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A prospective clinical and biomechanical analysis of feet following first metatarsophalangeal joint replacement

R.A. Rajan [a,b,c,*], M. Kerr [c], H. Evans [c], T. Outram [d]

[a] University Hospitals of Derby & Burton, Uttoxeter Road, Derby, DE22 2NE, UK
[b] University of Derby, Kedleston Road, Derby, DE22 1GB, UK
[c] Gait Laboratory, University Hospitals of Derby & Burton, London Road Site, Derby, UK
[d] Department of Sport, Outdoor & Exercise Science, School of Human Sciences, University of Derby, Kedleston Road, Derby, UK

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ABSTRACT

Background: There is a lack of research providing a biomechanical outcome following 1st MTPJ replacement for hallux rigidus. Despite this, 1st MTPJ replacement continues to be an alternative surgical option to fusion for this painful debilitating condition. Several studies do consider the patient reported outcomes which are subjective.
Research Question: The objective of this study is to provide an in depth biomechanical analysis to examine the effects of 1st MTPJ replacement for hallux rigidus on gait mechanics.
Methods: Kinematic data was collected at our CMAS (Clinical Movement Analysis Society) UK accredited gait laboratory during the gait cycle together with pressure plate pressure readings and a validated patient outcome measure before surgery and at 6 and 12 months after surgery. A complete literature review is performed.
Results: Kinematic data revealed a significant increase in stride length, cadence and velocity following 1st MTPJ replacement for hallux rigidus. Foot kinematic data revealed significantly reduced tibia-hindfoot abduction and pronation and reduced hindfoot-forefoot supination and adduction. There was no effect on 1st MTPJ weight bearing range of motion. Pressure plate data revealed an increase in peak pressure and pressure time integral towards the 1st metatarsal following surgery. There was a significant improvement in the patient reported outcome measure.
Significance: This study has demonstrated objectively that following 1st MTPJ replacement, biomechanically, a restoration of the foot posture to allow medialisation of foot pressures towards the medial column and normalisation of gait including an increase in the stride length, cadence and velocity and that clinically, there was an improvement in the MOXFQ.

1. Introduction

Degeneration of the first metatarsophalangeal joint (1st MTPJ) of the foot results from wear of the joint. The pathophysiological process involves reduction of joint space and formation of marginal osteophytes which capture the joint and leads to stiffness, especially in dorsiflexion [1]. Dorsiflexion in the MTPJ's is important for propulsion in walking as it provides stability during toe-off and facilitates the windlass effect [2]. In patients with hallux rigidus, normal function of the 1st MTPJ is impaired which leads to an increase in the load bearing of the affected foot and a shift in load from the medial to the lateral aspect [3].

Pain is the main complaint associated with hallux rigidus with some symptoms of locking or impingement of the dorsal osteophytes within the shoe. This is due to a combination of pushing the joint to the limits of movement within its captured state and the pressure effect of the osteophytes. Treatment for hallux rigidus varies according to the severity of symptoms and radiographic changes [4]. Conservative treatment includes activity modification, orthotic management, simple analgesics and intra articular corticosteroid injections. Surgical options include procedures such as cheilectomy, interposition arthroplasty, joint surface excision and fusion [5].

The goals of therapy for hallux rigidus are to eliminate pain, improve 1st MTPJ dorsiflexion range and normalise plantar pressure distribution [6]. For end stage hallux rigidus, arthrodesis is the most common surgical procedure [7,8] and it has been associated with good patient outcomes [8–11]. However, arthrodesis is not without complications

* Corresponding author at: University Hospitals of Derby & Burton, Uttoxeter Road, Derby, DE22 2NE, UK.
E-mail address: rohan.rajan@nhs.net (R.A. Rajan).

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such as non-union, malalignment and metalwork failure which has led to the development and increasing popularity of 1st MTPJ replacements (1st MTPJR). The primary advantage of 1st MTPJR is the preservation of dorsiflexion range of motion which allows normal gait via the windlass mechanism as well as assisting with balance [6]. When comparing surgical options, similar clinical outcomes, patient satisfaction and complication rates have been reported [12]. Although joint replacement has been associated with increased pain [13–14], favourable outcomes, clinical benefit, improved patient satisfaction and faster recovery rates have also been identified [15–21].

Despite the perceived mechanical advantages and positive clinical data associated with joint replacement, conflicting evidence has been presented regarding the effect of 1st MTPJR on gait mechanics. Following 1st MTPJR a medial shift in pressure [6] and greater force production under the hallux [22] have been demonstrated. Wetke et al [23] also reported positive changes such as significant reductions in bone mineral density, ground reaction force and peak pressure under the lateral column of the operated foot. However, they were unable to identify an increase in pressure under the 1st metatarsal. Additional research has also suggested that that following 1st MTPJR there is no change in pressure or force under the 1st metatarsal and a significant increase in pressure under the fifth metatarsal head [13,18]. Further, only limited studies have examined kinematics following 1st MTPJ replacement. Significant increases in passive dorsiflexion range of motion (ROM) have been reported [24–26]. However, it has also been suggested that 1st MTPJR had no effect on active dorsiflexion ROM [6, 13] and it is possible that longstanding stiffness in the 1st MTPJ leads to irreversible contraction and tightening of the plantar structures [6]. As data on functional outcomes is limited and no study has investigated the effects of 1st MTPJR on weight bearing kinematics, it has been suggested that investigating spatio-temporal gait parameters and three-dimensional joint kinematics may help to better understand post-operative effects of 1st MTPJR [18]. Therefore, the aim of this study is to provide an in-depth biomechanical analysis to examine the effects of 1st MTPJ replacement for hallux rigidus on gait mechanics.

