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Abstract

Introduction

Rheumatoid arthritis (RA) is a systemic autoimmune disease that can cause weakening and destruction of various joints of the foot and may result in pain and deformity. This clinical presentation can cause eventual loss of function, shoe-wear difficulties, and altered gait patterns.

Purpose

The goal of this prospective study was to quantify changes in temporal-spatial parameters and multisegmental foot and ankle kinematics in a group of patients with RA of the forefoot following surgery.

Methods

Three-dimensional (3-D) motion analysis was conducted preoperatively and postoperatively using a 15-camera Vicon Motion Analysis System (Vicon Motion Systems, Inc.; Lake Forest, CA) on 14 feet in 13 patients with forefoot RA. The Milwaukee foot model was used to characterize segmental kinematics and temporal-spatial parameters. Preoperative and postoperative data were compared using paired nonparametric methods; comparisons with normative data were performed using unpaired nonparametric methods.

Results

Preoperatively, the hallux was in a valgus position, the forefoot was abducted and in valgus, and range of motion was limited in various phases in all segments. Walking speed and stride length were decreased and stance prolonged when compared with normal controls. Postoperatively, the hallux alignment was restored to normal but a limited range of motion remained. Kinematics also demonstrated forefoot valgus and tibial internal rotation compared with the control population. Comparisons to healthy ambulators also showed decreased stride lengths and prolonged stance phase durations.

Conclusion

Surgery effectively restored alignment and weight-bearing capacity of the rheumatoid feet. Temporal-spatial parameters and kinematics, however, were not restored to control values, but rather were consistent with first metatarsophalangeal joint fusion effects. The altered mechanics after surgery demonstrate the importance of quantitative assessment in understanding the geometric and kinematic effects of surgical realignment with implications for postoperative rehabilitation and gait training.

Key words

Ankle, autoimmune disease, Milwaukee foot model, multisegmental motion analysis, orthopedics, rheumatoid arthritis

1. Introduction

Rheumatoid arthritis (RA) is a systemic autoimmune disease that affects multiple joints in the body but most commonly involves the foot.[1] The hallmark of the disease is destructive synovitis, which impairs the integrity of the capsular and ligamentous structures of the metatarsophalangeal (MTP) joints leading to joint instability. Furthermore, release of proteolytic enzymes destroys articular cartilage. Due to the mechanical stresses of

weight bearing, varying degrees of deformity such as hammertoe, mallet toe, or claw toe deformities may develop. Loss of medial soft-tissue support secondary to synovitis, together with subluxation and dislocation of the lesser MTP joints that act as lateral stabilizers, results in hallux valgus deformity. This is the predominant deformity of the great toe in RA.1, 2, 3, 4 Other common findings in the great toe are hallux rigidus, hallux tortus, and chisel toe. Eventual loss of function and shoe-wear difficulties are commonly observed.

Given this clinical picture, gait disturbance is a primary concern in patients with RA. Previous studies have demonstrated that RA may lead to a decrease in walking speed, lower limb muscle function, limited joint range of motion (ROM), loss of functional balance, shortened stride length, and increased double-stance period, which indicates a limitation of lower limb function.5, 6 In 1988, an electrogoniometry study by Isacson and Brostrom demonstrated that people with RA walked at slower speeds and that their foot and ankle motion were limited with reduced internal rotation, adduction, and plantar flexion at toe off.[7] Other authors have described similar findings in gait studies of patients with RA.5, 8, 9, 10, 11

Reports of multisegmental foot and ankle motion analyses in the RA population are limited.3, 12 In 2004, Woodburn and colleagues conducted a multisegment video-based motion analysis of five healthy feet in 11 patients with RA.[12] Reduced ranges of motion across all segments and all planes of motion was observed in the patients with RA, which was consistent with joint stiffness. Rearfoot motion was shifted toward eversion and external rotation with peak values increased to about 7° and 11°, respectively. Forefoot ROM was reduced in all three planes. The navicular height, during full foot contact, was on average 3 mm lower in the patients with RA compared with normal controls. The hallux was less extended in the patients with RA compared with controls (21° versus 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. In 2007, Khazzam and others compared 29 feet with RA and 25 healthy feet using the four-segment Milwaukee foot model (MFM).[3] Motion analysis results showed prolonged stance time, shortened stride length, increased cadence, and a walking speed that was 80% of control. Overall, kinematic data in the RA cohort showed significant differences in motion for tibial, hindfoot, and forefoot motion when compared with controls with decreased ranges across all segments. Common to all previously published reports on multisegmental gait in patients with RA is the characterization of patterns prior to treatment; biomechanical outcomes after surgery for RA are rarely described in the current literature and lack any details regarding segmental foot kinematics.

