The biomechanical consequences of hallux rigidus and treatment on gait and clinical functioning

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THE BIOMECHANICAL CONSEQUENCES OF HALLUX RIGIDUS AND TREATMENT ON GAIT AND CLINICAL FUNCTIONING

Dissertation

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CHAPTER 1

GENERAL INTRODUCTION

Degenerative arthritis, also known as osteoarthritis (OA), is the most common chronic disease affecting joints. OA has a complex pathogenesis involving mechanical, inflammatory and metabolic factors affecting the whole joint, which is composed of articular cartilage, subchondral bone, ligaments, capsule, synovium and periarticular muscles. Changes in composition and the loss of integrity makes the cartilage susceptible for mechanical forces, leading to erosions and fissures in early OA. Chondrocytes produce pro-inflammatory mediators and matrix degradation products in an attempt to repair these erosions, which subsequently activate synoviocytes and cells in the subchondral bone initiating a remodeling and repair state of the joint [1]. Risk factors for developing OA are age, obesity, female sex, previous injury or deformity of the joint and high impact activities during daily work or sports, while a genetic susceptibility is also known [1,2].

More than 1.5 million people were diagnosed with OA of any joint by their general practitioner in the Netherlands in 2020. The effect of aging on the prevalence of OA is evident, with women nearly twice as much affected as compared to men (see Figure 1) and knee OA being the most prevalent form of OA with more than 700,000 cases [2]. It is expected that the number of people with OA in Western countries will increase with approximately 40% between 2015 and 2040. Disability adjusted life years (DALY's) is a measure to express disease burden and describes the years of life lost due to premature mortality and the years lived with a disability due to disease. In 2018 in the Netherlands, OA is ranked fifth when looking at diseases with most DALYs, clearly showing the impact on society [2,3]. In addition, the medical costs of OA in high-income countries has been estimated to account for approximately 1 to 2.5% of the gross domestic product. The estimated costs of OA in the Netherlands in 2019 were 1.1 billion euro, which is 1.1% of the total healthcare expenses [2].

Foot pain affects at least 1 in 3 persons over the age of 45 years [4], and 1 in 6 persons older than 50 years with foot pain show radiographic evidence of OA. The first metatarsophalangeal (MTP1) joint is most often the affected joint. One out of 12 persons with foot pain exhibit radiological confirmed OA of this joint [5]. Symptomatic MTP1 OA is more prevalent in women, at older ages and in lower socio-economic classes [5-7]. When compared with estimates of symptomatic OA of the knee, hip and hand from similar elderly population, prevalence of symptomatic and radiographic OA in the MTP1 joint is higher than the hip (5.0-7.4%), similar to the knee (7.6-16.4%) and lower than the hand (21.6%) [8]. To date, our knowledge of OA of the foot and its burden is significantly less as compared to the previous mentioned joints.

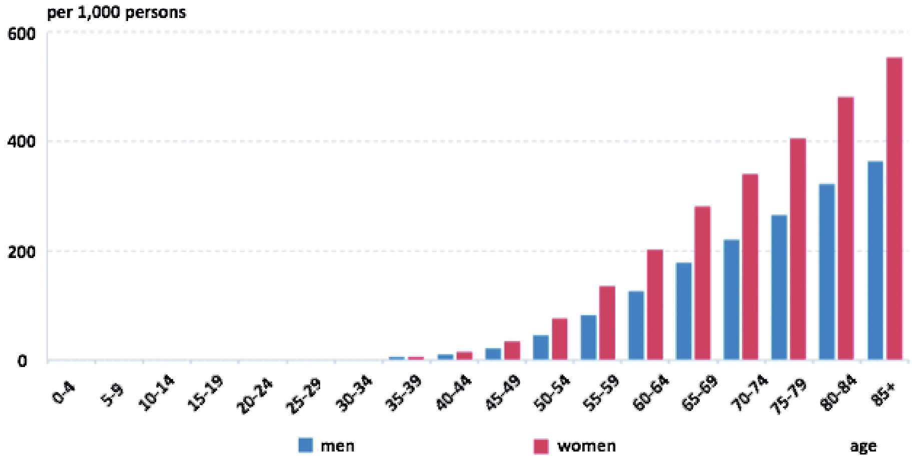

Figure 1. Prevalence of OA by gender and age in 2020 in the Netherlands

HALLUX RIGIDUS

Symptoms associated with OA of the MTP1 joint were described for the first time by Davies-Colley in 1887 [9], who described a plantar-flexed position of the proximal phalanx relative to the metatarsal head. Cotterill was the first person proposing the term hallux rigidus (HR), which literally mean 'stiff big toe' in Latin [10].

The anatomy of the first metatarsal is unique and its shape may contribute to the development of hallux rigidus (see Figure 2). The head of the first metatarsal is a transversely flattened quadrilateral structure with a smaller dorsoplantar diameter than transverse, and this is contrary to the lesser metatarsal heads which are longer in dorsoplantar direction and smaller in transverse plane. The articular surface can be divided in a superior and inferior field. The superior field is a convex dome larger than the concave articulating surface of the proximal phalanx and the larger inferior field articulates with the sesamoids, which are located in the plantar plate capsuloligamentous complex which is essential for providing stability of the first ray [11].

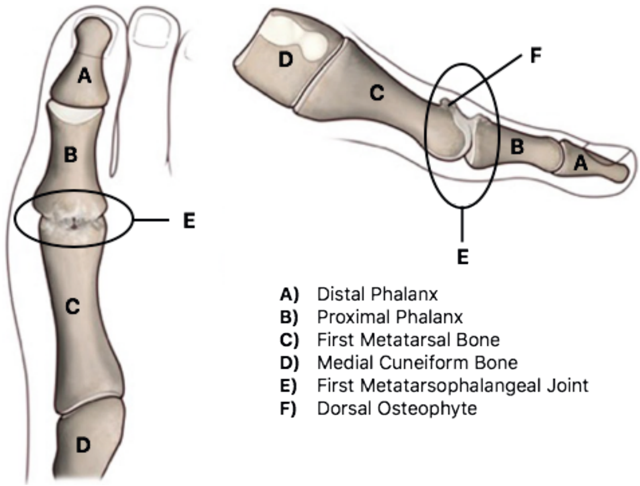

Figure 2. Anatomy of the first ray with osteoarthritic changes of the first metatarsophalangeal joint. Used and adapted with permission from Massimi et al.[12].

In literature, numerous factors contributing to HR were hypothesized. Nevertheless, there is no consensus about the exact causes of HR. A single isolated injury (e.g. fracture) and joint disease (i.e. rheumatic arthritis or gout), or multiple repetitive micro traumas, are likely to play a role in developing hallux rigidus, especially in unilaterally affected patients [11,13,14]. Metatarsus primus elevates (MPE), i.e. a fixed dorsal elevation of the first metatarsal in relation to the lesser metatarsals, is also frequently associated with hallux rigidus [14-16]. A positive family history likely plays a role in the development of hallux rigidus, where patients with a positive family history were affected bilaterally in the majority of the cases [13,17]. Age of onset of symptoms is generally in the 6th decade of life [6,7,13]. As in overall prevalence of OA, higher incidence of HR is reported in women [6,7,13].

HR is characterized by loss of motion of the MTP1 joint, which is normally between 75° dorsiflexion and 35° plantarflexion. Especially dorsiflexion is affected earlier and to a greater extent [11,14]. Common clinical signs are pain with joint motion, soft-tissue swelling, increase of joint size and signs of OA (i.e. joint space narrowing, osteophyte formation and subchondral sclerosis) on conventional radiographs. Initially pain is only present at extremes of motion, while pain will also be present in midrange motion during disease progression. Osteophytes usually arise at the dorsal aspect of the first metatarsal head (see Figure 2F) and limit MTP1 motion due to bony impingement. This subsequently causes difficulties in wearing shoes in a subgroup of HR patients. Classification systems predominantly used in literature to describe the severity of HR were the Hattrup and Johnson and Coughlin and Shurnas classification systems (see Table 1) although numerous grading systems have been described [18-20].

Table 1. Classification systems of HR as described by Hattrup and Johnson and Coughlin and Shurnas.

Hattrup and Johnson [18]			
Grade I	Mild to moderate osteophyte formation with preservation of joint space.		
Grade II	<50% narrowing of joint space, subchondral sclerosis and moderate osteophytes formation.		
Grade III	Marked osteophyte formation and >50% loss of visible joint space, with or without subchondral cyst formation and loose bodies.		
Coughlin and Shurnas [19]	**Clinical findings**	**Dorsiflexion MTP1 ROM**	**Conventional radiograph**
Grade 0	No pain, stiffness and loss of motion	40°-60° (20% loss)	Normal
Grade I	Mild or occasional pain and stiffness at the extremes of movements	30°-40° (20-60% loss)	Dorsal osteophyte, minimal joint space narrowing, periarticular sclerosis and flattening of MT head
Grade II	Moderate to severe pain and stiffness; pain occurs just before maximum dorsi- of plantarflexion	10°-30° (50-75% loss)	Periarticular osteophytes with mild to moderate joint narrowing, flattening and sclerosis
Grade III	Constant pain and substantial stiffness, with the pain elicited throughout range of motion	<10° (75-100% loss)	Same as grade II with cystic changes of subchondral bone and sesamoid irregularities
Grade IV	Pain present at mid-range motion	<10°	Same as grade III

IMPACT OF HALLUX RIGIDUS

Of all patients with symptomatic OA in the foot, HR patients report the most symptoms and about 3 out of 4 patients describe their symptoms as disabling [5]. Subjects with HR experience more foot pain, have more difficulties with performing weight-bearing activities and experience problems with a broad range of physical tasks and activities. In addition, more difficulties were reported during moderate to heavy exercise (e.g. cleaning tasks and running respectively), but also daily activities such as walking the stairs or strolling were affected in HR subjects [6,21].

Multiple studies have focused on how surgery improved pain and functioning in HR subjects, assessed with clinical outcome or patient-reported outcome measures. However, little is known on how HR affects one of the most basal and evident activities during normal life, i.e. normal walking.

The manner or style of walking is described by the word gait, where the gait cycle is defined as the time interval between two successive occurrences of one of the repetitive events of walking. A gait cycle can be divided in seven major events and in seven periods (see Figure 3).

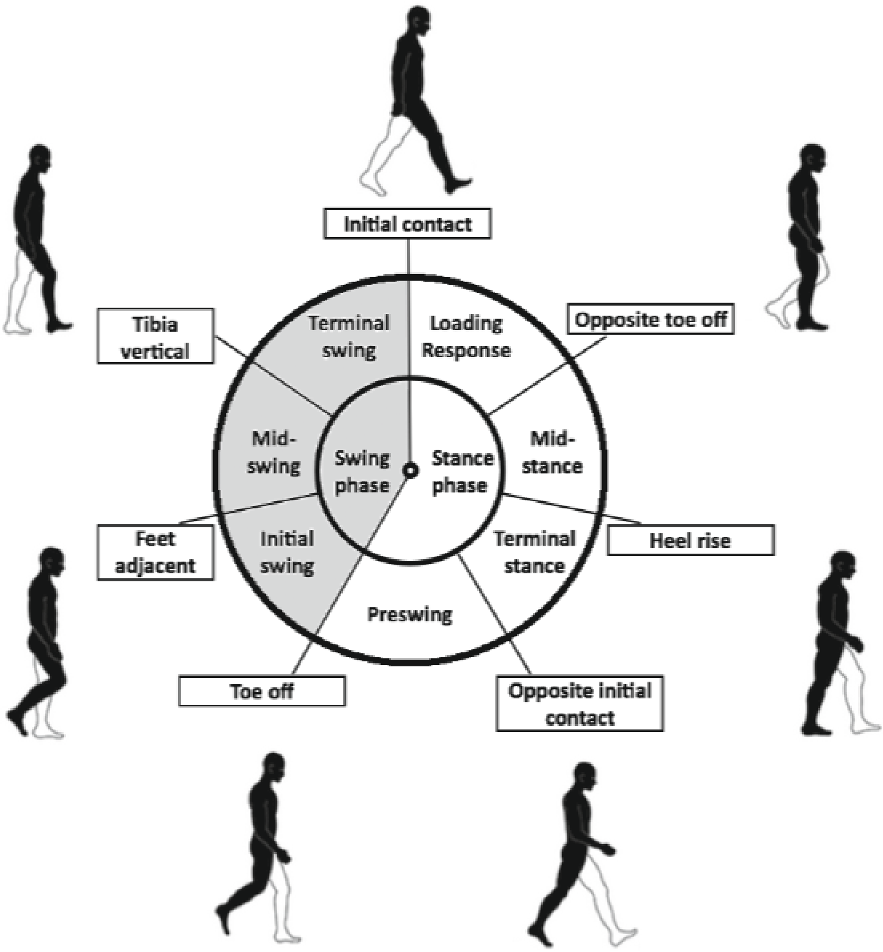

Figure 3. The seven events of gait (i.e. placed in rectangles) and the seven phases of gait (i.e. the outer circle).

In clinical gait analysis, three-dimensional (3D) motion of body segments is analyzed under the rigid-body assumption, which means that kinematics can be estimated from the trajectories of skin markers attached to palpable bony landmarks of the subject. For large body segments (i.e. thorax, pelvis, thigh) this landmark identification and marker placement is not complex. This is more challenging for the foot, since it is made up of 26 small bones and has only a few accessible landmarks. As a result, several methods have been developed over years to improve kinematic analysis of foot segments, which led to the development of multi-segment footmodels (MFMs). These MFMs vary in the number of segments, which bones are represented by each segment, and are used to describe foot motion in healthy subject and foot pathology [22]. A MFM which is validated, repeatable and frequently used is the Oxford Foot Model (OFM). This four-segment foot model divides the foot in a tibial (tibia and fibula), hindfoot (calcaneus and talus), forefoot (five metatarsals) and hallux (hallux/proximal phalanx) segment and can be used to analyze motion between those segment during the before mentioned phases of gait [23-25].

Only a few studies evaluated the effects of HR on gait. Canseco et al. investigated foot and ankle kinematics in a group of 22 HR patients and 25 healthy controls by using the four-segment Milwaukee Foot Model (tibia, hindfoot, forefoot, hallux segment). Less hallux dorsiflexion in stance and swing and decreased forefoot plantarflexion was observed in the HR group, resulting in an a-propulsive gait [26]. Kuni et al. evaluated gait in patients with HR, by using the Heidelberg Foot Measurement Method, which describes angular orientations of anatomical landmarks and showed less hallux dorsiflexion, talocrural motion, forefoot-midfoot pro-/supination and forefoot/hindfoot ab-/adduction in HR patients as compared to healthy controls [27].

Besides the expected limited hallux motion, changes in the other segments were detected in HR subjects. However, how the foot compensates for the loss of MTP1 joint motion and which segments were responsible for this compensatory mechanism was not explored by these studies and remains unknown. In literature, it is hypothesized that compensation occurs in proximal joints (increased ankle dorsiflexion, knee hyperextension and hip extension) to allow the body to move forward at toe-off [28], although the presence of this compensatory mechanism in HR is still not known.

TREATMENT

Both conservative and surgical interventions can be considered in the treatment of HR. Conservative management is possible in patients with low grade HR, low functional demands or with a poor general health condition. Conservative options are anti-inflammatory drugs, foot orthoses, shoe wear modifications (i.e. rigid sole) or physical therapy [29]. Nevertheless, none of the conservative therapies can oppose disease progression and clinical worsening. Surgical interventions should be considered in patients where conservative therapy failed.