2. Methods

2.1. Subjects

17 Rotoglide 1st MTPJ replacements were performed in 17 female patients with a mean; age of 65.2 ± 10.7 years (range 55-84 years) and follow up time of 21 months (range 14-33 months). All patients presented with Coughlin stage 3 and 4 hallux rigidus and were carefully counseled by the senior author about treatment options, including arthrodesis and total joint replacement. The senior author was the only surgeon in all cases and patients were referred for physiotherapy 4 weeks post operatively. Patients requiring surgical intervention on both feet, who required assistance walking or with inflammatory joint disease were excluded. The study was part of an ongoing audit of laboratory practice and was approved by the local ethics committee. Written informed consent was obtained from each participant.

2.2. The Implant

The Rotoglide prosthesis (Implants International UK) is a three-part mobile meniscus implant (Fig. 1). It is an uncemented, non-constrained, metal on polyethylene implant. This prosthesis is right and left sided, with 3 metatarsal and 4 phalangeal sizes while the meniscus has 3 thicknesses either in the standard or the anatomical shapes. The anatomical meniscus compensates for minor varus/valgus malalignment. The metatarsal and phalangeal stems are hydroxyapatite coated encouraging osteointegration. Surgical approach is dorsomedial, where the medial eminence of the 1st metatarsal is resected allowing the placement of the metatarsal and phalangeal resection jigs for accurate resection of the articular surfaces. Weight bearing post-operative radiographs were taken at 6 and 12 months (Fig. 2).

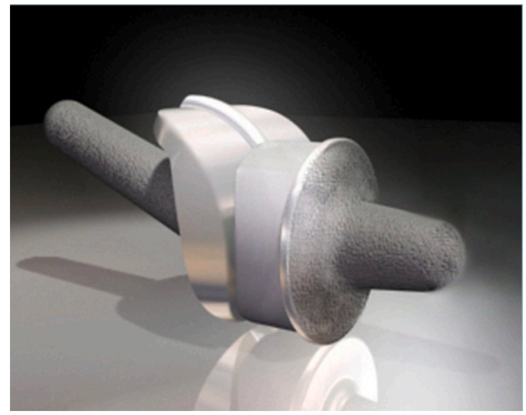

Fig. 1. Three-part mobile meniscus implant.

2.3. Data collection

Biomechanical data was collected pre-operatively (pre-op) and post-operatively (post-op) at 6 and 12 months in our CMAS UK accredited gait laboratory. Data was collected using a 10 camera BTS Smart DX motion capture system (BTS Bioengineering) capturing at 340 Hz. The foot was modelled using a modified Davis model [27] to include a hallux segment. An experienced Clinical Scientist practitioner placed 10 (9 mm) markers on the foot and one on each of the malleoli. This model was chosen as it reduces the hindfoot transverse plane error of the Oxford foot model [28] by using a different definition of the hindfoot coordinate system. A static trail was performed before the dynamic trails to enable ankle joint centers and subject specific axes to be identified.

During dynamic trails, patients walked at a self-selected speed along a 10 m long walkway within which 4 BTS P6000 force plates (60 cm x 40 cm) capturing at 680 Hz were embedded in the floor. For additional dynamic trials, a 1 m RS Scan footscan capturing data at 200 Hz was positioned in the middle of the 10 m walkway to collect pressure measurements. The pressure plate measures pressure using 8192 resistive sensors, arranged in a 128 × 64 matrix to provide an overall active sensing area of 975 mm x 325 mm. The RS footscan employed has demonstrated good repeatability for every variable of interest [29]. Due to the considerable pain associated with hallux rigidus, the data collection attempted to balance the requirements of pain management and research integrity. Therefore, on each visit to the laboratory, participants completed a maximum of 4 passes across the laboratory at a self-selected walking pace. Data collection was complete when 5 full gait cycles and 6 clear footprints were captured.

2.4. Data analysis

Markers were labeled using BTS Smart Tracker software and kinematic analysis was undertaken in Visual 3D. Stance and swing phases were calculated from the timings of heel strike and toe off with both events being identified using a 20 N vertical ground reaction force threshold. Stride lengths and timings were calculated from the relative position of the posterior calcaneus marker between two continuous heel strikes. Overall walking velocity was calculated by dividing stride length by stride time and cadence calculated as the number of strides taken per minute. Intersegment angles were measured between segment pairs namely tibia-hindfoot, hindfoot-forefoot and forefoot-hallux [30]. This enabled sagittal, frontal and transverse plane rotations for the tibia-hindfoot and hindfoot-forefoot and sagittal plane rotations for the forefoot-hallux to be calculated at heel strike, foot flat and toe-off. Measured dorsiflexion values were taken relative to the resting positions of the forefoot and hallux in relaxed standing in the static trial.