1.1. Purpose

The goal of this study was to investigate the temporal and kinematic characteristics of segmental foot motion in a group of patients with RA before and after surgery. Previous studies found that preoperative patients with RA demonstrated decreased walking speed and stride length, increased cadence, and prolonged stance phase.3, 8 Segments of the foot and ankle demonstrated altered kinematic patterns characterized by decreased ROM of the hallux, forefoot, hindfoot, and tibia as well as findings consistent with hallux valgus and hallux rigidus.1, 3 Based on these observations, we hypothesized that these altered temporal-spatial parameters and kinematics would be postoperatively restored toward normal.

2. Methods

2.1. Subjects

This prospective study of patients with RA of the forefoot was conducted at the Orthopaedic and Rehabilitation Engineering Center Motion Analysis Laboratory following approval by the Institutional Review Board of the Medical College of Wisconsin in Milwaukee, WI. The patients were recruited from the Medical College of Wisconsin and the Froedtert Hospital Foot and Ankle Clinics from 2000 to 2007. Written informed consents were obtained from all participants. Fourteen feet in 13 patients (two men, 11 women) were tested in this

study. The mean age at the time of preoperative testing was 57.7 years (range, 36–70 years). All patients demonstrated RA of the forefoot that required surgical intervention. A single orthopedic surgeon performed the clinical assessment and operative treatment. Thirteen of the 14 participants underwent first MTP fusion and lesser metatarsal head resection; the remaining patient underwent an Akin procedure with lesser metatarsal head resection. Thirteen of the 14 patients also had hammer toe correction, and four required extensor hallucis longus lengthening. All patients were tested postoperatively at 10 to 18 months for follow-up (mean, 13 months). Postoperative testing was conducted only after a complete clinical return to a stable ambulatory pattern.

2.2. Motion analysis

Foot and ankle motion analyses were performed using a video-based Vicon 524 Motion Analysis System (Vicon Motion Systems, Inc., Lake Forest, CA), with 15 cameras operating at 120 Hz. Data were collected as patients walked at a self-selected speed along a 6-m walkway. Temporal-spatial parameters (walking speed, stride length, cadence, and stance/swing ratio) as well as foot and ankle kinematics (position and ROM) were measured using the four-segment MFM, which has been validated for the adult and pediatric population.13, 14 This biomechanical model divides the foot and ankle into four segments (tibia, hindfoot, forefoot, and hallux) and measures motion of each segment in three planes (sagittal, coronal, and transverse). Marker positions were indexed to the underlying bony anatomy based on measurements from weightbearing radiographs.[15] Positions and ROM were compared preoperatively and postoperatively during each of the seven phases of gait as described by Perry.[16] These phases include load response, midstance, terminal stance, preswing, initial swing, midswing, and terminal swing. Preoperative and postoperative temporal-spatial and kinematic data comparisons were performed using paired nonparametric methods. Comparisons to a population of 25 healthy ambulators ("normal population": 13 men, 12 women) as controls were also made using unpaired nonparametric methods. A Bonferroni correction was used to achieve a family wise 5% overall error rate in adjusting for multiple tests over the set of seven test phases in the gait cycle.

3. Results

3.1. Temporal-spatial parameters

Preoperatively, persons with RA demonstrated significantly decreased walking speed ($p = 0.0074$) and stride length ($p = 0.0004$), with significantly prolonged stance ($p = 0.0113$) when compared with the normal population (Table 1). There were no statistical differences observed in temporal-spatial parameters between preoperative and postoperative data. Compared with healthy ambulators, postoperative stride length remained significantly decreased and stance duration remained significantly prolonged.