Joint preserving methods

Cheilectomy is primarily used in low grade HR and where dorsal impingement is the major problem (see Figure 4B). It consists of resection of the dorsal osteophyte and 20-30% of the metatarsal head, osteophyte of the base of the proximal phalanx, removal of loose bodies and release of lateral and medial capsuloligamentous structures [29,30]. Advantages are the relatively easiness of the intervention and MTP1 joint motion preservation, thereby allowing a fast return to normal activities. Furthermore, several types of ***phalangeal*** and ***metatarsal osteotomies*** have been described to restore in low grade HR [29,30].

Joint destructive methods

During a ***Keller resection arthroplasty***, the base of the proximal phalanx is removed in order to decompress the joint and preserve joint motion, thereby sacrificing MTP1 joint stability (see Figure 4C) [12,30]. This technique is used for decompression and restoration of ROM in high grade HR and is relatively easy to perform. It is mainly considered in low functional demanding patients, where pain relief is the main goal. However, MTP1 instability, cock-up deformity and transfer metatarsalgia are reported complications [12].

Other surgical options sacrificing the MTP1 joint, but saving MTP1 motion, are joint implants. Implants are especially considered in patients who want functional motion in the joint, stability and maintenance of first ray length. An ideal implant should relieve pain, restore joint motion, improve function, maintain joint stability, restore weight bearing of the hallux and should be a durable intervention [31]. In literature, prosthetic implants are historically grouped into four generations (i.e. silicone implants; 1st generation, silicone implants with grommets; 2nd generation, metal implants with press-fit fixation; 3th generation, and metal implants with threaded stem fixation; 4th generation) [12]. Another type of a MTP1 implant is a ***hemiprosthesis***, which is a joint sacrificing, but motion saving technique. It consists of a hemi-cap implant in which the articular surface of the first metatarsal head (see Figure 4E) or a unipolar constructs in which the proximal phalanx base is replaced. During placement of a ***total joint prosthesis*** both the metatarsal head and base of the proximal phalanx are replaced by the implant (see Figure 4D).

Arthrodesis is considered as the golden standard in HR treatment and is the most performed procedure in patients with high-grade, advanced HR. It provides a good pain reduction, good functional outcome, short hospital stay, low revision rate and relatively fast return to normal activity. In this procedure, motion of the MTP1 joint is sacrificed due to joint fusion (based on screws or plate fixation; see Figure 4F). It is primarily advised in active, more demanding young patients or as a salvage procedure after failed joint-preserving surgery [12,30]. However, the major disadvantage is the absence of MTP1 joint motion, thereby influencing activities which demands hallux functioning such as walking and running.

Lastly, promising results of a recently developed ***synthetic cartilage implant*** are presented in literature. The novel synthetic polyvinyl alcohol (PVA) hydrogel implant acts as a spacer between the first metatarsal and proximal phalanx and has properties similar to human articular cartilage. Studies showed significant improvements in reported pain scores, patient-reported outcome measures and a high implant survivorship 5 years after surgery [32,33].

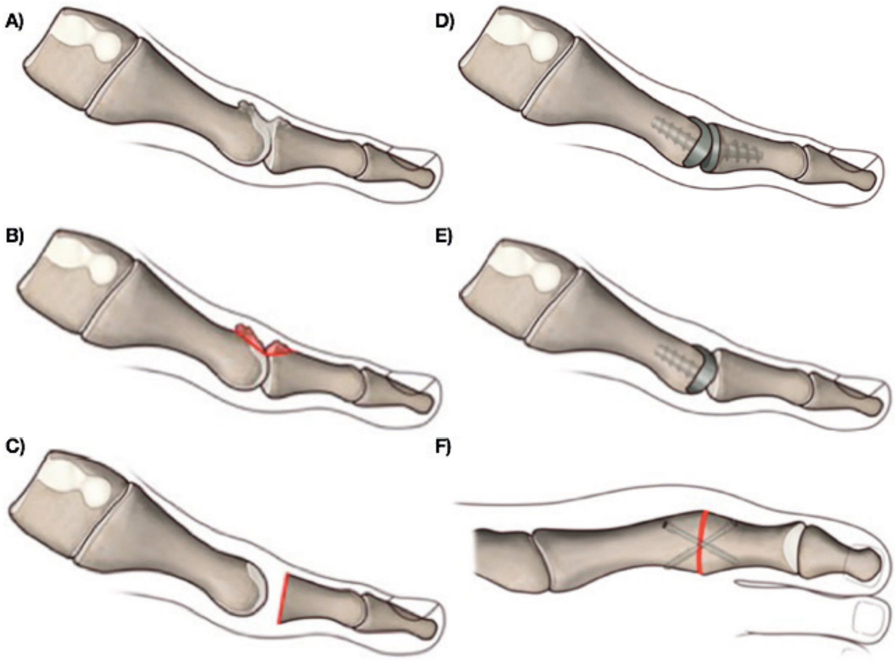

Figure 4. Surgical options for hallux rigidus. A: Hallux rigidus, B: Cheilectomy, C: Keller resection arthroplasty, D: Total joint replacement, E: Hemiprosthesis, F: Arthrodesis with crossed screw fixation (anteroposterior view). Used and adapted with permission from Massimi et al and Caravelli et al [12,29].

EFFECTS OF SURGICAL INTERVENTIONS ON GAIT

Little is known about the effects of the abovementioned surgical interventions for HR on gait. Nawoczenski et al. used a device to evaluate motion between the calcaneus, first metatarsal and hallux during gait and showed a significant increase in MTP1 joint ROM during gait after cheilectomy [34]. In a study of Kuni et al., which used the

Heidelberg Foot Measurement Method, cheilectomy was not able to restore hallux dorsi/plantarflexion towards a normal level while walking on level surface and stairs. In addition, MTP1 sagittal range of motion did not increase postoperatively [27]. Canseco et al. additionally showed no significant improvement in MTP1, forefoot and hindfoot range of motion after cheilectomy by using the Milwaukee Foot Model. However, walking speed, cadence and stride length improved and stance duration normalized after cheilectomy [35]. Smith et al. showed no differences in gait velocity or sagittal ankle ROM after cheilectomy [36].

Only 2 studies reported gait characteristics after an arthrodesis of the MTP1 joint for HR. These studies showed a decrease in step length and step width, while no differences in ankle, knee and hip kinematics were identified after arthrodesis as compared to healthy controls [37,38].

Hence, only two studies used a MFM to evaluate foot and ankle kinematics after cheilectomy, which is primarily performed in low grade HR as previously mentioned. There is a lack of knowledge on how the interventions which were performed in high grade HR (i.e. MTP1 arthrodesis, Keller resection arthroplasty and joint prosthesis) affect foot and ankle kinematics, since there are no studies evaluating these interventions with a MFM. This is a clinically relevant knowledge gap that should be addressed. When a MFM study would identify that a specific joint is responsible to compensate for altered or loss of motion after intervention, this could impact clinical decision making. For instance, a surgeon could dissuade an intervention in a subject with less compensatory capacity of the joint that should facilitate this compensatory motion. Before this knowledge can be applied in clinical decision making, the effects of the interventions on foot and ankle kinematics should be explored.

OBJECTIVE OF THIS THESIS

Given the high prevalence of hallux rigidus and the negative impact on performing normal daily tasks, it is of importance to increase our understanding of gait characteristics in patients with HR. However, in which manner HR affects one of our more basal activities during life; i.e. walking, is largely unknown. Therefore, the main objective of this thesis was to evaluate gait characteristics in patients with HR before and after treatment. Besides, the goal was to study which intervention yields the best patient-reported outcome. To achieve these objectives, three research questions were examined:

- In which manner is gait affected in symptomatic HR patients, assessed by using a MFM to evaluate foot and ankle motion and a Lower Body Model to evaluate ankle, knee, hip and pelvic motion? (**Chapter 3 & Chapter 4**)
- Which foot joints are responsible to compensate for the loss of MTP1 motion after a MTP1 joint arthrodesis in subjects with symptomatic HR? (**Chapter 5**)
- Which surgical technique is superior in the treatment of symptomatic HR patients in terms of improving clinical and patient-reported outcome and decreasing pain? (**Chapter 2 & Chapter 6**)

OUTLINE OF THE THESIS

This thesis aims to clarify how HR affects gait and how subsequent treatment will influence this gait pattern and patient-reported outcome. Encompassing a systematic review (**Chapter 2**) and three comparative studies (**Chapter 3-4, 5 & 6**), this thesis focusses on a number of targets aiming to gain a further insight in the biomechanical and clinical consequences of HR and subsequent surgical treatment.

In **Chapter 2**, a systematic review of the literature is presented aiming to answer the question whether total joint replacement or arthrodesis of the MTP1 joint is superior in improving clinical outcome and decreasing pain, and investigating which intervention showed lowest complication and revision rates, in patients with symptomatic end-stage HR. **Chapter 3** investigates how foot and ankle kinematics and foot pressure are affected in subjects with symptomatic HR by using the multi-segment Oxford Foot Model (OFM), in order to get an answer which joints are responsible to compensate for the loss of MTP1 joint motion. **Chapter 4** aims to study whether HR affects lower limb joint kinematics, and if so, if this correlates with patient-reported outcome. The Gait Profile Score, a single measure to qualify the quality of gait, and intersegmental range of motion are used. In **Chapter 5**, the goal is to elucidate where the foot compensates for the loss of motion after a MTP1 arthrodesis for symptomatic HR by analyzing foot and ankle kinematics and plantar pressure data. In **Chapter 6**, the long-term clinical and radiological outcome after cheilectomy, Keller resection arthroplasty and arthrodesis are investigated in a comparative follow-up study. In **Chapter 7**, a general discussion of the performed studies is provided. A summary and valorisation paragraph is even presented.

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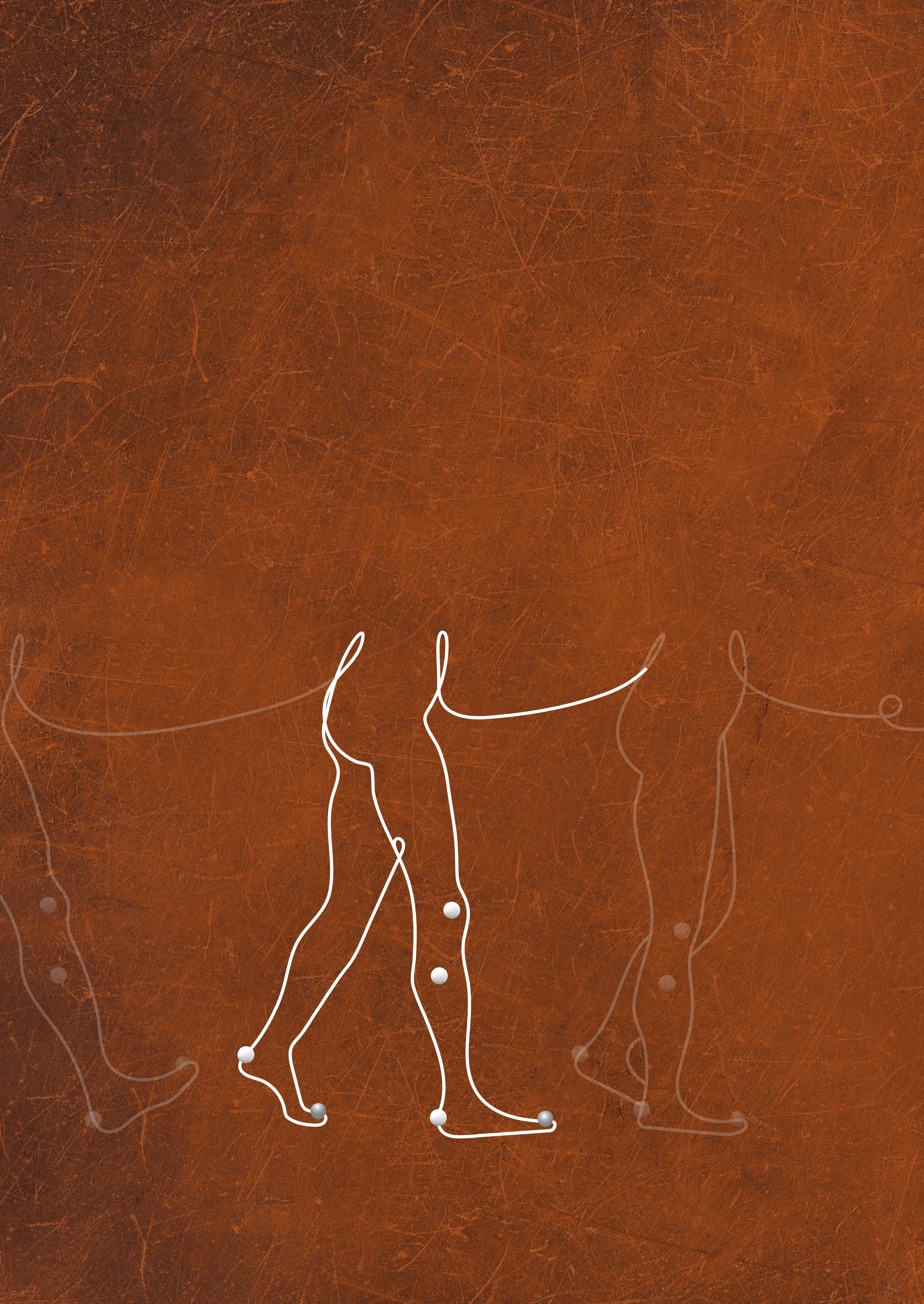

CHAPTER 2

CLINICAL OUTCOME FOLLOWING TOTAL JOINT REPLACEMENT AND ARTHRODESIS FOR HALLUX RIGIDUS

A SYSTEMATIC REVIEW

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Abbreviations

AOFAS-HMI	American Orthopaedic Foot & Ankle Society-Hallux Metatarsophalangeal Interphalangeal	VAS	Visual Analog Scale
FFI	Foot Function Index	HR	Hallux Rigidus
RCT	Randomized Controlled Trial	SF-36	Short Form-36

ABSTRACT

Background: Hallux rigidus is a common cause of foot pain in the elderly and has a negative impact on quality of life. Several operative treatment options are available for feet that are refractory to conservative treatment. Of these, total joint replacement and arthrodesis of the first metatarsophalangeal joint are the most commonly performed interventions. Nevertheless, it is still not known which intervention results in the best clinical outcome and the fewest complications.

Methods: PubMed/MEDLINE, Embase, and the Cochrane Library were systematically searched for studies assessing outcome with the American Orthopaedic Foot & Ankle Society-Hallux Metatarsophalangeal Interphalangeal (AOFAS-HMI) score, Foot Function Index (FFI), visual analog scale (VAS) for pain, or Short Form-36 (SF-36) in patients who underwent an arthrodesis or total joint replacement for the treatment of symptomatic hallux rigidus. Secondary outcomes were complications and revision rates. The screening of titles and abstracts, data collection, data extraction, and study quality assessment were performed independently by 2 reviewers. Study quality was determined with use of risk-of-bias tools. Results of included studies were presented in a qualitative manner, and the results of high-quality studies were pooled.