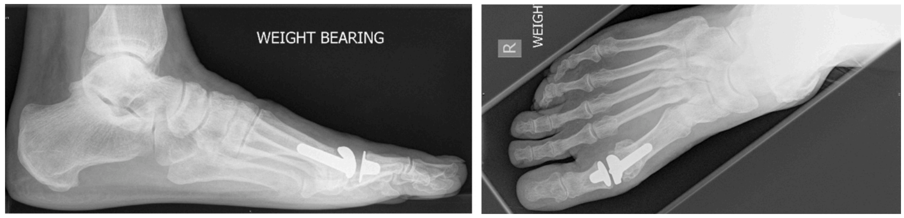

Fig. 2. Weight bearing 12-month post-op radiographs (a)Lateral (b)Anterior-Posterior.

For dynamic plantar pressure analysis, the Footscan 9 software automatically divided the forefoot into 5 zones corresponding to the respective metatarsals. This allowed peak pressures under the 1st and 5th metatarsal heads (MH) during the stance phase of gait to be identified. The ratio between these two was calculated to estimate medial-lateral weight bearing. Pressure-time integrals (PTI) were calculated using the force-time integral and contact area as described by Melia et al [31]. The PTI is a cumulative effect of pressure on a plantar area over time (area under the pressure-time curve), and is a more representative value of the total load exposure of a plantar area during stance [32].

2.5. Patient reported outcome measure

The MOXFQ score [33] was collated pre-op and at six and twelve months post-op to determine changes to patient reported quality of life. This validated patient reported outcome measure comprises a set of 16 questions assessing quality of life in the preceding 4 weeks.

2.6. Statistics

Statistical analysis was conducted using SPSS software (version 24; IBM, Arnmonk, NY, USA). Normality was assessed using the Shapiro-Wilk test whilst, two-way repeated measures ANOVAs were employed to examine the main effects of foot (unoperated vs operated) and time (preoperative, 6 months and 12 months postoperative) as well as the foot vs time interaction. A p value of less than 0.05 was considered to be statistically significant. Follow-up planned contrasts were performed to examine significant main effects and Tukey's honest significant difference (HSD) calculated to identify the specific causes of significant interactions [34].

3. Results

3.1. Kinematics

There was no effect of time or foot on gait cycle duration and the proportion of time spent in the stance phase (Table 1). However, a main effect of time (F (1, 16) = 5.05, $p = 0.039$) suggested that, regardless of foot, significantly longer strides were produced at 6 (1.16 ± 0.11 m) and 12-months (1.18 ± 0.13 m) post-op compared with the pre-op (1.08 ± 0.19 m) assessment (Table 1). There was also a main effect of time (F (1,16) = 4.92 $p = 0.041$) on cadence which indicated that there was a significant increase from the 6-month (57.13 ± 5.56 str/min) to the 12-month (58.08 ± 4.96 str/min) post-op assessments (Table 1). Self-selected walking velocity during the 6-month post-op assessment (1.11 ± 0.16 m/s) was also significantly faster (F (1,16) = 4.880**,** $p = 0.014$) than during the pre-op analysis (1.05 ± 0.17 m/s) and this increase in velocity was maintained in the 12 months post-op assessment (1.13 ± 0.13 m/s).

Comprehensive results for the assessment of 3D kinematics are presented in Table 2. Significant interactions were identified for tibia-hindfoot abduction at heel strike (F (1,16) = 7.81, $p = 0.013$), foot flat (F (1,16) = 8.42, $p = 0.01$) and toe off (F (1,16) = 8.33, $p = 0.011$). Follow-up Tukey HSD identified that these interactions were caused by significant ($p = 0.05$) reductions in tibia-hindfoot abduction for the operated foot between the pre-op and 12-month post-op assessments (Table 2). Significant interactions were also identified in transverse plane tibia-hindfoot rotations at heel strike (F (1,16) = 6.70, $p = 0.02$), foot flat (F (1,16) = 8.45, $p = 0.01$) and toe off (F (1,16) = 9.42, $p = 0.007$). At all three events, a significant reduction ($p = 0.05$) in tibia-hindfoot pronation for the operated foot from the pre-op to the 12-month post-op assessments was identified (Table 2). Significant interactions were identified in the hindfoot-forefoot transverse plane rotations at heel strike (F(1,16) = 6.08, $p = 0.025$) and foot flat (F (1,16) = 6.26, $p = 0.023$). Tukey HSD suggested that these were caused by significant reductions ($p < 0.05$) in supination between the pre-op and 12-month post-op assessments (Table 2). A significant interaction was also identified for hindfoot-forefoot adduction at toe off (F(1,16) = 6.99, $p = 0.018$) with Tukey HSD suggesting a significant decrease in adduction ($p = 0.05$) in the operated foot between the pre-op (3.8 ± 6.6 °) and 12 months post-op (0.8 ± 8.0 °) assessments (Table 2). Finally, a non-significant interaction (F (1,16) = 1.717, $p = 0.196$), effect of time (F (1,16) = 0.395, $p = 0.677$) and effect of foot (F (1,16) = 2.304, $p = 0.149$) demonstrated that the sagittal plane range of motion for the forefoot-hallux was similar in all 3 assessments (Table 2).