Table 1. Temporal-Spatial Parameters (mean ± 1 SD)

Temporal-spatial parameters	**Pre**	**Post**	**Normal**	**Pre vs. post *p***	**Pre vs. normal *p***	**Post vs. normal *p***
Stride length (m)	1.06 ± 0.18	1.12 ± 0.15	1.28 ± 0.10	0.0785	0.0004∗	0.0020∗
Cadence (steps/min)	107.69 ± 10.00	107.99 ± 10.67	104.65 ± 7.89	1.0000	0.4041	0.1556
Walking speed (m/s)	0.95 ± 0.20	1.01 ± 0.19	1.12 ± 0.10	0.1531	0.0074∗	0.0923
Stance (%)	64.45 ± 1.95	64.87 ± 1.88	62.27 ± 2.60	0.4631	0.0113∗	0.0047∗

∗Significant at $p < 0.05$.

3.2. Kinematics

Kinematics (position and ROM) of the hallux, forefoot, hindfoot, and tibia segments are illustrated in Figure 1, Figure 2, Figure 3, Figure 4, respectively.

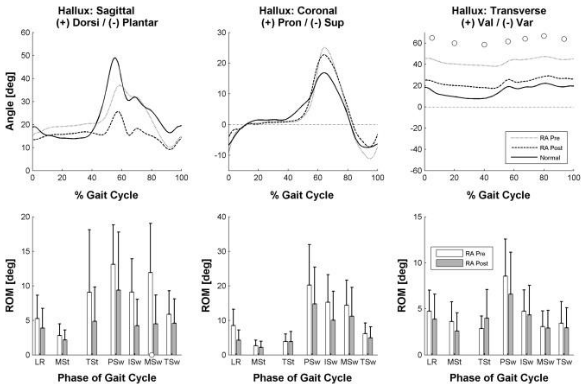

Figure 1. Upper: Average hallux kinematics during complete gait cycle (pre-rheumatoid arthritis [RA] vs. post-RA vs. normals). Circles denote phases of gait cycle with significantly different minimum and maximum positions (pre-RA vs. post-RA). Lower: Hallux range of motion (ROM; average ± 1SD). Circles denote phases of gait cycle with significantly different ROMs (pre-RA vs. post-RA). Note: Hallux kinematics are calculated relative to the forefoot.

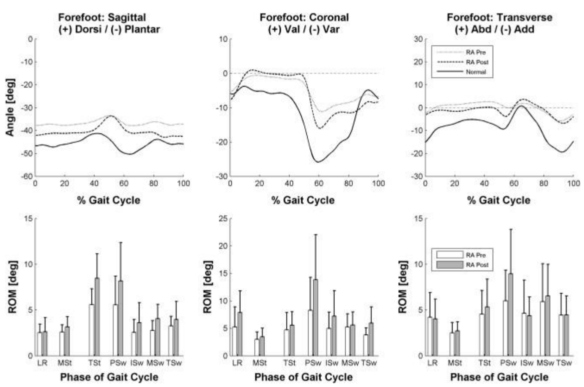

Figure 2. Upper: Average forefoot kinematics during complete gait cycle (pre-rheumatoid arthritis [RA] vs. post-RA vs. normals). Circles denote phases of gait cycle with significantly different minimum and maximum positions (pre-RA vs. post-RA). Lower: forefoot range of motion (ROM; average ± 1SD). Circles denote phases of gait cycle with significantly different ROMs (pre-RA vs. post-RA). Note: Forefoot kinematics are calculated relative to the hindfoot.