Results: Thirty-three studies, describing a total of 741 arthrodeses and 555 total joint replacements, were included in the qualitative analysis. Six different prostheses were used for total joint replacement, and various fixation techniques were used for arthrodesis. The results of 6 arthrodesis studies and 7 total joint replacement studies were pooled in the quantitative analysis. Pooled results showed superiority of arthrodesis compared with total joint replacement for improving clinical outcome (by 43.8 versus 37.7 points on the AOFAS-HMI score) and reducing pain (a decrease of 6.56 versus 4.65 points on the VAS pain score). Because of the rare reporting of the FFI and SF-36, no comparison could be made for these outcomes. Fewer intervention-related complications (23.1% versus 26.3%) and revisions (3.9% versus 11%) were reported after arthrodesis as compared with total joint replacement, with pain and nonunion and prosthetic loosening being the most commonly reported complications after arthrodesis and total joint replacement, respectively.

Conclusions: The present systematic review of the literature indicated that arthrodesis is superior for improving clinical outcome and reducing pain, and is less often accompanied by intervention-related complications and revisions, compared with total joint replacement in patients with symptomatic hallux rigidus. Prospective, randomized controlled trials will need to be conducted to verify this conclusion.

BACKGROUND

Severe osteoarthritis of the first metatarsophalangeal joint, or hallux rigidus, is a common orthopaedic disorder resulting in pain. The prevalence increases with age and is higher among women than among men [1,2]. In addition to causing pain, hallux rigidus has a major detrimental effect on the quality of life as patients experience more difficulties during daily and sport activities [3-6]. Operative treatment may be considered for feet that are refractory to conservative treatment in order to reduce pain and improve foot function, resulting in fewer foot-related complaints. Ideally, the intervention additionally restores the range of motion of the joint, results in good alignment, and maintains the length of the metatarsal and phalanx. Despite the availability of numerous surgical techniques, including cheilectomy, osteotomy, arthrodesis, implants, resection, and interpositional arthroplasty, none of these interventions completely fulfil all of those requirements [7,8].

Currently, arthrodesis and total joint replacement of the first metatarsophalangeal joint are the most commonly performed interventions in patients with end-stage hallux rigidus as it is still not known which intervention is superior for reducing pain and improving clinical outcome [8,9].

Cook et al. reported high satisfaction rates after total joint replacement of the first metatarsophalangeal joint, ranging from 80.5% to 89.7% based on 3,049 procedures, with silicone prostheses scoring better than ceramic and metal protheses [10]. However, it is well known that silicone prostheses are associated with higher complication rates and have a limited survival time [11-13]. The limitations of that review were the range of indications for total joint replacement and the absence of a comparison with arthrodesis, leaving unanswered the question about which procedure is superior. Brewster reported high postoperative scores ranging from 74 to 95 points and 78 to 89 points for total joint replacement and arthrodesis, respectively, as measured with the American Orthopaedic Foot and Ankle Society- Hallux Metatarsophalangeal-Interphalangeal scale (AOFAS-HMI) scoring system [14]. However, that report was limited because studies that involved the use of scoring systems other than the AOFAS-HMI were excluded. McNeil et al., on the basis of a qualitative review, concluded that arthrodesis seemed to be superior to total joint replacement for the treatment of hallux rigidus, although the quality of the included studies was fair to poor [11]. However, quality was assessed on the basis of study design only. In addition, the grade of recommendation for total joint replacement was based on all types of non-tissue implants, although differences in functional outcome and survival for different prostheses were well known [11-13]. Those previous reviews had some major limitations, and none of them involved a quantitative analysis in which studies were included on the basis of methodological quality.

The primary objective of the present systematic review of methodologically good-quality studies was to answer the question whether total joint replacement or arthrodesis of the first metatarsophalangeal joint is superior for improving clinical outcome and decreasing pain in patients with symptomatic end-stage hallux rigidus. The secondary objective was to investigate which of those interventions had the lower complication and revision rate.

METHODS

Search strategy

The PubMed/MEDLINE, Ovid Embase, and the Cochrane Library electronic databases were searched to identify potentially eligible studies. The following search terms were used; *Hallux, Hallux Rigidus, Hallux Limitus, First metatarsophalangeal joint, Metatarsophalangeal, Osteoarthritis, Arthrosis, Arthroplasty, Total joint prosthesis, Total joint replacement, Total joint arthroplasty, Joint implant, Arthrodesis, Joint fusion*. A full electronic search strategy is shown in Appendix 1. No search limits were applied for language or publication date. The initial search was performed on August 24, 2016, and the last search was run on December 22, 2016. Reference lists of included studies and previously published reviews were screened for additional potentially eligible studies.

Study and report eligibility criteria

Inclusion and exclusion criteria were developed using the participants, interventions, comparators, outcomes, timing and study design (PICOTS) framework:

- *Participants*: Subjects of any age or sex with symptomatic hallux rigidus who underwent one of the two interventions.
- *Interventions*: Arthrodesis or total joint replacement of the first metatarsophalangeal joint. No restrictions were applied for fixation technique to achieve joint fusion. Studies describing silicone prostheses, hemiprosthesis and interpositional arthroplasty were not eligible. Participants who had a previous procedure for the treatment of a symptomatic hallux rigidus (i.e. cheilectomy, Keller's arthroplasty) and subsequently underwent a first metatarsophalangeal joint arthrodesis or total joint replacement were included.
- *Comparators*: A comparative group in an original article was not necessary.

- *Outcome*: Primary outcomes were the AOFAS-HMI score [15], Foot Function Index (FFI) [16], visual analogue scale (VAS) pain score or Short Form-36 (SF-36) score [17]. Secondary outcomes were the rates and causes of complications and revisions.
- *Timing*: Minimum mean duration of follow-up of 12 months.
- *Study design*: Randomised controlled trials (RCTs), cohort studies, and case series involving a minimum of 10 feet.
- Reviews, case reports, conference and poster abstracts, nonpublished reports, and non-English-language articles were not eligible. No restrictions were applied regarding the year of publication.

Study selection and data extraction

Titles and abstracts of studies retrieved by the search were screened for eligibility. Subsequently, full-text reports were assessed on the basis of the inclusion and exclusion criteria.

Data from included studies were extracted with use of a standardized, pre-piloted tested data extraction form (see Appendix 2). The following information was extracted: (1) study characteristics (study design, level of evidence, intervention, and mean duration of follow-up), (2) patient characteristics (number of participants, mean age, sex distribution, and number of feet), (3) primary and secondary outcome measures (AOFAS-HMI, FFI, VAS Pain, SF-36, rates and causes of complications and revisions), and (4) study quality. The difference between preoperative clinical score and postoperative outcome was the primary measure of treatment effect. Level of evidence was assigned as described by *Wright et al* [18]. Two reviewers independently searched for, included, and extracted data from eligible studies. Disagreement during this process were resolved by discussion. Included reports were compared on the basis of authors' names, affiliations, study periods, and intervention to assess whether different reports described the same patient population.

Study quality assessment

For RCTs, the risk-of-bias tool developed by the Cochrane Collaboration was used [19]. Risk of bias for each item was defined as high (1 point), low (0 points) or unclear (0.5 point). An adapted version of the quality-assessment tool as developed by Rangel et al. was used to assess the quality of cohort studies and case series (see Appendix 3) [20]. With use of this quality-assessment tool, the external validity and risk of bias in included studies were estimated, and studies were defined as having a high or a low risk of bias. The items and scoring method are explained in detail in the study protocol [21]. Study quality was independently assessed by 2 reviewers, and discrepancies between those reviewers were resolved by discussion.

Synthesis of results

For both interventions types (i.e. arthrodesis and total joint replacement), a narrative description of study characteristics and primary and secondary outcomes of included studies were reported. Differences in preoperative and postoperative scores were provided when available. Criteria for pooling of primary outcomes of individual study were (1) low risk of bias, (2) evaluation of the same intervention, and (3) reporting of preoperative clinical score and postoperative outcome with a nonmodified scoring system. For cohort studies and case series, risk of bias was high when >2 items scored positive. For RCTs, risk of bias was high when the total score was >2. Weighted means of primary outcomes were calculated as previously described [22], and means with corresponding standard deviations were calculated when medians were reported [23]. Data were analyzed with use of SPSS, (version 23; IBM Statistics) and were presented as the weighted means with standard deviations. The paired t test was used to compare preoperative and postoperative scores within interventions. The unpaired t test was used to compare both interventions in terms of treatment effect, preoperative score, and postoperative score. The level of significance was set at $p < 0.05$.

RESULTS

Study selection procedure

The final literature search provided 1,309 citations. Twenty-one citations were identified through other sources. After the removal of duplicates, 816 citations were screened on the basis of the title and abstract and, of these, 93 were assessed for eligibility on the basis of the full text. Overall, 33 reports fulfilled the selection criteria and were included in the qualitative synthesis, whereas 12 reports were included in the quantitative analysis. The selection process is summarized in Figure 1.

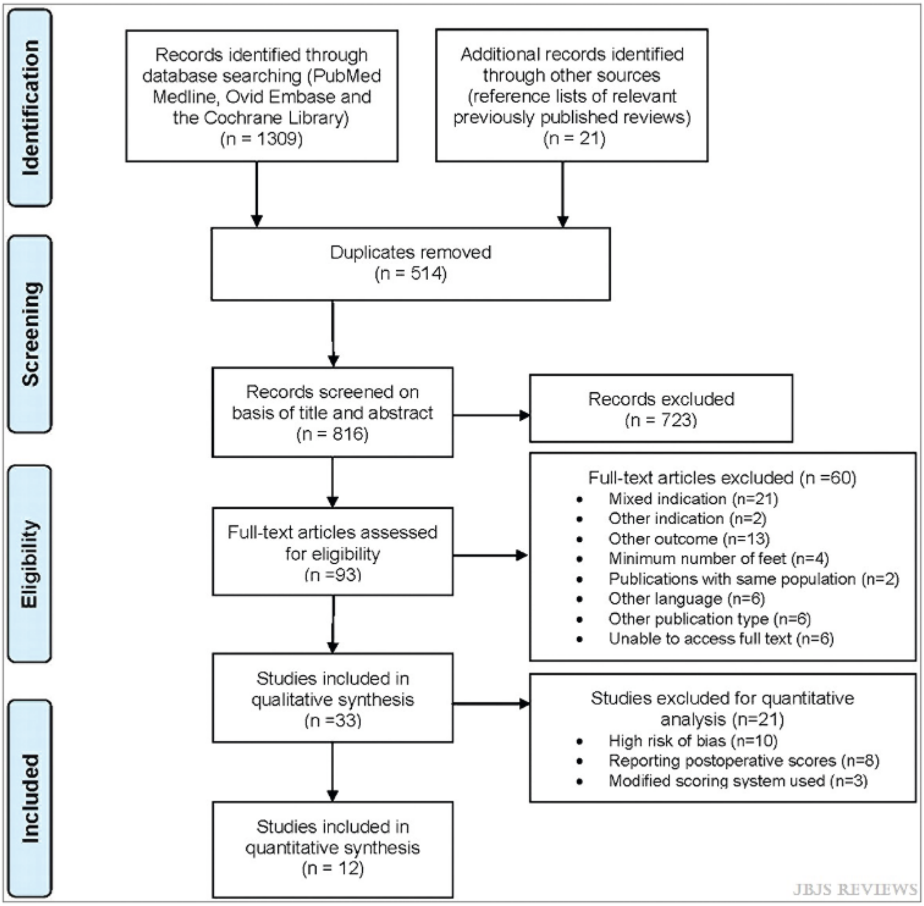

Figure 1. PRISMA flow diagram of the study selection procedure [66].

Characteristics of included studies

Arthrodesis studies (Table 1)

Study Design: Two of the 16 studies were RCTs in which arthrodesis was compared with total joint replacement or the use of a cartilage implant [24,25]. Seven retrospective cohort studies compared arthrodesis with hemiarthroplasty, resection arthroplasty, cheilectomy and/or total joint replacement [26-32]. In addition, 7 case series were included [33-39].

Participants: All subjects underwent treatment for symptomatic hallux rigidus. In 7 studies, the radiographic severity of hallux rigidus was used as an inclusion criteria [25,27-30,35,39]. In total, 741 feet in 678 patients with mean ages ranging from 50 to 68.5 years were included.

Intervention: Screw fixation [26,28,30,34,36-38], plate fixation[27,31,39], cerclage fixation with Kirschner-wires [24], or a combination of fixation techniques [25,29,32,33,35] were used to achieve fusion (see Appendix 4)

Timing: The mean duration of follow-up ranged from 24 months to 8 years.

Total joint replacement studies (Table 2)
Study Design: One RCT directly compared total joint replacement with an arthrodesis of the first metatarsophalangeal joint [24]. In addition, 7 prospective case series [4,40-45] and 10 retrospective case series were included [46-55].

Participants: All participants underwent treatment for symptomatic hallux rigidus. In 2 studies, a minority of the patients underwent total joint placement after failed primary treatment of hallux rigidus [44,48]. The radiographic severity of hallux rigidus was an inclusion criteria in 7 studies [4,41,43,46,47,49,54]. In total, 555 feet in 482 participants with mean ages ranging from 49.8 to 63.1 years were included, although 1 study did not include any information on age [42].

Intervention: Six different types of total joint prostheses were included: Biomet-Merck [24], TOEFIT-PLUS [4,40,46,55], METIS [43], Roto-Glide [41], MOJE ceramic press-fit [42,44,45,47-53], and Bio-Action [54] (see Appendix 4).

Timing: The mean duration of follow-up ranged from 12 to 81 months.

We identified 2 total joint replacement reports describing the same study population [28,46]. The results of the report with the longer duration of follow-up were used in this review [46].

Risk of bias within included studies
RCTs: Both RCTs scored not more than 2 points in the risk-of-bias tool, with 1 study having a high risk of performance and attrition bias [24], and the other study having an unclear risk of selection and performance bias [25] (Table 3).

Cohort studies and case series: One arthrodesis study was free of bias [36], and 4 studies scored >2 points on the risk-of-bias tool and were therefore classified as studies with a high risk of bias [26,29,33,35]. None of the total joint replacement studies were free of bias, whereas 6 studies had a high risk of bias [40,42,45,50-52] (Table 4).