Table 1
Spatio-temporal parameters of gait for the affected and non-affected feet.

Foot	Time	Stance (% gait cycle)	Stride length (m)	Cycle duration (s)	Cadence (strides/min)
Operated	Pre-op	64.38 ± 1.93	1.08 ± 0.19	1.01 ± 0.22	56.55 ± 5.50
	6 months	63.55 ± 1.84	1.16 ± 0.11*	1.06 ± 0.11	57.13 ± 5.56
	12 months	63.54 ± 1.90	1.18 ± 0.13	1.05 ± 0.99	58.08 ± 4.96**
Non-Operated	Pre-op	64.52 ± 2.17	1.11 ± 0.14	1.02 ± 0.19	56.66 ± 5.38
	6 months	63.68 ± 1.94	1.13 ± 0.18*	1.06 ± 0.32	56.96 ± 5.30
	12 months	63.45 ± 1.77	1.17 ± 0.12	1.09 ± 0.15	57.82 ± 4.99**

Note. * significant difference between 0 and 6 months, ** significant difference between 6 and 12 months

3.2. Pressure Measurements

A significant interaction (F (1,16) = 23.71, $p = 0.000$) was identified for the magnitude of peak pressure under the 1st MH. Tukey HSD suggested that this was caused by a significant increase ($p = 0.05$) in 1st MH pressure for the operated foot from the pre-op (138.4 ± 53.6 kPa) to the 6-month post-op assessment (202.2 ± 90.9 kPa). A significant interaction (F (1,16) = 8.534, $\boldsymbol{p = 0.010}$) was also evident in the 1/5 MH peak pressure ratio as a significant ($p = 0.05$) increase in the 1/5 MH pressure ratio for the operated foot from the pre-op (0.60 ± 0.50) to the 6-month post-op assessment (0.97 ± 0.72) was identified. When analysing 1st MH PTI, there was a significant effect of time (F (1,16) = 18.299, $p = 0.000$) which indicated that 1st MH PTI increased significantly from the pre-op to the 6-month post-op assessment (F(1,16) = 14.31 $p = 0.002$) and again from the 6-month to 12 month post-op assessments (F(1,16) =

Table 2
3D kinematics during gait for affected and non-affected feet with weight bearing ROM of 1 st MTPJ.

			Operated Foot (affected foot)			Non-Operated (non-affected foot)		
Segment	Rotation	Event	Pre	6 months	12 months	Pre	6 months	12 months
Tibia-Hindfoot	Dorsiflexion / Plantarflexion	HS	1.9 ± 4.4	3.0 ± 4.0	2.1 ± 4.0	1.7 ± 2.2	1.0 ± 3.6	0.6 ± 4.5
		FF	0.2 ± 5.9	5.8 ± 24.9	0.4 ± 4.2	−0.8 ± 1.9	−0.4 ± 5.0	−1.9 ± 3.7
		TO	0.4 ± 5.7	1.4 ± 4.6	0.0 ± 6.1	−0.8 ± 5.6	−1.9 ± 6.2	−1.5 ± 6.0
	Adduction / Abduction	HS	−13.4 ± 8.4*	−10.7 ± 7.5	−7.3 ± 10.0	−10.4 ± 6.7	−10.6 ± 7.0	−10.7 ± 7.9
		FF	−16.2 ± 9.1*	−12.5 ± 7.8	−9.0 ± 10.7	−12.8 ± 7.0	−12.9 ± 7.2	−12.6 ± 8.2
		TO	−7.8 ± 6.8*	−3.4 ± 6.9	−0.3 ± 10.1	−4.9 ± 6.9	−4.3 ± 6.9	−4.6 ± 7.5
	Pronation / Supination	HS	1.6 ± 2.1*	0.6 ± 2.9	−0.1 ± 2.6	0.5 ± 2.8	0.6 ± 3.8	1.3 ± 3.6
		FF	4.8 ± 2.5*	3.4 ± 3.4	2.9 ± 3.2	3.3 ± 3.0	3.4 ± 4.2	4.4 ± 3.7
		TO	−4.8 ± 4.6*	−6.4 ± -4.0	−7.0 ± 2.6	−5.1 ± 3.7	−4.0 ± 3.6	−3.9 ± 3.7
Hindfoot-Forefoot	Dorsiflexion / Plantarflexion	HS	−1.8 ± 4.3	−3.8 ± 5.3	−1.3 ± 6.5	−2.9 ± 2.9	−3.6 ± 3.3	−3.3 ± 3.1
		FF	0 ± 4.6	−2.1 ± 4.2	−1.3 ± 4.3	−1.5 ± 2.7	−1.9 ± 3.3	−1.2 ± 2.1
		TO	−7.3 ± 5.2	−7.8 ± 5.2	−6.5 ± 5.1	−8.0 ± 4.8	−8.5 ± 5.9	−8.7 ± 3.8
	Adduction / Abduction	HS	−0.9 ± 6.9	−2.9 ± 7.1	−3.4 ± 8.2	−4.7 ± 4.4	−3.3 ± 7.0	−2.6 ± 7.3
		FF	−1.2 ± 6.8	−3.4 ± 7.3	−3.4 ± 8.1	−5.4 ± 4.5	−3.8 ± 7.0	−3.1 ± 7.5
		TO	3.8 ± 6.6*	1.3 ± 7.4	0.8 ± 8.0	0 ± 5.3	1.6 ± 6.6	2.2 ± 7.0
	Pronation / Supination	HS	−8.5 ± 2.9*	−7.8 ± 3.2	−6.0 ± 3.8	−6.8 ± 3.0	−6.4 ± 4.5	−7.0 ± 3.5
		FF	−5.7 ± 2.9*	−4.7 ± 3.0	−3.5 ± 3.2	−4.5 ± 3.5	−4.1 ± 4.5	−4.8 ± 3.8
		TO	−8.1 ± 4.7	−8.2 ± 4.5	−6.5 ± 4.2	−6.1 ± 3.6	−6.4 ± 5.1	−6.3 ± 4.3
Forefoot-Hallux	Dorsiflexion / Plantarflexion	HS	8.3 ± 6.0	9.6 ± 6.7	9.3 ± 7.9	10.7 ± 6.0	11.4 ± 6.2	12.1 ± 5.3
		FF	4.2 ± 4.2	5.4 ± 6.9	7.1 ± 4.7	5.4 ± 4.2	6.1 ± 5.9	6.7 ± 4.2
		TO	16.6 ± 11.3	15.2 ± 8.9	17.2 ± 8.0	21.0 ± 8.5	20.7 ± 10.0	22.4 ± 10.6
		ROM	18.0 ± 10.9	15.7 ± 8.2	17.9 ± 7.6	21.6 ± 10.9	21.7 ± 9.5	21.2 ± 8.4