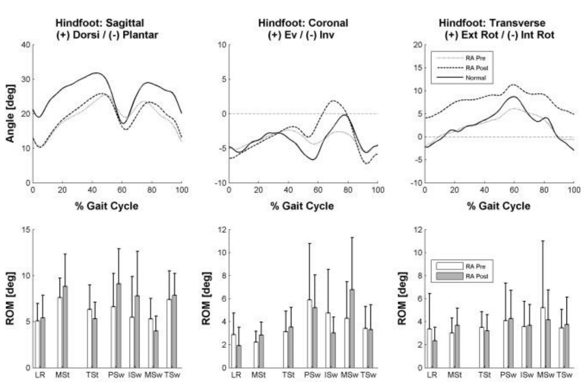

Figure 3. Upper: Average hindfoot kinematics during complete gait cycle (pre-rheumatoid arthritis [RA] vs. post-RA vs. normals). Circles denote phases of gait cycle with significantly different minimum and maximum positions (RApre vs. RApost). Lower: Hindfoot range of motion (ROM; average ± 1SD). Circles denote phases of gait cycle

with significantly different ROMs (pre-RA vs. post-RA). Note: Hindfoot kinematics are calculated relative to the tibia.

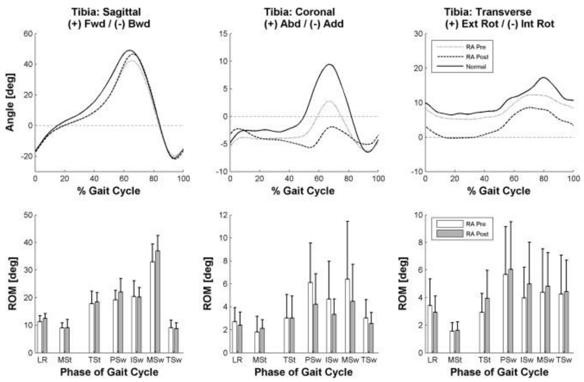

Figure 4. Upper: Average tibia kinematics during complete gait cycle (pre-rheumatoid arthritis [RA] vs. post-RA vs. normals). Circles denote phases of gait cycle with significantly different minimum and maximum positions (pre-RA vs. post-RA). Lower: Tibia range of motion (ROM; average ± 1SD). Circles denote phases of gait cycle with significantly different ROMs (pre-RA vs. post-RA). Note: Tibia kinematics are calculated relative to the laboratory global.

Preoperatively, the hallux was in a valgus position ($p \leq 0.0015$) throughout the gait cycle compared with the normative data (Figure 1). Significantly decreased transverse hallux ROM was seen from initial swing through load response ($p \leq 0.0016$). Sagittal range was also significantly limited from terminal stance through preswing ($p = 0.0001$), and coronal ROM was significantly decreased from midstance through terminal stance ($p \leq 0.0015$).

Forefoot kinematics showed an abducted position from terminal swing through load response ($p \leq 0.0018$) and decreased transverse ROM ($p \leq 0.0015$) throughout the gait cycle compared with normals (Figure 2). Sagittal range was also decreased from initial swing through midstance ($p \leq 0.0005$). In the coronal plane, there was a significant valgus shift from preswing to initial swing ($p \leq 0.0005$). Coronal range was also significantly decreased at terminal stance, midswing, and terminal swing ($p \leq 0.0001$). Isolated significant decreases in ROM were seen in various phases of gait at the hindfoot and tibia.

Postoperatively, the valgus position of the hallux significantly shifted toward normal ($p \leq 0.0017$) compared with preoperative values. There were no other significant changes postoperatively in terms of proximal segment positions and ROM.

Compared with the healthy population, the postoperative hallux had decreased dorsiflexion from preswing through initial swing and decreased ROM from load response through the initial swing. Forefoot transverse ROM was decreased from initial swing through midstance and demonstrated a valgus shift at initial swing in the coronal plane. Hindfoot coronal ROM was decreased from terminal swing through terminal stance and at initial swing. Hindfoot transverse range was also decreased from initial swing through load response and at terminal stance. Tibial coronal ROM was decreased from initial swing through terminal swing with less external rotation (Figure 4).