Table 1. Studies Evaluating First Metatarsophalangeal Joint Arthrodesis for Symptomatic Hallux Rigidus

Study	Study Design (Level of Evidence)	Arthrodesis fixation technique	Indication	No. of Patients (M/F)	No. of Feet (L/R)	Age[a] (yr)	Duration of Follow-up[a]
Gibson and Thomson (2005)[24]	Monocenter randomized controlled trial; arthrodesis vs total joint arthroplasty (I)	Cerclage with Kirschner wire	Symptomatic HR with failed conservative treatment	22	38 (21/17)	54.2 ± 10.6 (34 to 77)	24 mo
Baumhauer et al. (2016)[25]	Multicenter randomized controlled trial; arthrodesis vs. cartilage implant (I)	2 crossed screws or plate-screw fixation	Symptomatic HR, grade II-IV[c], with indication for arthrodesis	50 (12/38)	50	54.9 ±10.5 (32.4 to 78.2)	24 mo
Beertema et al. (2006)[26]	Retrospective cohort study; arthrodesis vs. Keller arthroplasty vs. cheilectomy (III)	2 crossed screws	Symptomatic HR	34	34	54 (31 to 68)	7 yr (2 to 13 yr)
Coughlin and Shurnas (2003)[27]	Retrospective cohort study; arthrodesis vs cheilectomy (III)	Vitallium 6-hole mini- compression plate and lag-screw	Symptomatic HR, grade III-IV[c]	30	34	50 (16 to 76)	6.7 yr (2.1 to 12.2 yr)
Erdil et al. (2013)[28]	Retrospective cohort study; arthrodesis vs. hemiarthroplasty vs. total joint replacement (III)	2 compression screws	Symptomatic HR, grade III-IV[c]	12 (4/8)	12 (7/5)	58.17 ± 8.45	35.3 mo (24 to 66 mo)
Kim et al. (2012)[29]	Retrospective cohort study; arthrodesis vs. hemiarthroplasty vs. resection arthroplasty (III)	Various techniques	Symptomatic HR, grade III-IV[c]	51 (20/31)	51	60.5 ± 9.7 (36 to 84)	194 wk[b]
Raikin et al. (2007)[30]	Retrospective cohort study; arthrodesis vs. hemiarthroplasty (III)	2 crossed screws	Symptomatic HR grade III-IV[c]	26 (10/16)	27 (14/13)	54.1 (32 to 73)	30 mo (13 to 67 mo)
Simons et al. (2015)[31]	Retrospective cohort study; arthrodesis vs. hemiarthroplasty (III)	Hallu-Lock plate	Symptomatic end-stage HR	132	132	59.6 ± 9.5	39.5 mo (12 to 96 mo)[b]
Voskuijl and Onstenk (2015)[32]	Retrospective cohort study; arthrodesis vs. hemiarthroplasty (III)	Various techniques	Symptomatic HR	50 (8/42)	58 (26/32)	63 ±7.1 (47 to 78)	4.4 yr (1.3 to 7.0 yr)
DeFrino et al. (2002)[34]	Prospective case series (IV)	2 parallel cortical screws	Symptomatic HR	9 (4/5)	10	56 (38 to 72)	34 mo (26 to 44 mo)
van Doeselaar et al. (2010)[36]	Prospective case series (IV)	2 crossed screws	Symptomatic HR	27 (9/18)	27	58 (42 to 72)[b]	37 mo (14 to 54 mo)[b]
Aas et al. (2008)[33]	Retrospective case series (IV)	Various techniques	Symptomatic HR	35 (14/21)	39	52 (34 to 69)	8 yr (2 to 15 yr)
Ettl et al. (2003)[35]	Retrospective case series (IV)	2 crossed screws or Kirschner wires with wire sutures	Symptomatic HR grade III[c], with failed conservative treatment	34 (7/27)	38	52 (24 to 71)	54 mo (18 to 116 mo)
Wassink and van den Oever (2009)[37]	Retrospective case series (IV)	Single lag compression screw	Symptomatic HR	89 (19/70)	109 (47/62)	59 ± 10 (41 to 82)	69 mo (7 to 114 mo)
Lombardi et al. (2001)[38]	Retrospective case series (IV)	2 crossed screws	Symptomatic HR	17 (7/10)	21	53.2 (36 to 77)	28.1 mo (10 to 66 mo)
Chraim et al. (2016)[39]	Retrospective case series (IV)	Vitallium 6-hole mini- compression plate and lag screw	Symptomatic HR grade III[d]	60 (6/54)	61	68.5 (55 to 81)	47.3 mo (39 to 56 mo)

[a] Unless otherwise stated, the values are given as the mean, with or without the standard deviation and/or range.

[b] The values are given as the median, with or without the range in parantheses.

[c] Radiographic system for grading HR as developed by Coughlin and Shurnas [27].

[d] Radiographic system for grading HR as developed by Hattrup and Johnson [67].

Table 2. Studies Evaluating First Metatarsophalangeal Joint Total Joint Replacement for Symptomatic Hallux Rigidus*

Study	Study Design (Level of Evidence)	Type of Prosthesis	Indication	No. of Patients (M/F)	No. of Feet (L/R)	Age (yr)[a]	Duration of Follow-up (mo)[a]
Gibson and Thomson (2005)[24]	Monocenter randomized controlled trial; arthrodesis vs. total joint arthroplasty (I)	Biomet-Merck	Symptomatic HR with failed conservative treatment	27	39 (18/21)	55 (34 to 77)	24
Daniilidis et al. (2010)[4]	Prospective case series (IV)	TOEFIT-PLUS	Symptomatic HR grade III[c] with indication for surgery	23 (7/16)	23	57 ± 3.7	18
Gupta and Mallya (2008)[40]	Prospective case series (IV)	TOEFIT-PLUS	Symptomatic HR	20 (7/13)	21	57	12.2 ± 5.4 (6 to 21)
Titchener et al. (2015)[55]	Retrospective case series (IV)	TOEFIT-PLUS	Symptomatic HR	73 (10/63)	86 (37/49)	60.3 (38 to 83)	33 (2 to 72)
Erkocak et al. (2013)[46]	Retrospective case series (IV)	TOEFIT-PLUS	Symptomatic HR grade III-IV[c], failed conservative treatment	24 (8/18)	26 (12/14)	55 (38 to 78)	29.9 (25 to 62)
Horisberger et al. (2016)[43]	Prospective case series (IV)	METIS	Symptomatic HR grade III-IV[c]	25 (10/15)	29	63.1 ± 10.2 (48 to 87)	49.5 (36 to 62)
Wetke et al. (2012)[41]	Prospective case series (IV)	Roto-Glide	Symptomatic HR grade III-IV[c]	12 (3/9)	12	56 (49 to 63)	3.1 yr (1.0 to 7.2 yr)
Omonbude and Faraj (2004)[45]	Prospective case series (IV)	MOJE ceramic press-fit	Symptomatic HR with failed conservative treatment	13 (5/8)	14	49.8 (29 to 65)	12 (11 to 14)
McGraw et al. (2010)[44]	Prospective case series (IV)	MOJE ceramic press-fit	Symptomatic HR (n=58), failed arthrodesis (n=3), failed Keller arthoplasty (n=2)	48 (15/33)	63	56 (34 to 77)	44 (17 to 76)
Arbuthnot et al. (2008)[42]	Prospective case series (IV)	MOJE ceramic press-fit	Symptomatic HR with failed conservative treatment	40	42	-	21 (3 to 36)
Barwick and Talkhani (2008)[47]	Retrospective case series (IV)	MOJE ceramic press-fit	Symptomatic HR grade I-III[d]	22 (5/17)	24 (13/11)	54.5 (43 to 68)[b]	26 (12 to 47)
Brewster et al. (2010)[48]	Retrospective case series (IV)	MOJE ceramic press-fit	Symptomatic HR with failed conservative treatment (n=28), failed primary prosthesis (n=3), failed Keller arthroplasty (n=1)	29 (9/20)	32 (15/17)	56 (38 to 79)	34 (6 to 74)
Chee et al. (2011)[49]	Retrospective case series (IV)	MOJE ceramic press-fit	Symptomatic HR grade I-III[d]	37 (6/31)	41	62 (50 to 77)	33 (12 to 60)
Dawson-Bowling et al. (2012)[50]	Retrospective case series (IV)	MOJE ceramic press-fit	Symptomatic HR	30 (9/21)	32 (14/18)	61.9 (37 to 76)	58 (28 to 97)
Fadel et al. (2005)[51]	Retrospective case series (IV)	MOJE ceramic press-fit	Symptomatic HR	13 (1/12)	14	51.3 (28 to 61)	25.9 (20 to 40)
Ibrahim and Taylor (2004)[52]	Retrospective case series (IV)	MOJE ceramic press-fit	Symptomatic HR	8 (1/7)	11	58 (51 to 80.5)	17 (10 to 22)
Nagy et al. (2014)[53]	Retrospective case series (IV)	MOJE ceramic press-fit	Symptomatic HR with failed conservative treatment	24 (0/24)	31 (13/18)	55 ± 6 (41 to 67)	81 ± 27 (36 to 143)
Sinha et al. (2010)[54]	Retrospective case series (IV)	Bio-Action	Symptomatic HR grade III[d]	14 (4/10)	15	59	61 (48 to 65)

* The manufacturers are as follows: Biomet-Merck, Biomet; TOEFIT-PLUS, Smith & Nephew; METIS, Integra Life Sciences; Roto-Glide, Implants International; MOJE ceramic press-fit, Moje Keramik-Implantate; Bioaction, MicroAire Surgical Instruments.

[a] Unless otherwise states, the values are given as the mean, with or without the standard deviation and/or range.

[b] The values are given as the median, with the range in parentheses.

[c] Radiographic system for grading HR as developed by Coughlin and Shurnas [27].

[d] Radiographic system for grading HR as developed by Hattrup and Johnson [67].

Table 3. Risk of Bias of Included RCTs Evaluating First Metatarsophalangeal Joint Arthrodesis and Total Joint Replacement for Symptomatic Hallux Rigidus

Study	Random Sequence Generation		Allocation Sequence Concealment		Blinding of Participants and Personnel		Blinding of outcome assessors	
	Risk of Bias	**Support for judgement**	**Risk of Bias**	**Support for judgement**	**Risk of Bias**	**Support for judgement**	**Risk of Bias**	**Support for judgement**
Gibson and Thomson (2005)[24]	Low	Shuffled, closed, opaque envelopes (50 x 2 interventions numbered 1 to 100) were opened in sequence	Low	Shuffled, closed, opaque envelopes (50 x 2 interventions numbered 1 to 100) were opened in sequence	High	No blinding performed. In addition, treatment with both intervention types in bilaterally affected patients might have influenced outcome reporting	Low	No blinding performed; however, unlikely to influence outcome (VAS pain)
Baumhauer et al. (2016)[25]	Unclear	Not described	Unclear	Not described. High amount of patients withdrew after randomization to arthrodesis group (23%)	Unclear	No blinding performed. Patients with bilateral hallux rigidus were not eligible for inclusion in this study	Low	No blinding performed, however, unlikely to influence outcome (VAS and SF-36)

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Table 3. (Continued)

Study	Incomplete Outcome Data		Selective Reporting		Other Sources of Bias		Total Risk of Bias[a]
	Risk of Bias	**Support for judgement**	**Risk of Bias**	**Support for judgement**	**Risk of Bias**	**Support for judgement**	
Gibson and Thomson (2005)[24]	High	More loss to follow-up in arthroplasty group (33.3% [9 of 27 patients, 6 of whom underwent revision surgery]), compared with arthrodesis group (13.7% [3 of 22 patients]). Selective loss to follow-up is likely to be intervention-related. In addition, despite the intention-to-treat protocol, 6 patient managed with revision arthroplasty were excluded from the final analysis	Low	All outcomes described in the Methods section were described in the Results and Discussion sections	Low	No other concerns or sources of bias identified	Low (2 points)
Baumhauer et al. (2016)[40]	Low	Slight difference in patient loss to follow-up between the cartilage implant group (3% [5 of 152 patients] and arthrodesis group (6% [3 of 50 patients]), unlikely to introduce bias. In addition, modified intention-to-treat analysis was performed to correct for high amount of withdrawal after randomization in arthrodesis group	Low	All outcomes described in the Methods section were described in the Results and Discussion sections	Low	No other concerns or sources of bias identified	Low (1.5 points)

[a] The total risk of bias of a study was determined based on the number of points scored on the several items of the Risk of Bias Tool (high risk = 1 point, unclear risk = 0.5 point, low risk = 0 points). A total of >2 points resulted in the conclusion that the study had a high risk of bias.

Table 4. Risk of Bias and External Validity of Cohort Studies and Case Series evaluating First Metatarsophalangeal Joint Arthrodesis and Total Joint Replacement for Symptomatic Hallux Rigidus

Study	Study Design	Poor External validity?	Risk of Selection Bias?	Risk of Performance Bias?	Risk of Detection Bias?	Risk of Attrition Bias?	Risk of Reporting Bias?	Total Risk of Bias[a]
Arthrodesis								
Beertema et al. (2006)[26]	Retrospective cohort study	No	Yes	No	Yes	No	Yes	High (3/6)
Coughlin and Shurnas (2003)[27]	Retrospective cohort study	No	No	No	Yes	Yes	No	Low (2/6)
Erdil et al. (2013)[28]	Retrospective cohort study	No	No	No	Yes	Yes	No	Low (2/6)
Kim et al. (2012)[29]	Retrospective cohort study	Yes	Yes	Yes	Yes	Yes	No	High (5/6)
Raikin et al. (2007)[30]	Retrospective cohort study	No	Yes	No	No	No	No	Low (1/6)
Simons et al. (2015)[31]	Retrospective cohort study	No	Yes	No	Yes	No	No	Low (2/6)
Voskuijl and Onstenk (2015)[32]	Retrospective cohort study	No	No	Yes	Yes	No	No	Low (2/6)
DeFrino et al. (2002)[34]	Prospective case series	Yes	No	No	Yes	No	No	Low (2/6)
van Doeselaar et al. (2010)[36]	Prospective case series	No	No	No	No	No	No	Low (0/6)
Aas et al. (2008)[33]	Retrospective case series	Yes	Yes	Yes	Yes	Yes	Yes	High (6/6)
Ettl et al. (2003)[35]	Retrospective case series	Yes	Yes	No	No	Yes	No	High (3/6)
Wassink et al. (2009)[37]	Retrospective case series	No	No	No	Yes	No	No	Low (1/6)
Lombardi et al. (2001)[38]	Retrospective case series	Yes	No	No	Yes	No	No	Low (2/6)
Chraim et al. (2016)[39]	Retrospective case series	Yes	No	No	No	Yes	No	Low (2/6)
Total Joint Replacement								
Daniilidis et al. (2010)[4]	Prospective case series	Yes	No	No	No	Yes	No	Low (2/6)
Gupta and Mallya (2008)[40]	Prospective case series	Yes	Yes	No	Yes	Yes	No	High (4/6)
Titchener et al. (2015)[55]	Prospective case series	No	No	No	Yes	No	Yes	Low (2/6)
Erkocak et al. (2013)[46]	Retrospective case series	Yes	No	No	Yes	No	No	Low (2/6)
Horisberger et al. (2016)[43]	Prospective case series	Yes	No	No	No	No	No	Low (1/6)

Table 4. (Continued)

Study	Study Design	Poor External validity?	Risk of Selection Bias?	Risk of Performance Bias?	Risk of Detection Bias?	Risk of Attrition Bias?	Risk of Reporting Bias?	Total Risk of Bias[a]
Wetke et al. (2012)[41]	Prospective case series	Yes	No	No	No	No	No	Low (1/6)
Omonbude and Faraj (2004)[45]	Prospective case series	Yes	Yes	Yes	Yes	Yes	No	High (5/6)
McGraw et al. (2010)[44]	Prospective case series	Yes	Yes	No	No	No	No	Low (2/6)
Arbuthnot et al. (2008)[42]	Prospective case series	No	Yes	No	Yes	Yes	Yes	High (4/6)
Barwick and Talkhani (2008)[47]	Retrospective case series	No	No	No	Yes	No	No	Low (1/6)
Brewster et al. (2010)[48]	Retrospective case series	Yes	No	No	No	No	No	Low (1/6)
Chee et al. (2011)[49]	Retrospective case series	No	No	No	Yes	Yes	No	Low (2/6)
Dawson-Bowling et al. (2012)[50]	Retrospective case series	Yes	Yes	No	No	Yes	No	High (3/6)
Fadel et al. (2005)[51]	Retrospective case series	Yes	Yes	Yes	Yes	Yes	No	High (5/6)
Ibrahim and Taylor (2004)[52]	Retrospective case series	Yes	Yes	Yes	No	No	No	High (3/6)
Nagy et al. (2014)[53]	Retrospective case series	No	No	Yes	No	No	No	Low (1/6)
Sinha et al. (2010)[54]	Retrospective case series	No	No	No	Yes	Yes	No	Low (2/6)

[a] The total risk of bias of a study was determined based on the number of points scored on items of the Quality Assessment Tool. A total of >2 high-risk items resulted in the conclusion that the study had a high risk of bias.