Note, *denotes a significant difference from12 month post-op assessment for operated foot.
Positive sagittal, frontal and transverse rotations refer to dorsiflexion, adduction and pronation respectively

8.73 $p = 0.009$) – Table 3. There was a significant effect of time on the 1/5 PTI ratio (F (1,16) = 34.112, $p = 0.000$) which similarly suggested that there was a significant increase from the pre-op to the 6-month post-op assessment (F (1,16) = 42.23 $p = 0.000$) and again from the 6-month to the 12-month post-op assessment (F(1,16) = 8.80 $p = 0.009$) - Table 3.

3.3. MOXFQ

The validated MOXFQ, revealed no statistically significant difference when comparing the pre-op (44.18 ± 11.79) and 6-monts post-op results (48.47 ± 12.95). However, a significantly improved MOXFQ outcome measure was reported (F (2, 32) = 29.140, $p < 0.000$) in the 12-month post-op assessment (62.29 ± 9.57).

4. Discussion

The aim of this study was to investigate whether 1st MTPJR improves clinical and functional outcomes. The results suggested that 1st MTPJR had no effect on weight bearing sagittal plane function of the 1st MTPJ. No effects of 1st MTPJR were identified on 1st MTPJ dorsiflexion at each event within the gait cycle and on the total sagittal plane range of motion. Although research has previously identified a significant improvement in the passive ROM of the hallux [24–26], 1st MTPJR does not appear to impact active ROM [6,13] or hallux function during weight bearing activity such as walking. During walking, the full passive sagittal plane ROM of the 1st MTPJ is not required [18]. However, it is likely that greater ROM and post-op improvements in joint function may be called upon in more strenuous activities such as running or jumping. It may also be the case that improvement of passive sagittal plane ROM restores the alignment, length and strength of the great toe and improves the function of the entire foot via the windlass mechanism [6].

Despite 1st MTPJR having no effect on weight bearing sagittal plane function of the 1st MTPJ, significant reductions in hindfoot-forefoot adduction and supination were identified at 12 months post-op. Normally, dorsiflexion at the 1st MTPJ stretches the plantar fascia which is attached to the plantar pads of the MTPJ's. The plantar fascia originating from the calcaneus is made taught with MTPJ dorsiflexion known as the windlass mechanism which then pulls the calcaneus into varus or inversion [2]. With a painful 1st MTPJ in hallux rigidus, weight bearing alters to favour the lateral column of the foot as propulsion is shifted to the lesser toes [3,38,39]. This antalgic protective mechanism against hallux rigidus also places the midfoot in adduction and supination. This study demonstrated a normalisation towards less hindfoot-forefoot supination and adduction post 1st MTPJR which is most likely caused by a decrease in pain and an increase in 1st MTPJ flexibility, length and strength [6] and subsequent restoration of the windlass mechanism [2]. The decreased hindfoot-forefoot adduction and supination would also allow for the heel to be corrected back into neutral from the valgus position as demonstrated in this study where the tibia-hindfoot segment was found to have a significantly reduced abduction towards neutral. This study also found a significant reduction in tibia-hindfoot pronation towards a more normal neutral position at 12 months post-op. These foot kinematic changes at 12 months following surgery would suggest that as a result of the more flexible 1st MTPJ, the windlass mechanism is

Table 3
Pressure & PTI measurements to compare affected versus non-affected feet (preop, 6 and 12 months).