4. Discussion

Results of the current study demonstrated diminished gait function in patients with RA, which was indicated by decreased kinematic and temporal-spatial parameters preoperatively. Decreased walking speed and stride length support previous observations of the rheumatoid foot's impaired ability to bear weight and propel the limb at pushoff.[3, 12, 17] This lack of propulsion may be due to pain, deformity, or both, and may lead to

prolonged stance duration as observed in our study. Prolonged stance phase in RA has been found to be significantly correlated with disability in daily activities.5, 18, 19 Kinematic results of the current study also support common clinical findings in RA such as hallux valgus, forefoot abduction and pronation consistent with medial longitudinal arch collapse, and decreased ROM.1, 12

In the current study, all but one foot underwent first MTP fusion. Postoperative kinematic results demonstrate that although hallux transverse alignment was corrected, sagittal dorsiflexion and ROM was reduced as a result of the first MTP fusion. The result is a stable, pain-free, anatomically aligned, MTP joint, but a joint that is biomechanically inefficient in terms of foot propulsion with the loss of the third rocker. Other gait changes that occur with the loss of hallux MTP motion, such as loss of ankle plantarflexion moment and ankle power at toe off, may be seen in patients after first MTP arthrodesis.[20] The resulting lack of foot propulsion may account for the persistent decrease in stride length and prolonged stance after surgery noted in our study.

In the literature, long-term follow-up of such patients who underwent similar surgeries has yielded good clinical results. In 2000, Coughlin followed 47 feet in 32 patients with severe rheumatoid forefoot deformities who underwent MTP fusion and second to fifth MTP resection arthroplasties.[2] Patients subjectively rated the procedure as excellent for 23 feet, good for 22, and fair for two. Postoperative pain was rated as absent in 18 feet, mild in 25, moderate in four, and severe in none. In arthrodesis, the lack of motion in the first MTP joint may cause undue stress in adjacent joints, possibly resulting in long-term complications, including interphalangeal joint arthritis.21, 22 Severe interphalangeal joint arthritis was found in eight patients, but the rate of metatarsalgia was low (6%). This was attributable to the increased weightbearing on the first day, which diminished lateral translation pressure beneath the lesser metatarsals.2, 23 This particular finding was consistent with other pedobarographic studies showing maximum pressure on the medial side underneath the first metatarsal head, restoring its weightbearing function during gait after surgery.20, 24 Our findings of forefoot valgus on initial swing and tibial internal rotation are consistent with the acquired pes planovalgus seen in RA.12, 25 Whether these altered forefoot and tibia kinematics are a result of an acquired flatfoot or simply a compensatory mechanism is currently unclear.

Multiple joint involvement in the rheumatoid foot results in a complex and varied pattern of gait impairment. Depending on the joints involved, surgical intervention often involves varied combinations of operative procedures. Multisegmental foot and ankle motion analysis provides a useful tool to evaluate kinematic changes in different segments involved pre- and postoperatively. Our current study effectively demonstrates segmental differences from normal controls preoperatively, as well as postsurgical changes following treatment. Preoperatively, the hallux was in a valgus position, the forefoot was abducted and in valgus, and ROM was limited in various phases in all segments. Postoperatively, the hallux alignment was restored to normal but with limited ROM. Kinematics also demonstrated forefoot valgus and tibial internal rotation compared to the normal population. These findings support the future use of 3-D fluoroscopy and development of a kinetic model, which may allow a more complete understanding of *in vivo* intertarsal mechanics associated with RA, as well as alterations following surgical intervention.

5. Conclusion

Based on the results of the study, our hypothesis that altered temporal-spatial parameters and kinematics would be restored postoperatively is partially supported. Hallux position was significantly restored. Forefoot abduction decreased and was no longer significantly different from normal; forefoot valgus also decreased, although this was not significant. However, hallux ROM significantly decreased and significant tibial internal rotation was observed after surgery. Although stride length continued to decrease and stance duration prolonged, walking speed showed slight improvement. However, this did not reach statistical significance.

The purpose of the surgery is the restoration of alignment and weightbearing capacity in the rheumatoid foot. Although this has been achieved by the surgery, a fused MTP joint is neither mechanically nor physiologically normal and continues to produce an altered gait pattern when compared with healthy ambulators. The presence of altered mechanics following surgery alerts the surgeon to anticipated outcomes, and its presence stresses the importance of postoperative rehabilitation and gait training.

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