Primary outcomes

AOFAS-Hallux Metatarsal Interphalangeal score

Twelve arthrodesis studies evaluated AOFAS-HMI scores as an outcome measure [26-30,32-35,37-39]. Of the 6 studies that presented both preoperative and postoperative scores, all showed an improvement in the mean AOFAS-HMI score from a range of 33.6 to 40.9 points before treatment to a range of 75.6 to 90 points after treatment (Table 5) [27,28,30,34,38,39]. Of the 6 studies that included only postoperative scores, 3 demonstrated scores within this postoperative range [26,29,32], and 3 demonstrated lower scores [33,35,37].

2

Sixteen total joint replacement studies included the AOFAS-HMI score as outcome measure [4,40,42-55], with 8 studies demonstrating an improvement from a range of 36 to 56 points preoperatively to a range of 72 to 95.3 points postoperatively (Table 6) [4,40,42-46,55]. Five studies demonstrated postoperative scores in this range [47-49,51,52]. Three studies showed lower postoperative scores, and, interestingly, those studies had the longest follow-up periods [50,53,54]. In contrast, the highest postoperative score was detected in the study with the shortest follow-up [45].

VAS pain score

Ten arthrodesis studies reported VAS ain scores [24-28,30,31,33,35,36]. Five studies demonstrated a decrease when the preoperative values (range, 6.2 to 8.7 points) were compared with the postoperative values (range, 0.4 to 2.7 points) [24,25,27,28,35]. The postoperative values in the other 5 studies were within that postoperative range (Table 5) [26,30,31,33,36].

Five total joint replacement studies evaluated VAS pain scores, and all showed a decrease when the preoperative values (range, 5.9 to 7.9 points) were compared with the postoperative values (range, 1.2 to 2.7 points) (Table 6) [4,24,41,43,46].

Foot Function Index

Three arthrodesis and 2 total joint replacement studies evaluated the FFI as outcome measure [31,36,39,52,53]. Two arthrodesis studies showed an improvement of approximately 30 points in the FFI score postoperatively [36,39], with the third arthrodesis study showing a slightly higher postoperative FFI score (Table 5) [31]. One total joint replacement study showed a higher postoperative FFI score than those in the arthrodesis studies [53], whereas the other total joint replacement study was comparable with those in the arthrodesis studies (Table 6) [52].

Short-Form 36

One arthrodesis study showed an improvement in the SF-36 physical component score after first metatarsophalangeal joint arthrodesis (Table 5) [25]. Only one study included postoperative SF-36 scores of patients treated with a total joint replacement (Table 6) [50].

Secondary outcomes

Complication and revision rate

The most frequently reported complication after first metatarsophalangeal joint arthrodesis was pain and/or irritation necessitating implant removal (16.2%; 120 of 741) [25,27,30,31,33,37-39], with nonunion or delayed union as the second most frequently reported complication (6.6%; 49 of 741) [24-27,29,31-33,37-39]. Overall, the rate of arthrodesis-related complications was 23.1% (171 of 741). Superficial wound infection (2.3%; 17 of 741) and metatarsalgia (2.7%; 20 of 741) were less commonly reported, although the rates were high in studies in which those complications were observed (range, 3% to 18% and 9 to 25% for infection and metatarsalgia, respectively) [24,26-29,32,35,39]. Rare complications included hallux malalignment, interphalangeal joint pain, implant breakage, deep venous thrombosis and skin numbness of the hallux (Table 5) [25,29,32,34,35,37].

The most frequently reported complication after total joint replacement was radiographic and/or clinical loosening of the prosthesis, which was reported in the Biomet-Merck prosthesis (36%; 14 of 39) [24], TOEFIT-PLUS prosthesis (10.3%; 16 of 156) [4,40,46,55], MOJE implant (27%; 72 of 266) [42,44,45,48-50,52,53], and Bio-Action prosthesis (93%; 14 of 15) [54]. In total, signs of loosening were observed in association with 20.9% of the prostheses. No signs of loosening were reported in association with the METIS and Roto-Glide prosthesis [41,43]. Prosthesis subluxation was observed in association with the TOEFIT-PLUS prosthesis (1.9%; 3 of 156) [40,55], METIS prosthesis (3.4%; 1 of 29) [43], and MOJE implant (2.3%; 6 of 266) [44,45,49,50,52]. Malalignment and fracturing of the prosthesis were less frequently reported [4,40,43,47,48,50,53,55]. Intraoperative fractures of the metatarsal or phalanx were only reported in association with the TOEFIT-PLUS prosthesis [46,55]. The overall rate of prosthesis-related complications was 26.3% (146 of 555). Nine infections (1.6%) were reported, while persistent pain was reported in 15 toes (2.7%) [4,42-49,51-55]. Less-common complications included Morton neuromas and transfer metatarsalgia (Table 6) [42,48].

The rate of revision following arthrodesis was 3.9% (29 of 741); the revisions were performed because of 27 nonunions and 2 malunions [25,26,29,31-33,37]. The rate of revision following total joint replacement was 11% (61 of 555), 28 prostheses were revised, 24 were converted to arthrodesis, and 9 were converted to another intervention [24,40,42-45,47-50,53-55].

Syntheses of results

The results of 6 arthrodesis studies [24,25,27,28,30,39] and 7 total joint replacement studies [4,24,41,43,44,46,55] with a low risk of bias were pooled for the AOFAS-HMI or VAS pain score (see Table 7). Three arthrodesis [31,32,36], and 5 total joint replacement studies were excluded because they included only postoperative scores [47-49,53,54], and 3 arthrodesis studies were excluded because they involved the use of a modified scoring system [34,37,38]. No study reporting the FFI or SF-36 score fulfilled the criteria for pooling. The arthrodesis group had significantly lower AOFAS-HMI scores, both preoperatively and postoperatively, than the total joint replacement group ($p < 0.0001$). However, the treatment effect of an arthrodesis was significantly higher than that of a total joint replacement based on the AOFAS-HMI score ($p < 0.0001$). A significantly higher VAS pain score ($p < 0.0001$) was observed in the arthrodesis group than in the total joint replacement group preoperatively, and a significantly lower VAS pain score was observed in the arthrodesis group than in the total joint replacement group postoperatively ($p < 0.0001$). As a result, an arthrodesis had a greater treatment effect on the VAS pain score as compared with a total joint replacement ($p < 0.0001$).

Table 5. Primary and Secondary Outcomes of Studies Evaluating First Metatarsophalangeal Arthrodesis for Symptomatic Hallux Rigidus

Study	AOFAS-HMI *(points)*	VAS pain[a] *(points)*	Other[a] *(points)*	Complications	Revisions
Gibson and Thomson (2005)[24]	–	Pre: 6.2 ± 1.8 Post: 1.1 ± 1.6 Change: -5.1	–	Superficial wound infection treated with oral antibiotics (18%; 7 of 38), delayed union (16%; 6 of 38), Kirschner wire extraction at surgery unit (5.3%; 2 of 38)	None
Baumhauer et al. (2015)[25]	–	Pre: 6.9 ± 1.4 (3.8 to 9.8) Post: 0.6 ± 1.2 (0 to 7.0) Change: -6.3	SF-36 Pre: 49.8 ± 23.6 (15 to 100) SF-36 Post: 85.1 ± 19.5 (5 to 100) Change: +35.3	Isolated screws or plate and screw removal due to persistent pain (14%; 7 of 50), nonunion (10%; 5 of 50), broken screw (1%; 1 of 50)	Revision arthrodesis because of nonunion (4%; 2 of 50)
Beertema et al. (2006)[26]	Post: 78[b]	Post: 2.1	–	Symptomatic nonunion (9%; 3 of 34), asymptomatic nonunion (3%; 1 of 34), metatarsalgia (21%; 7 of 34)	Revision arthrodesis because of symptomatic nonunion (9%; 3 of 34)
Coughlin and Shurnas (2003)[27]	Pre: 38 (24 to 60) Post: 89 (72 to 90) Change: +51	Pre: 8.7 (6.0 to 10) Post: 0.4 (0 to 5.0) Change: -8.3	–	Superficial wound infection treated with oral antibiotics (7%; 2 of 30), painless fibrous nonunion (6%; 2 of 34), plate removal due to pain (6%; 2 of 34)	None
Erdil et al. (2013)[28]	Pre: 33.6 ± 3.8 Post: 76.1 ± 5.7 Change: +42.5	Pre: 8.00 ± 0.7 Post: 0.50 ± 0.7 Change : -7.5	–	Mild metatarsalgia (25%; 3 of 12)	None
Kim et al. (2012)[29]	Post: 90[c,e]	–	–	Nonunion (8%; 4 of 51), malalignment (8%; 4 of 51), delayed union (2%; 1 of 51), metatarsalgia (10%; 5 of 51), interphalangeal joint pain (4%; 2 of 51)	Revision because of nonunion (4%; 5 of 132)
Raikin et al. (2007)[30]	Pre: 36.1 (19 to 62)[d] Post: 83.8 Change: +47.7	Post: 0.7	–	Screw removal (7%; 2 of 27)	None
Simons et al. (2015)[31]	–	Post: 1.0 (0 to 10)	FFI Post: 13.8 (0 to 81.0)	Nonunion (4%; 5 of 132), plate removal due to persistent pain or infection (11%; 15 of 132)	Revision because of nonunion (4%; 5 of 132)
Voskuijl and Onstenk (2015)[32]	Post: 77 ± 18[b]	–	–	Nonunion (12%; 7 of 58), malunion (2%; 1 of 58), metatarsalgia (9%; 5 of 58), complex regional pain syndrome (2%; 1 of 58)	Revision arthrodesis (14%; 8 of 58) because of nonunion (n = 7) and malunion (n = 1)
DeFrino et al. (2002)[34]	Pre: 38 (20 to 62) Post: 90 (74 to 100)[b] Change: +52	–	–	Deep venous thrombosis requiring anticoagulation therapy (10%; 1 of 10)	None

Table 5. (Continued)

Study	AOFAS-HMI *(points)*	VAS pain[a] *(points)*	Other[a] *(points)*	Complications	Revisions
van Doeselaar et al. (2010)[36]	–	Post: 0.5 (0 to 7.9)[c]	FFI Pre: 34 (0 to 80)[c] FFI Post: 5 (0 to 50)[c] Change: -29	None	None
Aas et al. (2008)[33]	Post: 74 ± 15 (23 to 90)	Post: 1.0 ± 2.3 (0 to 8.4)	–	Nonunion (10%; 4 of 39 [painful n=3; not painful n=1]) , implant removal (13%; 5 of 39)	Revision arthrodesis because of painful nonunion (8%; 3 of 39)
Ettl et al. (2003)[35]	Post: 53 (5 to 84)	Pre: 8.0 Post: 2.7 Change: -5.3	–	Superficial wound infection treated with oral antibiotics (16%; 6 of 38), numbness in dorsum of the hallux (8%; 2 of 38)	None
Wassink and van den Oever (2009)[37]	Post: 50 ± 12 (10 to 60)[f]	–	–	Nonunion (4%; 4 of 109), malunion (1%; 1 of 109), screw removal because of pain (78%; 85 of 109)	Revision arthrodesis (5%; 5 of 109) because of nonunion (n = 4) or malunion (n = 1)
Lombardi et al. (2001)[38]	Pre: 39.1 (10 to 70)[d] Post: 75.6 (22 to 90) Change: +36.5	–	–	Nonunion (14%; 3 of 21 [painful n = 2, not painful n = 1]), screw removal because of pain (10%; 2 of 21)	None
Chraim et al. (2016)[39]	Pre: 40.9 ± 18.8 Post: 79.3 ± 11.2 Change: +28.4	–	FFI Pre: 38 (0 to 80)[c] FFI Post: 8 (0 to 59)[c] Change: -30	Painless nonunion (7%; 4 of 60), implant removal (3.3%; 2 of 60), superficial wound infection treated with oral antibiotics (3%; 2 of 60)	None

[a] Unless otherwise stated, the values are given as the mean, with or without the standard deviation and/or range.
[b] Ten points are assigned to the range of motion of the MTP1 joint in the AOFAS-HMI, which is eliminated because of the arthrodesis, yielding a maximum of 90 points achievable. In this study, a modified AOFAS_HMI was used not including these 10 points, thereby resulting in a total amount of achievable points of 100 points in patients with an arthrodesis.
[c] The values are given as the median, with or without the range in parentheses.
[d] Retrospective assessment of preoperative values.
[e] A modified AOFAS-HMI score was used as described by Roukis et al.[65]
[f] A subjective modified AOFAS-HMI score was used by removing questions regarding first metatarsophalangeal and interphalangeal joint motion and stability, callosity formation and alignment of the hallux from the original AOFAS-HMI score[37].

Table 6. Primary and Secondary Outcomes of Studies Evaluating First Metatarsophalangeal Total Joint Replacement for Symptomatic Hallux Rigidus

Study	AOFAS-HMI[a] *(points)*	VAS pain[a] *(points)*	Other[a] *(points)*	Complications	Revisions
Gibson and Thomson (2005)[24]	–	Pre: 6.0 ± 2.0 Post: 2.7 ± 2.8 Change: -3.3	–	Prostheses with phalangeal component loosening (15%; 6 of 39), prosthesis with radiolucency on radiographs (21%; 8 of 39)	Prostheses revised because of loosening (15%; 6 of 39)
Daniilidis et al. (2010)[4]	Pre: 44.6 ± 7.2 Post: 82.5 ± 14.4 Change: +37.9	Pre: 7.0 ± 0.8 Post: 2.0 ± 1.7 Change: -5.0	–	Superficial wound infection treated with oral antibiotics (4%; 1 of 23), prostheses with radiolucent lines on radiographs (13%; 3 of 23), varus malalignment prosthesis causing metatarsalgia (4%; 1 of 23)	None
Gupta and Mallya (2008)[40]	Pre: 39.4 ± 12.0 Post: 76.7 ± 16.4 Change: +27.3	–	–	Varus malalignment prosthesis (5%; 1 of 21), prosthesis subluxation (5%; 1 of 21)	Prostheses revised because of subluxation (5%; 1 of 20)
Titchener et al. (2015)[55]	Pre: 41.4 (27 to 78) Post: 91 (37 to 100) Change: +50	–	–	Intraoperative metatarsal/phalangeal fractures treated with cerclage wires (11%; 8 of 75) , prosthetic loosening or progressive radiolucency (15%; 11 of 75), prosthetic fracture (3%; 2 of 75), dislocation (3%; 2 of 75), deep infection (1%; 1 of 75), varus malalignment of prosthesis (1%; 1 of 75), persistent hallux pain (1%; 1 of 75)	Prostheses required revision or awaiting revision (24%; 18 of 75) (including conversion to arthrodesis n = 5, revision of phalangeal component n = 5, revision of total prosthesis n = 2, removal of phalangeal component n = 2, removal of entire prosthesis n = 1, waiting for revision n = 3
Erkocak et al. (2013)[46]	Pre: 42.7 (36 to 59) Post: 88.5 (64 to 98) Change: +45.8	Pre: 7.4 Post: 1.9 Change: -5.5	–	Metatarsal fracture treated conservatively (4%, 1 of 26), superficial wound infection with oral antibiotics (4%, 1 of 26), prostheses with radiolucency (8%, 2 of 26)	None
Horisberger et al. (2016)[43]	Pre: 54.8±16.6 (0-80) Post: 83.5±11.8 (58-95) Change: +28.7	Pre: 5.9 ±1.6 (3-9) Post: 1.2 ± 1.6 (0-5) Change: -4.7	–	Painful arthrofibrosis (17%, 5 of 29), persistent pain (10%, 3 of 29), prosthesis subluxation (3%, 1 of 29), varus instability of prosthesis (3%, 1 of 29), varus malalignment of prosthesis (3%, 1 of 29)	Prostheses converted to arthrodesis (14%, 4 of 29 [because of painful arthrofibrosis, n = 3, and dorsal subluxation, n = 1]), in situ prosthetic revision involving lateral release and soft-tissue reconstruction (7%, 2 of 29)