Foot	Time	1st MT max P (kPa)	5th MT max P (kPa)	1/5MTmax P ratio	1st MT PTI (kPa/s)	5th MT PTI (kPa/s)	1/5 MT PTI ratio
Operated	Preop	138.4 ± 53.6	347.8 ± 185.2	0.60 ± 0.50	41.2 ± 16.8	76.6 ± 31.7	0.66 ± 0.42
	6 months	202.2 ± 90.9*	313.2 ± 203.7	0.97 ± 0.72*	55.1 ± 21.1*	69.1 ± 28.5	0.94 ± 0.53*
	12 months	245.2 ± 78.2**	325.5 ± 182.6	1.23 ± 1.18**	63.9 ± 23.0**	68.9 ± 26.5	1.11 ± 0.70**
Non Operated	Preop	186.4 ± 76.5	297.9 ± 190.4	0.89 ± 0.57	45.5 ± 23.6	71.5 ± 26.7	0.68 ± 0.34
	6 months	170.2 ± 72.7	307.5 ± 190.6	0.80 ± 0.56	55.4 ± 20.8*	71.5 ± 23.2	0.91 ± 0.55*
	12 months	209.6 ± 86.2**	287.5 ± 160.1	0.98 ± 0.74**	59.6 ± 25.7**	73.6 ± 23.9	0.92 ± 0.59**

* Significant difference between pre op and 6 months post op.
** Significant difference between 6 months and 12 months post op.

restored allowing for the heel to correct to neutral from a valgus position, while the supinated adducted forefoot is corrected to a more neutral position of less supination and adduction.

Significant biomechanical improvements of spatio-temporal gait parameters were reported in this study, including an increase in stride length, cadence and velocity in the 6 month post-op assessment which were all maintained at 12 months post-op. Canseco et al [35] had previously suggested that hallux rigidus caused a significant increase in stance phase duration and slowing down in patients which they associated with discomfort in the 1st MTPJ. Betts et al. [36] also observed that patients walked more slowly and with shorter stride lengths. The results of this study suggest that 1st MTPJR is also capable of returning spatio-temporal gait parameters to normal and offers a viable alternative to arthrodesis.

In the 6 months following 1st MTPJR, there was a significant increase in peak pressure and PTI under the 1st MH for the operated foot. A significant increase in 1/5 MH pressure and PTI ratios were also found with a further increase in 1/5 PTI ratio in the 12-months post-op assessment. The importance of the hallux in the push-off phase of the gait cycle has previously been established [37] and these findings demonstrate a significant post-op normalisation of pressure and transference of weight onto the medial column of the foot which helps to re-establish its weight-bearing role [38]. Furthermore, our results suggest that 1st MTPJR can return pressure distribution and weight bearing back to that expected of a normal foot. The mean values for pressure under the 1st MH at 6- and 12-months post-op are similar to that produced by the non-operated foot. They are closer to the mean (372.8 kPa) and within the range (145 - 1180 kPa) previously identified for a healthy foot [38]. In the 12-month post-op assessment, the 1/5 pressure ratio was also greater than 1 indicating that the highest pressures occurred in the medial column which is what would be expected in a healthy foot [38].

A medialisation of load and increased pressure under the 1st MH have previously been reported following 1st MTPJ arthrodesis [13,39]. This is the first study to report consistent medialisation of load following 1st MTPJR. Although Wetke et al [23] reported some positive changes, they did not identify a significant increase in the pressure under the medial column. An increase in 1st MH pressure and medial load has been reported following 1st MTPJR [6] but this was only evident for 26% of patients and pressure values remained higher than in their control. Following 1st MTPJR, less positive findings such as an increased lateral forefoot plantar pressure have also been reported [13,18]. It is possible that changes in the characteristics of our patient group were responsible for the favorable outcomes observed in this study. Previous research has included hemiprostheses as well as total replacement [22] and patients with bilateral disease [13,18]. Furthermore, post-op assessment in this study was completed at 6 and 12 months which was considerably earlier than other assessments of 1st MTPJR [13,18,22,23]. It should be recognised that there may yet be further improvement in joint function but equally the long terms effects of joint replacement may not yet be apparent and further research is required to establish the longevity of this medialisation in pressure distribution.

The MOXFQ clinical outcome measure improved after 1st MTPJR in the first 6 months although this was not statistically significant. The main effect occurred after 12 months where there was a significant improvement. The clinical outcome results are in agreement with previous studies that reported reduced pain [6,13,23] and functional improvements using scores such as the AOFAS score [20,40]. Interestingly, the spatiotemporal parameters and pressure measurements seem to improve sooner (6 months) than those of foot kinematics and clinical outcomes. It is postulated that this is the result of the time taken for the contracted plantar soft tissues to adapt and post-surgery pain and swelling to dissipate.

