, Metaxiotis HG, Wolf SI. The Heidelberg foot measurement model: development, description and assessment. Gait Posture 2006;23:411–24.
22. Dubbeldam R, Nene AV, Burrke J, Groothuis-Oudshoorn CG, Baan H, Drossaers-Bakker KW, et al. Foot and ankle joint kinematics in rheumatoid arthritis cannot only be explained by alteration in walking speed. Gait Posture 2011;33:390–5.
23. Rosenberg ZS, Beltran J, Bencardino JT. MR imaging of the ankle and foot. RadioGraphics 2000;20:S153–79.
24. Baan HB, Bezooijen R, Avenarius JK, Dubbeldam R, Drossaers-Bakker WK, van de Laar MA. Magnetic resonance imaging of the rheumatic foot according to the RAMRIS system is reliable. J Rheumatol 2011;38:1003–8.
25. Cohen J. Statistical power analysis for the behavioral sciences. 2nd ed. Hillsdale (NJ): Lawrence Erlbaum; 1988.
26. Rosenbaum D, Hautmann S, Gold M, Claes L. Effects of walking speed on plantar pressure patterns and hindfoot angular motion. Gait Posture 1994;2:191–7.
27. Dubbeldam R, Buurke JH, Simons C, Groothuis-Oudshoorn CG, Baan H, Nene AV, et al. The effects of walking speed on forefoot, hindfoot and ankle joint motion. Clin Biom 2010;25:796–801.
28. Morag E, Cavanagh PR. Structural and functional predictors of regional peak pressures under the foot during walking. J Biomech 1999;32:359–70.
29. Eppeland SG, Myklebust G, Hodt-Billington C, Moe-Nilssen R. Gait patterns in subjects with rheumatoid arthritis cannot be explained by reduced speed alone. Gait Posture 2009;29:499–503.
30. Van der Leeden M, Steultjens M, Dekker J, Prins A, Dekker J. Forefoot joint damage, pain and disability in rheumatoid arthritis patients with foot complaints: the role of plantar pressure and gait characteristics. Rheumatology (Oxford) 2006;45:465–9.
31. Canseco K, Long J, Marks R, Khazzam M, Harris G. Quantitative characterization of gait kinematics in patients with hallux rigidus using the Milwaukee foot model. J Orthop Res 2008;26:419–27.
32. Keenan MA, Peabody TD, Gronley JK, Perry J. Valgus deformities of the feet and characteristics of gait in patients who have rheumatoid arthritis. J Bone Joint Surg Am 1991;73:237–47.
33. Chuter VH. Relationships between foot type and dynamic rearfoot frontal plane motion. J Foot Ankle Res 2010;3:9.
34. Blackman AJ, Sangeorzan BJ, Ledoux WR. Cadaveric flatfoot model: ligament attenuation and Achilles tendon overpull. J Orthop Res 2009;27:1547–54.
35. Carlson RE, Fleming LL, Hutton WC. The biomechanical relationship between the tendoachilles, plantar fascia and metatarsophalangeal joint dorsiflexion angle. Foot Ankle Int 2000;21:18–25.
36. Cheng HY, Lin CL, Wang HW, Chou SW. Finite element analysis of plantar fascia under stretch: the relative contribution of windlass mechanism and Achilles tendon force. J Biomech 2008;41:1937–44.
37. Cheung JT, Zhang M, An KN. Effect of Achilles tendon loading on plantar fascia tension in the standing foot. Clin Biomech 2006;21:194–203.
38. Bouysset M, Tavernier T, Tebib J, Noel E, Tilmann K, Bonnin M, et al. CT and MRI evaluation of tenosynovitis of the rheumatoid hindfoot. Clin Rheumatol 1995;14:303–7.
39. DiGiovanni BF, Fraga CJ, Cohen BE, Shereff MJ. Associated injuries found in chronic lateral ankle instability. Foot Ankle Int 2000;21:809–15.
40. Park HJ, Cha SD, Kim HS, Chung ST, Park NH, Yoo JH, et al. Reliability of MRI findings of peroneal tendinopathy in patients with lateral chronic ankle instability. Clin Orthop Surg 2010;2:237–43.
41. Imhauser CW, Siegler S, Abidi NA, Frankel DZ. The effect of posterior tibialis tendon dysfunction on the plantar pressure characteristics and the kinematics of the arch and the hindfoot. Clin Biomech (Bristol, Avon) 2004;19:161–9.
42. Rosenbaum D, Becker HP, Wilke HJ, Claes LE. Tenodeses destroy the kinematic coupling of the ankle joint complex: a three-dimensional in vitro analysis of joint movement. J Bone Joint Surg Br 1998;80:162–8.
43. Pisani G. Peritalar destabilisation syndrome (adult flatfoot with degenerative glenopathy). Foot Ankle Surg 2010;16:183–8.
44. Barton CJ, Levinger P, Crossley KM, Webster KE, Menz HB. Relationships between the Foot Posture Index and foot kinematics during gait in individuals with and without patellofemoral pain syndrome. J Foot Ankle Res 2011;4:10.
45. Neptune RR, Sasaki K, Kautz SA. The effect of walking speed on muscle function and mechanical energetics. Gait Posture 2008;28:135–43.
46. Hamilton J, Brydson G, Fraser S, Grant M. Walking ability as a measure of treatment effect in early rheumatoid arthritis. Clin Rehabil 2001;15:142–7.