Table 6. (Continued)

Study	AOFAS-HMI[a] *(points)*	VAS pain[a] *(points)*	Other[a] *(points)*	Complications	Revisions
Wetke et al. (2012)[41]	–	Pre: 7.9 (0.9 to 9.5) Post: 2.1 (0 to 6.1) Change: -5.8	–	None	None
Omonbude and Faraj (2004)[45]	Pre: 43.1 Post: 95.3 Change: +52.2	–	–	Prosthetic subluxation and loosening (7%, 1 of 14), superficial wound infection (7%, 1 of 14)	Prosthesis converted to arthrodesis because of loosening (7%, 1 of 14)
McGraw et al. (2010)[44]	Pre: 56 (39 to 64)[b] Post: 72 (15 to 100)[b] Change: +16	–	–	Prosthetic loosening (5%, 3 of 63), prosthetic dislocation (2%, 1 of 63), deep infection (2%, 1 of 63), prosthetic subsidence and loosening phalangeal component (56%, 35 of 63), prosthetic subsidence (57%, 36 of 63) and loosening metatarsal component (60%, 38 of 63)	Prostheses converted to arthrodesis (6%, 4 of 63) because of loosening (n = 3) and dislocation (n = 1)
Arbuthnot et al. (2008)[42]	Pre: 36.0 ± 10.8 Post: 87.0 ± 10.6 Change: +51[c]	–	–	Wound problems in toe (7%, 3 of 42), Morton neuroma of toe (7%, 3 of 42), osteoarthritis of first metatarsocuneiform joint (2%, 1 of 42), osteoarthritis of sesamoid (2%, 1 of 42), plantar fasciitis (2%, 1 of 42), radiographic evidence of prosthetic loosening (10%, 4 of 42)	Prosthesis revised because of loosening (2%, 1 of 42)
Barwick and Talkhani (2008)[47]	Post: 80 (49 to 95)[b]	–	–	Superficial wound infection treated with antibiotics (4%, 1 of 24), complex regional pain syndrome that resolved with mobilization (4%, 1 of 24), radiographic evidence of prosthetic malalignment (17%, 4 of 24)	Prostheses revised (13%, 3 of 24) because of persistent pain (n = 1) or malpositioning (n = 2)
Brewster et al. (2010)[48]	Post: 74.2 ± 17.5 (9 to 100)	–	–	Prosthesis loosening (3%, 1 of 32), persistent pain (3%, 1 of 32), prosthetic fragmentation (3%, 1 of 32), poor range of motion requiring intervention (3%, 1 of 32), transfer metatarsalgia (6%, 2 of 32)	Prosthesis converted to arthrodesis (6%, 2 of 32) because of loosening (n = 1) or persistent pain (n = 1)
Chee et al. (2011)[49]	Post: 83.7	–	–	Superficial wound infection (2%, 1 of 41), prosthetic dislocation (2%, 1 of 41), prosthetic loosening and subsidence (7%, 3 of 41), increasing radiolucency of phalangeal component (from 2% [1 of 41] to 47% [9 of 19] and metatarsal component (from 5% [2 of 41] to 26% [5 to 19] from 1 year to 3 years of follow-up	Prostheses converted to arthrodesis (5%, 2 of 41) because of dislocation (n = 1) or loosening (n = 1), prosthesis revised (5%, 2 of 41) because of loosening (n = 1) or pain (n = 1)

Table 6. (Continued)

Study	AOFAS-HMI[a] *(points)*	VAS pain[a] *(points)*	Other[a] *(points)*	Complications	Revisions
Dawson-Bowling et al. (2012)[50]	Post: 61.3 (18 to 100)	–	Post: Physical 48.6 (27.6 to 58.7) Mental 52.2 (19.5 to 62.2)	Prosthetic fracture (6%, 2 of 31), prosthetic dislocation (3%, 1 of 31), prosthetic loosening and/or subsidence (52%, 16 of 31)	Prostheses failed (26%, 8 of 31), converted to excisional arthroplasty (n = 3), converted to arthrodesis (n = 2), revised to cemented MOJE implant (n = 3)
Fadel et al. (2005)[51]	Post: 85.4 (59 to 100)	–	–	Deep infection requiring excision of prosthesis (7%, 1 of 14), persistent pain requiring exploration (7%, 1 of 14)	None
Ibrahim and Taylor (2004)[52]	Post: 83 (62 to 95)	–	FFI Post: 7.5 (0 to 56)	Prosthetic dislocation (18%, 2 of 11), persistent pain (9%, 1 of 11), prosthetic subsidence (18%, 2 of 11)	None
Nagy et al. (2014)[53]	Post: 72 ± 19 (35 to 98)	–	FFI Post: 27 ± 26 (0 to 94)	Superficial wound infection treated with oral antibiotics (3% 1 of 31), prosthetic fracture (3% 1 of 31), prosthetic loosening (10% 3 of 31), persistent pain (3% 1 of 31)	Prosthetic failure (16% 5 of 31) followed by revision (n = 2, including 1 failure due to prosthetic fracture and 1 due to prosthetic loosening) or conversion to arthrodesis (n = 3, including 2 failures due to loosening and 1 due to persistent pain)
Sinha et al. (2010)[54]	Post: 62 (10 to 82)	–	–	Persistent pain requiring revision surgery (13%, 2 of 15), radiographic loosening of the phalangeal and metatarsal components (93% [14 of 15] and 87% [13 of 15], respectively)	Conversion to arthrodesis because of progressive pain (13%, 2 of 15)

[a] Unless otherwise stated, the values are given as the mean, with or without the standard deviation and/or range.

[b] The values are given as the median.

Table 7. Comparison of the AOFAS-HMI score and VAS Pain Scores Between Arthrodesis and Total Joint Replacement in Preoperatively and Postoperatively

AOFAS-HMI score *(points)*	**Arthrodesis[a]**	**Total Joint Replacement[a]**	**P value[b]**
Preop.	38.54 ± 2.46	47.42 ± 6.82	<0.0001*
Postop.	82.38 ± 4.42	85.15 ± 9.39	<0.0001*
Treatment Effect	43.84 ± 5.46	37.73 ± 15.87	<0.0001*
P value[c]	<0.0001*	<0.0001*	
VAS Pain score *(points)*	**Arthrodesis[a]**	**Total Joint Replacement[a]**	**P value[b]**
Preop.	7.24 ± 1.00	6.69 ± 0.68	<0.0001*
Postop.	0.68 ± 0.28	2.03 ± 0.54	<0.0001*
Treatment Effect	6.56 ± 1.25	4.65 ± 0.84	<0.0001*
P value[c]	<0.0001*	<0.0001*	

[a] The values are given as the mean and the standard deviation.
[b] Arthrodesis vs. total joint replacement.
[c] Preoperative vs. postoperative.
* A P value <.05 was considered as statistically significant.

DISCUSSION

The aim of the present systematic review was to use the literature to provide, on the basis of high-quality studies, an answer to the question whether arthrodesis or total joint replacement of the first metatarsophalangeal joint results in the best clinical outcome in patients with a symptomatic hallux rigidus. Our results showed that arthrodesis is more effective for improving clinical outcome and decreasing pain as measured with the AOFAS-HMI and the VAS pain score. Nevertheless, both interventions improved outcomes compared with the preoperative status.

The AOFAS-HMI score is an instrument that is used to measure outcome in patients with complaints related to the hallux and includes questions about pain and function and includes a physical examination [15,56]. Although the postoperative AOFAS-HMI score after total joint replacement was significantly higher than that after arthrodesis (p <0.0001), the treatment effect of arthrodesis was greater because the preoperative AOFAS-HMI score for patients who underwent arthrodesis was significantly lower than that for patients who underwent total joint replacement (i.e., patients who were more impaired as measured with the AOFAS-HMI were more likely to receive an arthrodesis than a total joint replacement). This greater treatment effect was observed despite a difference in total achievable amount of points. Ten points are allocated to the range of motion in the first metatarsophalangeal joint in the AOFAS-HMI; however, as motion is eliminated after an arthrodesis, the maximum achievable postoperative score is 90 points [15]. Therefore, although the direct comparison of total joint replacement and arthrodesis is unfair because of the difference in achievable score and the significantly lower preoperative score in the arthrodesis group, arthrodesis seems to be superior to total joint replacement for improving AOFAS-HMI score on the basis of the greater treatment effect.

Similarly, the pain-reducing effect of arthrodesis was significantly greater than that of total joint replacement when assessed according to the VAS pain score, which is a generic, simple and frequently used instrument to assess the severity of pain in patients with osteoarthritis [57,58]. This difference in pain-reducing effect between the 2 interventions might explain the greater treatment effect of arthrodesis as observed with the AOFAS-HMI score as 40 points are assigned to the item of pain in that scoring system [15].

The significantly higher rate of intervention-related complications might be a logical explanation for the lower treatment effect of total joint replacement. An unacceptably high rate of prosthesis-related complications was observed (26.3%), with the majority due to prosthesis loosening causing instability and pain during gait (20.9%) [4,24,40,42,44-46,48-50,52-55]. Interestingly, the highest rates of prosthetic loosening were observed in studies with the longest follow-up, indicating a limited survival of the investigated prostheses in the intermediate term, which seems to further decrease over time; the longest follow-up duration was 81 months [44,49,50,53-55].

In contrast, the most frequently reported arthrodesis-related complications were pain requiring hardware removal (16.2%) and nonunion or delayed union (6.6%) [25,27,30,31,33,37-39]. It should be noted that the majority of these implant-related complications were observed in 1 study, in which screw removal was required following 85 (78%) of 109 arthrodesis [37]. By eliminating the results of that study, hardware removal was only required in 5.8% of the patients, yielding a total rate of arthrodesis-related complications of 13.6%. In addition, approximately 20% of patients had an asymptomatic nonunion that did not require any further treatment [25-27,33,38,39].

It is important to keep in mind that implant removal or repeat arthrodesis in patients with a painful nonunion results in the elimination of pain and a long-lasting fused, stable, painless first metatarsophalangeal joint [25,26,31,33,37]. Such a long-lasting treatment effect is not evident for a total joint replacement, as indicated by the unacceptably high frequency of prosthesic loosening, subluxation, and fracturing [4,24,40,42,44-50,52-55]. This high rate of complications was associated with an unacceptably high revision rate of 11% in the intermediate term, which is even expected to increase further over time. However, it should be noted that only a few prosthesis-related complications were reported for the Roto-Glide and METIS prosthesis, although only intermediate-term results were reported (at 3.1 years and 49.5 months , respectively) and more studies with longer follow-up are needed to confirm whether these prostheses are associated with a lower rate of complications [41,43]. Thus, in addition to providing clinical improvement, arthrodesis was found to be superior to total joint replacement in terms of the rates of complications and revisions and the longevity of the intervention.

Unfortunately, we were not able to investigate which of the interventions yields the best outcome as assessed with the FFI (a self-administered questionnaire used to assess foot complaints in terms of pain and disabilities [16,36]) or the SF-36 (a commonly used questionnaire to determine quality of life [17]). None of the total joint replacement studies provided both the preoperative and postoperative values of these scoring systems, making a comparison impossible. Therefore, it remains unknown whether an arthrodesis is also superior for improving foot function and quality of life compared with total joint replacement as assessed with those questionnaires.

To our knowledge, the present report is the first systematic review that has quantitatively analyzed clinical outcomes after arthrodesis and total joint replacement of the first metatarsophalangeal joint on the basis of study quality. Our results showed that arthrodesis is superior to total joint replacement on the basis of clinical outcomes, complication rates and revision rates. Despite these valuable findings, we acknowledge that the present review has some limitations. It should be noted that only a limited number of studies (6 arthrodesis and 7 total joint replacement studies) fulfilled the criteria for pooling of results. The major limiting factor of included studies was study design as most of the included studies were retrospective cohort studies or case series, and it is known that those study designs are more prone for bias. Nevertheless, they are of substantial clinical value in the field of orthopaedic surgery and should be considered [59]. Therefore, a quality-assessment tool was used to assess the risk of bias of included cohort studies and case series. Only studies at low risk of bias were included in the pooling of results, which was contrary to previous reviews in which study quality was determined on the basis of the level of evidence [11,14]. However, in our opinion, level of evidence is an inappropriate method for considering pooling of results of individual studies as studies with high level of evidence (i.e. RCTs) are not necessarily at a low risk of bias. Therefore, a low risk of bias was the major determinant for inclusion of an individual study in the quantitative analysis.

Another potential limitation of this review was the use of the AOFAS-HMI score as a primary outcome measure. An outcome instrument must be reliable, valid, and responsive to change before it should be clinically applied [56]. The FFI and SF-36 are validated, reliable, and responsive for the assessment of general health in patients with foot and ankle complaints [16,60,61]. Although the AOFAS-HMI score is reliable and responsive [61,62], only parts seem to be valid resulting in uncertainty about the validity of the whole score system [62-64]. In addition, the AOFAS-HMI score is less suitable for the comparison of any other type of treatment with arthrodesis as the 10 points that are assigned to range of motion of the first metatarsophalangeal joint which are eliminated after an arthrodesis. Nevertheless, we decided to include studies that evaluated this outcome score as it is the most commonly used scoring system [14,56].

A last point to bear in mind is the relatively short duration of follow-up in the included studies. Especially for total joint replacement studies, it is highly relevant to obtain further insight in prosthesis survival and clinical outcome over the long-term as the present systematic review clearly showed unacceptable prosthesis survival in the intermediate term, which is expected to decrease further over time. On the basis of their intermediate-term results, several authors of included studies restricted, discontinued, or no longer recommended the use of the types of prostheses in their original studies [43,47,50,53-55]. However, the results of long-term follow-up studies are needed and should be considered in the choice of intervention as most patients with hallux rigidus are relatively young and active and therefore need a long-lasting intervention that fulfils their demands.

In conclusion, the present systematic review showed that a first metatarsophalangeal joint arthrodesis is superior to total joint replacement for improving clinical outcome and decreasing pain in patients with symptomatic hallux rigidus. In addition, arthrodesis is associated with lower rates of procedure-related complications and revisions compared with total joint replacement at intermediate-term follow-up, with a further increase in prosthesis-related complications and revisions being expected over time. On the basis of these results, we recommend arthrodesis as the gold-standard treatment for patients with symptomatic, end-stage hallux rigidus. Nevertheless, the performance of high-quality studies investigating clinical outcome with validated scoring systems is highly encouraged to further strengthen the evidence regarding the treatment of hallux rigidus.