5. Conclusion

Following 1st MTPJR, there is an increase of pressure and total load of the plantar area under the 1st metatarsal head as the patient redistributes more weight to the medial column. The foot inter-segment kinematics also demonstrate changes which allow for the above pressure redistribution. These positive mechanical changes and improved MOXFQ scores also appear to increase confidence and allow increased gait velocity, stride length and cadence to be achieved. This is the first prospective study that has demonstrated the above improved combined effects following 1st MTPJR for end stage hallux rigidus.

6. Ethical approval

From the College of Life and Natural Sciences Research Ethics Committee of The University of Derby, study number ETH1920-3375.

Declaration of Competing Interest

There are no conflicts of interest for the authors of this study. There were no grants or financial payments made for this study.

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References

[1] M.J. Coughlin, P.S. Shurnas, Hallux rigidus: demographics, etiology, and radiographic assessment, Foot Ankle Int. 24 (10) (2003) 731–743.
[2] J.H. Hicks, The mechanics of the foot. II. The plantar aponeurosis and the arch, J Anat 88 (1954) 25–30.
[3] G.V. Zammit, H.B. Menz, S.E. Munteanu, K.B. Landorf, Plantar pressure distribution in older people with OA of the 1st MTPJ (Hallux limitus/rigidus), JOResearch 26 (December (12)) (2008) 1665–1669.
[4] M.J. Coughlin, P.S. Shurnas, Hallux rigidus. Grading and long-term results of operative treatment, JBJSA 85A (11) (2003) 2072–2088.
[5] J.V. Vanore, J.C. Christensen, S.R. Kravitz, J.M. Schuberth, J.L. Thomas, L.S. Weil, H.J. Zlotoff, S.D. Couture, Diagnosis and treatment of first metatarsophalangeal joint disorders section 2: hallux rigidus, JFASurg 42 (3) (2003) 124–136.
[6] R.A. Fuhrmann, A. Wagner, J.O. Anders, First metatarsophalangeal joint replacement: the method of choice for end stage hallux rigidus? Foot Ankle Clin N Am 8 (2003) 711–712.
[7] E.L. DelaCruz, A.R. Johnson, B.L. Clair, First metatarsophalangeal joint interpositional arthroplasty using a meniscus allograft for the treatment of advanced hallux rigidus: surgical technique and short term results, FA Spec. 4 (3) (2011) 157–164.
[8] G. Fadel, D. Rowley, R. Abboud, Hallux metatarsophalangeal joint arthrodesis: various techniques, The Foot 12 (2) (2002) 88–96.
[9] J.W. Brodsky, R.N. Passmore, F.E. Pollo, S. Shabat, Functional Outcome of Arthrodesis of the First Metatarsophalangeal Joint Using Parallel Screw Fixation, FAI 26 (2) (2005) 140–146.
[10] S.F. Conti, S. Dhawan, Arthrodesis of the First Metatarsophalangeal and Interphalangeal Joints of the Foot Foot Ankle Clinics of N America, 1, 1996, pp. 33–53.
[11] M.J. Coughlin, Arthrodesis of the first metatarsophalangeal joint, Orthopedics 13 (9) (1990) 1037–1044.
[12] Y.H. Park, J.H. Jung, S.H. Kang, G.W. Choi, H.J. Kim, Implant Arthroplasty versus Arthrodesis for the Treatment of Advanced Hallux Rigidus: A Meta-analysis of Comparative Studies, JF&ASug. 58 (1) (2019) 137–143.
[13] J.N.A. Gibson, C.E. Thomson, Arthrodesis or total replacement arthroplasty for hallux rigidus: a randomized controlled trial, FAInt 26 (9) (2005) 680–690.
[14] J. Stevens, R. de Bot, Hermus JPS, van Rhijn LW, Witlox AM. Clinical outcome following total joint replacement and arthrodesis for hallux rigidus: a systematic review, JBJS Rev 5 (11) (2017) e2.
[15] Younger Glazebrook, F. Daniels, A. Surg, Treatment of first metatarsophalangeal joint arthritis using hemiarthroplasty with a synthetic cartilage implant or arthrodesis: A comparison of operative and recovery time, 24 (5), 2018, pp. 440–447.
[16] N.S. Duncan, N.G. Farrar, R.A. Rajan, Early results of first metatarsophalangeal joint replacement using the ToeFit-Plus™ prosthesis, JFAS. 53 (3) (2014) 265–268.
[17] H. Kofoed, L. Danborg, J. Grindsted, S. Merser, The Rotoglide total replacement of the first metatarso-phalangeal joint. A prospective series with 7-15 years clinic-radiological follow-up with survival analysis, JFAS 23 (3) (2017) 148–152.

[18] C. Nuesch, A. Mundermann, M. Horisberger, Mid-term functional outcome of a total arthroplasty of the first metatarsophalangeal joint, Clin Biomech (41) (2017) 9–13.
[19] A.G. Titchener, N.S. Duncan, R.A. Rajan, Outcome following first metatarsophalangeal joint replacement using TOEFIT-PLUS™: A midterm alert, JFAS. 21 (2) (2015) 119–124.
[20] C. Tunstall, P. Laing, R. Limaye, C. Walker, S. Kendall, D. Lavalette, P. Mackenney, A. Adedapo, M. Al-Maiyah, 1st metatarso-phalangeal joint arthroplasty with ROTO-glide implant, JFAS 23 (3) (2017) 153–156.
[21] E. Cook, J. Cook, B. Rosenblum, A. Landsman, J. Giurini, P. Basile, Meta-analysis of First Metatarsophalangeal Joint Implant Arthroplasty, JF&ASurg. 48 (2) (2009) 180–190.
[22] J. Knessl, S.E. Frank, H.P. Kundert, H. Kies, H. Jacob, Ground reaction forces under the great toe after implantation of the Toefit plus prosthesis, JFAS (11) (2005) 131–134.
[23] E. Wetke, B. Zerahn, H. Kofoed, Prospective analysis of a first MTP total joint replacement. Evaluation by bone mineral densitometry, pedography and visual analogue score for pain, F&A 18 (2) (2012) 136–140.
[24] Erkocak O.F., Senaran H., Altan E., Aydin B., Acar M. Short term functional outcomes of first metatarsophalamgeal joint replacement for hallux rigidus. FAI. 34 (11)1569-1579.
[25] K. Olms, A. Dietze, Replacement arthroplasty for hallux rigidus, Int. Orth. (SICOT) 23 (1999) 240–243.
[26] K. Daniilidis, N. Martinelli, A. Marinozzi, V. Denaro, Z. Pejman, T. Buchhorn, Recreational sport activity after total replacement of the first metatarsophalangeal joint: a prospective study, Int Otyhop 34 (2010) 973–979.
[27] R.B. Davis, E.G. Jameson, J.R. Davids, L.M. Christopher, B.M. Rogozinski, J. P. Anderson, The design, development, and initial evaluation of a multisegment foot model for routine clinical gait analysis, Foot and Ankle Motion Analysis Clinical Treatment and Technology (2006) 425–444.
[28] S. Van Hoeve, J. De Vos, P. Weijers, Repeatability of the Oxford Foot Model for kinematic gait analysis of the foot and ankle, Clin Res Foot Ankle. 3 (2) (2015), 711.
[29] C. Xu, X.-X. Wen, L.-Y. Huang, L. Shang, X.-X. Cheng, Y.-B. Yan, W. Lei, Normal foot loading parameters and repeatability of the Footscan platform system, J F&A Research (10) (2017), 30.
[30] E.S. Grood, W.J. Suntay, A joint coordinate system for the clinical description of three-dimensional motions: application to the knee, Transactions of ASME-Journal of Biomechanical Engineering 105 (1983) 136–144.
[31] T. Melai, T.H. IJzerman, N.C. Schaper, Calculation of plantar pressure time integral, an alternative approach, Gait Posture 34 (3) (2011) 379–383.
[32] J. Stevens, K. Meijer, W. Bijnens, M. Fuchs, L. van Rhijn, J. Hermus, S. van Hoeve, M. Poeze, A. Witlox, Gait analysis of foot compensation after arthrodesis of the first metatarsophalangeal joint, FAI 38 (2) (2017) 181–191.
[33] J.1 Dawson, I. Boller, H. Doll, G. Lavis, R. Sharp, P. Cooke, C. Jenkinson, The MOXFQ patient-reported questionnaire: assessment of data quality, reliability and validity in relation to foot and ankle surgery, Foot 21 (2) (2011) 92–102.
[34] W. Vincent, J. Weir, Statistics in kinesiology, 4th ed, Human Kinetics, Champaign, IL, 2012.
[35] K. Canseco, J. Long, R. Marks, M. Khazzam, G. Harris, Quantitative Characterization of Gait Kinematics in Patients with Hallux Rigidus Using the Milwaukee Foot Model, J Orth Research (2008) 419–427.
[36] R.P. Betts, C.I. Franks, T. Duckworth, Foot pressure studies: normal and pathologic gait analyses, in: M.H. Jahss (Ed.), Disorders of the foot and ankle., 2nd ed., W.B. Saunders, Philadelphia, 1991, pp. 484–519.
[37] J. Hughes, P. Clark, L. Klenerman, The importance of the toes in walking, J Bone Joint Surg (1990) 245–251, 72-B.
[38] N. Hayafune, Y. Hayafune, H.A.C. Jacob, Pressure and force distribution characteristics under the normal gait during the push-off phase in gait, The Foot 9 (1999) 88–92.
[39] P.F. DeFrino, J.W. Brodsky, F.E. Pollo, S.J. Crenshaw, A.D. Beischer, First metatarsophalangeal arthrodesis: a clinical, pedobarographic and gait analysis study, Foot Ankle Int 23 (6) (2002) 496–502.
[40] R.A. Rajan, P. Kodumuri, Y. Papamerkouriou, M. Kerr, H. Evans, A consecutive, prospective analysis of the rotoglide 1st metatarsophalangeal joint replacement, The Foot 39 (2019) 72–75.