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SUPPLEMENTARY FILES

Appendix 1

Search strategy MEDLINE Pubmed

1. "Hallux" [Mesh]
2. "Hallux Rigidus" [Mesh]
3. "Hallux Limitus" [Mesh]
4. Hallux Rigidus
5. Hallux Limitus
6. First metatarsophalangeal joint
7. Metatarsophalangeal
8. 1 or 2 or 3 or 4 or 5 or 6 or 7
9. "Osteoarthritis" [Mesh]
10. Osteoarthritis
11. Arthrosis
12. 9 or 10 or 11
13. "Arthroplasty Replacement" [Mesh]
14. Total joint prosthesis
15. Total joint replacement
16. Total joint arthroplasty
17. Joint implant
18. 13 or 14 or 15 or 16 or 17
19. "Arthrodesis" [Mesh]
20. Arthrodesis
21. Joint fusion
22. 19 or 20 or 21
23. 8 and 12 and 18 and 22

Appendix 2 - Data-Extraction Form

Study Characteristics									
Author *(yr)*	**Study Design**	**Level of Evidence**	**Indication**	**Operation**	**Type of Prosthesis**	**Type of Arthrodesis**	**No. of Patients (M/F)**	**No. of Feet (L/R)**	**Age *(yr)***

Study Characteristics				
Author *(yr)*	**Duration of Follow-up *(mo)***	**Complications**	**Revisions**	**Specific information**

Primary Outcomes				
Author (Intervention)	**AOFAS-HMI ***	**VAS Pain***	**FFI score***	**SF-36 score***
	Preoperative: Postoperative: Δ:	Preoperative: Postoperative: Δ:	Preoperative: Postoperative: Δ:	Preoperative: Postoperative: Δ:
	Preoperative: Postoperative: Δ:	Preoperative: Postoperative: Δ:	Preoperative: Postoperative: Δ:	Preoperative: Postoperative: Δ:

*Expressed as the mean, standard deviation, and range.

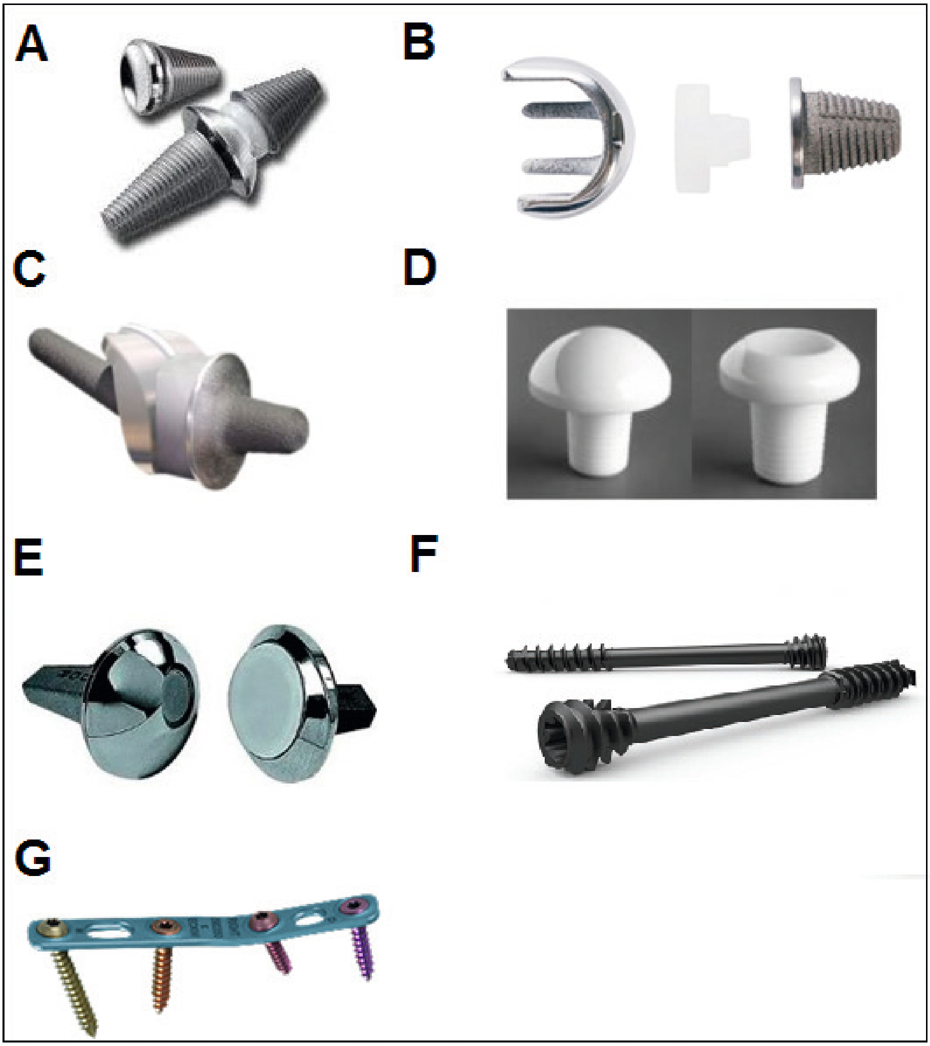
2

Appendix 3 – Risk of Bias Tool for Cohort studies and Case Series, adapted from Rangel et al.[20]

	1. External Validity ***2 Yes - Low*** ***<2 Yes – High***		***2. Selection Bias*** ***≥4 Yes – Low*** ***<4 Yes – High*** ***Comparative study:*** ***≥6 Yes – Low*** ***<6 Yes – High***						*Only applicable for comparative studies*	*Only applicable for comparative studies*	
Author (Year)	*Number of participating centres described? – Yes/No*	*Number of participating surgeons described? – Yes/No*	*Was the patient population from which cases were selected adequately described? – Yes/No*	*Diagnostic criteria used to identify cases clearly described? - Yes/No*	*Inclusion and/ or inclusion criteria clearly described? – Yes/No*	*Numbers and reasons for non-attenders given? – Yes/No*	*Age mean and range given for the participants? – Yes/No*	*Outcome variables presented with appropriate statistical ranges (SD's, SEM's)? – Yes/No*	*Patient demographics between both groups comparable? - Yes/No*	*Authors describe how patients were chosen into treatment group? – Yes/No*	**Risk of Selection Bias – High/Low**

Appendix 3 – (Continued)

3. Performance Bias ***≥2 Yes – Low <2 Yes – High*** ***Comparative study:*** ***≥3 Yes – Low <3 Yes – High***			*Only applicable for comparative studies*		***4. Detection Bias*** ***2 Yes - Low*** ***<2 Yes – High***			***5. Attrition Bias*** ***≥2 Yes – Low*** ***<2 Yes – High*** ***Retrospective studies:*** ***1 Yes - Low*** ***0 Yes - High***	*Not applicable for retrospective studies*	*Not applicable for retrospective studies*		***6. Reporting bias*** ***1 Yes - Low*** ***0 Yes – High***	
Is the surgical technique adequately described? *– Yes/No*	*Is there any mention of an attempt to standardize operative technique?* *– Yes/No*	*Is there any mention of an attempt to standardize perioperative care?* *– Yes/No*	*Were patients in each group treated along similar timelines?* *– Yes/No / Unclear*	**Risk of Performance Bias – High/Low**	*Standardized assessment tools for assessing primary outcomes were used?* *– Yes/No*	*Outcome assessors were blinded for type of intervention (if possible) or other persons than the treating surgeons?* *– Yes/No*	**Risk of Detection Bias – High/Low**	*Are drop-out rates/numbers of non-included participants stated?* *– Yes/No*	*Missing data adequately addressed?* *– Yes/ No/ Not applicable*	*Analysis by intention to treat?* *-Yes/No/ Not applicable*	**Risk of Attrition Bias – High/Low**	*All outcomes and comparisons described in Methods section reported and discussed* *– Yes/No*	**Risk of Reporting Bias – High/Low**



Appendix 4 – Overview of Total Joint Implants and Arthrodesis Constructs
A TOEFIT-PLUS (Smith & Nephwew), B METIS (Integra Life Sciences), C Roto-Glide (Implants International), D MOJE ceramic press-fit (Moje Keramik-Implantate), E Bio-Action (MicroAire Surgical Instruments), F Fixos 2 compression screws (Stryker), G HALLU-Lock MTP arthrodesis system (Integra Life Sciences)

CHAPTER 3

GAIT ANALYSIS OF FOOT COMPENSATION IN SYMPTOMATIC HALLUX RIGIDUS PATIENTS

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Key words

Hallux rigidus, Kinematics, Plantar pressure, First metatarsophalangeal joint, Multisegmental foot model

Abbreviations

HR	hallux rigidus	OFM	Oxford Foot Model
HC	healthy controls	ROM	range of motion
MTP1	first metatarsophalangeal		

ABSTRACT

Background: Compensatory motion of foot joints in hallux rigidus (HR) are not fully known. This study aimed to clarify the kinematic compensation within the foot and to detect whether this affects plantar pressure distribution.

Methods: Gait characteristics were assessed in 16 patients (16 feet) with HR and compared with 15 healthy controls (30 feet) with three-dimensional gait analysis by using the multi-segment Oxford Foot Model, measuring spatio-temporal parameters, joint kinematics and plantar pressure.

Results: HR subjects showed less hallux plantar flexion during midstance and less hallux dorsiflexion during push-off, while increased forefoot supination was detected during push-off. No significant differences in plantar pressure were detected. Step length was significantly smaller in HR subjects, while gait velocity was comparable between groups.

Conclusions: HR significantly affects sagittal hallux motion, and the forefoot compensates by an increased supination during push-off. Despite this kinematic compensatory mechanism, no significant differences in plantar loading were detected.

INTRODUCTION

Hallux Rigidus (HR) is a degenerative condition of the first metatarsophalangeal (MTP1) joint and characterized by pain while walking, joint swelling and difficulties in wearing shoes. Restricted joint motion and gait alterations were observed during physical examination [1]. The etiology seems to be multifactorial, with female gender, aging, interphalangeal hallux valgus, trauma history and a positive family history being predisposing factors [1,2]. HR negatively affects quality of life, since patients experience more difficulties with performing daily tasks and recreational activities [3,4].

When conservative treatment failed, surgical treatment is often necessary. MTP1 joint arthrodesis, hemiarthroplasty, resection arthroplasty and total joint arthroplasty have been utilized for HR. Arthrodesis seems to be superior in terms of patient reported outcome and treatment longevity of these options [5-7]. However hallux motion is eliminated after an arthrodesis, which subsequently affects spatiotemporal gait parameters [8,9] and causes aberrations in foot and ankle kinematics [10]. It is not fully known which joints compensate for the altered MTP1 motion after these interventions, which deems to be important in preoperative planning. It is likely that surgery, after which motion of these joints is necessary, results in poorer postoperative outcomes when these joint are osteoarthritic as well. Therefore, it is essential to know how HR affects foot kinematics before investigating this hypothesis, since it is reasonable to assume that most compensatory motion will take place in the foot.

Previous pedobarographic studies showed an increased loading of the lateral plantar zones and the lesser metatarsal heads in patients with HR (i.e. “lateral loaders”), most likely to avoid the painful hallux [11-13]. Although a decrease in lateral loading was expected after surgery, this effect was not observed after cheilectomy [14], and MTP1 arthrodesis [8,15]. In contrast, even increased loading of the lateral metatarsal heads was observed after MTP1 total joint arthroplasty in some [15,16], but not all studies [17,18]. Increased loading of the lateral plantar zones in HR suggests a compensatory motion in the foot and ankle in order to facilitate motion while avoiding the painful and degenerative hallux during push-off. Three-dimensional motion capturing provides a possibility to elucidate which joints facilitate this compensatory mechanism. A decreased sagittal hallux ROM was observed in two kinematic studies comparing HR patients with healthy controls [19,20]. In addition, diminished forefoot plantar flexion were detected in pre-swing, while decreased ankle motion during the whole gait cycle was observed [19,20]. Although two studies addressed multi-segment foot motion in HR subjects [19,20], no former study evaluated segmental foot and ankle kinematics together with plantar pressures.

It is assumed that surgeons may benefit from further knowledge which joints compensate for the loss of hallux motion in HR subjects. Joint preserving or replacing surgery should be advised to a subject with a less functioning compensatory mechanism, while an arthrodesis can be advised in subjects with a proper functioning compensatory mechanism. To investigate whether this is true, the compensatory mechanism should be elucidated first. Therefore, the aim of this study was to characterize multi-segmental foot and ankle kinematics in HR subjects by using the 4-segment Oxford Foot Model (OFM), and combine segmental kinematics with plantar pressure distributions in order to identify which foot joints are responsible to compensate for the loss of motion of the MTP1 joint in HR.

It was hypothesized that patients with HR have an increased forefoot supination or hindfoot inversion resulting in increased plantar pressures beneath the lesser metatarsals, due to the decreased motion in the MTP1 joint.

METHODS

Study population

Patient files of the Departments of Orthopedic surgery were screened for eligible patients. Inclusion criteria were a symptomatic, radiologically confirmed HR, in which conservative therapy failed and surgery was planned. Patients with medical conditions affecting foot and ankle kinematics (e.g. inflammatory joint diseases or arthrodesis of foot joints) were not eligible for inclusion. Additional exclusion criteria were the inability to walk more than 100m barefoot without assistance. Patients were compared to healthy controls without a medical history of foot complaints or resulting in an abnormal gait pattern. Sixteen HR subjects (16 feet) were included and compared to 15 healthy controls (30 feet). This study was approved by the local ethics committee and patients provided their written informed consent.

Motion analysis

Motion capture was conducted using a Vicon system (*Vicon Motion Systems, Oxford, UK*), consisting of 8 infrared cameras (six MX3 and 2 T20 running at 200Hz). Subjects were asked to walk on a ten-meter platform equipped with a forceplate (*AMTI OR6 Series, Advanced Mechanical Technology Inc., Watertown, NY, USA)*. Dynamic plantar pressures were measured using a pressure plate (*High Speed Advanced Footscan® System, RSscan International, Paal, Belgium),* which was mounted on top of the forceplate.

Subject height, weight, knee and ankle width and leg length were measured and markers were placed by two trained researchers at specific bony landmarks according to the OFM guidelines [21-23]. One static trial was performed in which the markers were calibrated and subject-specific axes were calculated. Next, subjects were asked to walk at a comfortable speed and 15 recordings with the subject cleanly striking the pressure plate were obtained.

Data processing

Marker tracking and labelling were performed by using Vicon Nexus 1.8.5 and further processed with MATLAB (version R2012A, The MathWorks Inc, Natick, MA, USA). Gait velocity, stance time, step length and step width were calculated as previously reported [10]. Kinematic waveforms and ROM in push-off were gained for the hallux-forefoot, forefoot-hindfoot and hindfoot-tibia segment in the sagittal plane and for the forefoot-hindfoot and hindfoot-tibia segment in the frontal plane after time normalisation of a stride (i.e. 0-100%). Gait cycle was divided in stance (i.e. 0-62% of the gait cycle), consisting of loading response (0-12%), midstance (13-31%), terminal stance (32-50%) and pre-swing (51-62%) and swing phase (i.e. 63-100% of the gait cycle) consisted of initial swing (63-75%), midswing (76-87%) and terminal swing (88-100%) [24]. ROM in push-off was identified as the difference between maximal and minimal intersegmental angle in time interval 45-75% of the gait cycle. Intersegmental ROM was averaged for at least 6 trials per subject, which has proven to be a sufficient number of trials to achieve high intraclass correlation coefficients for the OFM [25].

The force plate was used to identify initial contact and toe-off (i.e. onset of a vertical ground reaction force exceeding and below 20 Newton respectively). Off-set correction was performed for the intersegmental kinematic waveforms, by summing the intersegmental angles at timepoint 0-100 and subsequently divided by 100 to gain the value of off-set correction.

The foot was automatically divided in 10 anatomical zones by Footscan® 7.0 Gait 2nd generation software to investigate plantar pressure. Inconsistencies in the automatic masking procedure were manually adjusted. The pressure-time integral (PTI) was calculated as previously described [26], by using the obtained force-time integrals and contacts areas. The PTI is the cumulative effect of pressure on a plantar area over time (i.e. area under the peak pressure-time curve) instead of summing the peak pressure per timeframe for an entire trial, and provides a representative value of the total load exposure of a plantar area during stance.

Statistical analysis

Graphpad Prism 8.3 (Graphpad Software Inc., San Diego, USA) was used for statistical analysis. Differences in patients demographics, temporal-spatial parameters, intersegmental ROM and PTI between groups were compared by using the non-parametric Mann-Whitney U test. Statistical Parametric Mapping (SPM; version M.0.4.5), a statistical approach which allows hypothesis testing on kinematic waveforms without the need of a priori data reduction, was performed to test for differences in intersegmental motion between groups. A SPM unpaired t-test was used. A *P*-value of less than .05 was considered as statistically significant.

RESULTS

Subject characteristics

Baseline subject characteristics showed that the HR group had a significant lower height (*P* =.015) and contained more female patients, as compared to healthy controls (see Table 1). No significant differences in age, weight, foot side analyzed and body mass index were detected between groups.

Table 1. Subject characteristics.[a]

	Hallux Rigidus	Healthy Controls	*P* Value
No. of subjects (No. of feet)	16 (16)	15 (30)	
Age (Years)	63.7 ± 10.5 (40-79)	59.1 ± 5.0 (53-70)	0.137
No. (% of subjects) male	5 (31.3)	9 (60)	-
No. (% of feet) right side	8 (50)	15 (50)	-
Height (m)	1.68 ± 0.09 (1.55-1.85)	1.74 ± 0.09 (1.62-1.88)	0.015[b]
Weight (kg)	75.5 ± 18.5 (50.5-122.0)	83.0 ± 11.9 (56.5-98.2)	0.187
Body Mass Index (kg/m^2)	26.7 ± 5.9 (20.4-43.2)	27.4 ± 3.9 (20.2-33.3)	0.811

[a] Mean values and standard deviations with range in parentheses are presented.
[b] Significant difference between hallux rigidus and healthy controls $P < .05$

Temporal-spatial parameters

No significant differences in gait velocity, stance time and step width were detected between HR subjects and healthy controls (see Table 2). Step length (*P* =.002) was significant shorter in HR subjects.

Table 2. Temporal-Spatial parameters of gait for the hallux rigidus group and healthy controls.[a]

	Hallux Rigidus	Healthy Controls	*P* Value
Gait velocity (m/s)	1.05 ± 0.20 (0.64-1.44)	1.14 ± 0.19 (0.73-1.46)	0.160
Stance time (s)	0.71 ± 0.09 (0.59-0.91)	0.71 ± 0.11 (0.52-0.96)	0.980
Step length (m)	0.57 ± 0.06 (0.48-0.78)	0.64 ± 0.07 (0.49-0.76)	0.002[b]
Step width (m)	0.12 ± 0.05 (0.05-0.20)	0.13 ± 0.04 (0.07-0.20)	0.750

[a] Mean values and standard deviations with range in parentheses are presented.
[b] Significant difference between hallux rigidus and healthy control $P < .05$

Foot and ankle kinematics

Significant less hallux plantarflexion in midstance (*P* =.007) and dorsiflexion in pre-swing (*P* =.013) was observed in HR subjects (see Figure 1A). Less forefoot plantarflexion in initial swing (*P* =.046) and increased plantarflexion (*P* =.004) in terminal swing (see Figure 1B), and significant less hindfoot plantarflexion (*P*=.035) in loading response were observed in HR subjects (see Figure 1C).

Increased forefoot pronation during midstance (*P* =.012) and increased forefoot supination during pre-swing (*P* =.012) were detected in HR subjects (see Figure 1D). No statistically significant differences in frontal plane motion were observed between groups in the hindfoot-tibia segment (Figure 1E).

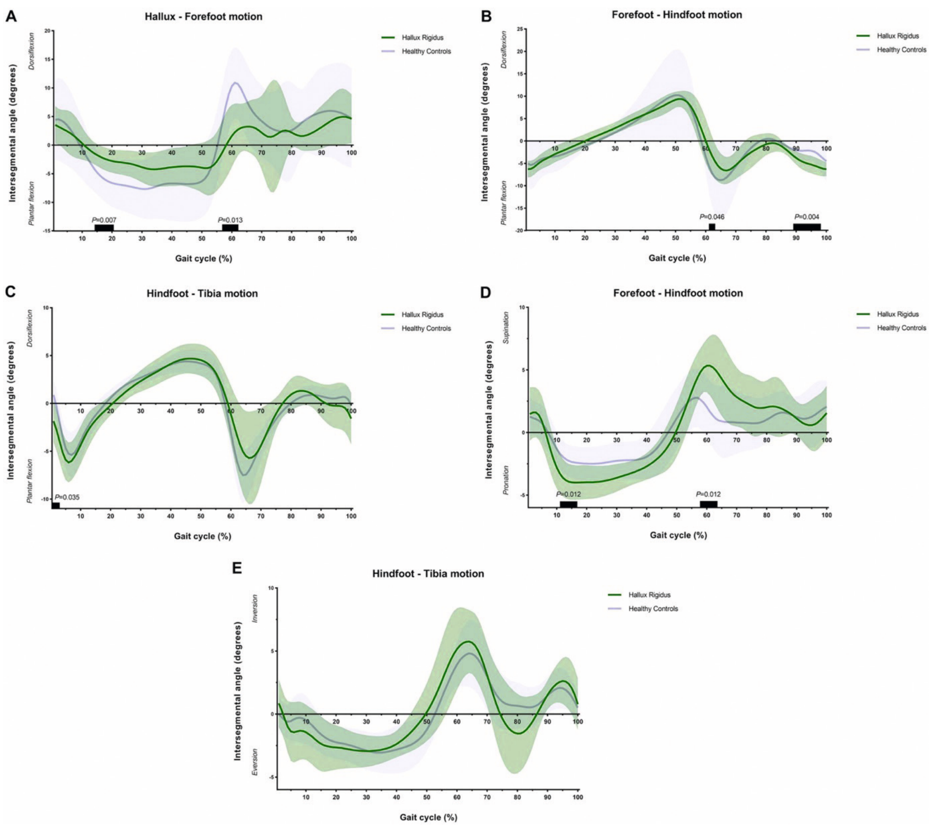

Figure 1. Averaged absolute joint angles in sagittal plane after off-set correction in the hallux-forefoot, forefoot-hindfoot and hindfoot-tibia segment (1A, 1B and 1C respectively) and in the frontal plane for the forefoot-hindfoot and hindfoot-tibia segment (1D and 1E respectively) during gait for the hallux rigidus group and healthy controls.

Intersegmental ROM during push-off

Hallux ROM (i.e. plantar/dorsiflexion) was significantly lower in HR subjects during push-off (*P*=.003, see Figure 2A). No significant differences in sagittal ROM were detected in the forefoot-hindfoot and hindfoot-tibia segment (see Figure 2B and 2C respectively). An increased ROM (i.e. supination/pronation) was present in the forefoot-hindfoot segment in HR subjects (*P*=.006, see Figure 2D), while no difference in frontal plane hindfoot-tibia intersegmental ROM (i.e. inversion/eversion) was detected between groups (see Figure 2E).

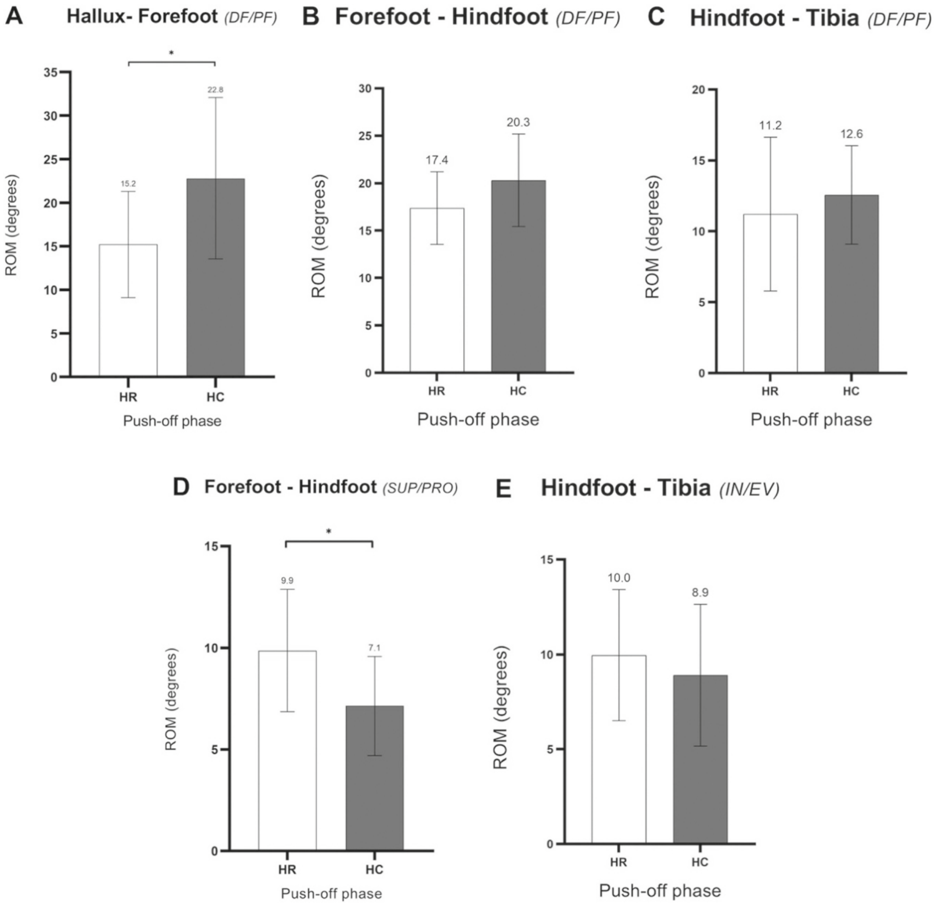

Figure 2. Intersegmental range of motion in the sagittal plane (A-C) and frontal plane (D-E) during gait for the hallux rigidus group and healthy controls, Abbreviations: ROM – range of motion, SUP – supination, PRO – pronation, IN – inversion, EV – eversion, HR – hallux rigidus, HC – healthy controls. *Indicates a significant difference in range of motion ($P < .05$).

Plantar pressure

No significant differences in PTI were detected between HR subjects and healthy controls in the 10 plantar zones of interest (see Figure 3).

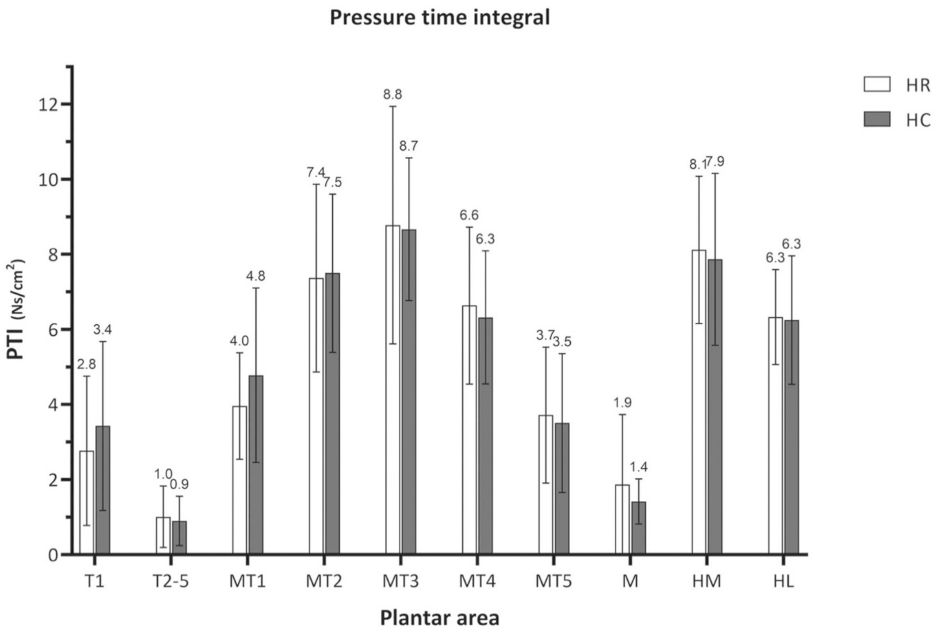

Figure 3. Pressure time integrals for the 10 anatomical areas of the foot for the hallux rigidus group and healthy controls. Abbreviations: PTI – Pressure Time integral, T1 - hallux, T2–5 - lesser toes, MT1–5 - metatarsal heads 1–5, M - midfoot, HM - medial heel, HL - lateral heel, HR – hallux rigidus, HC – healthy controls.

DISCUSSION

This study aimed to determine how the foot compensates for the loss of sagittal hallux motion in HR and how this subsequently affects plantar pressure. It was hypothesized that an increased forefoot supination or hindfoot inversion will compensate for the limited MTP1 motion in HR. As a consequence, increased plantar loading of the lesser metatarsals was expected.

As expected, HR significantly affects hallux sagittal plane motion. Less plantar flexion of the hallux in midstance and less hallux dorsiflexion in pre-swing were detected, where intersegmental ROM analysis confirmed this decreased hallux ROM during push-off. Additionally, the expected compensatory motion was found in the forefoot-hindfoot segment, where an increased forefoot supination was seen in HR during pre-swing. This result was confirmed with the intersegmental ROM analysis where a greater frontal ROM (i.e. increased supination/pronation) in the forefoot-hindfoot segment was present in the HR group. Additionally, some significant differences in sagittal motion in the forefoot-hindfoot in swing and hindfoot-tibia segment during stance were detected. However since these differences were small, it was concluded that these differences were not clinically relevant.

These results confirmed the hypothesis that the forefoot compensates for the loss of motion in MTP1 joint motion in HR. Canseco et al. also showed a significantly reduced hallux motion in HR subjects from pre-swing till midswing by using the 4-segment Milwaukee Foot Model. However, an increased forefoot supination during push-off was not seen in this study [20]. Kuni et al. also showed a significantly lower hallux ROM in HR subjects with the Heidelberg foot measurement measure when analyzing a whole stride [19]. Contrary to our results, HR subjects showed less forefoot frontal motion (i.e. supination/pronation) as compared to healthy controls in this study. Nawoczenski et al. showed a significant increase in dynamic MTP1 joint motion in HR subjects which underwent cheilectomy, but no healthy control group was reported in these studies [14]. A study in which arthrodesis was performed for HR showed that both the forefoot and hindfoot were responsible to compensate for the loss of MTP1 joint motion, due to a decreased hindfoot eversion during midstance followed by an increased forefoot supination during pre-swing [10]. Based on presented results and previous studies, it can be concluded that the forefoot is particularly important to compensate for a loss of motion in the MTP1 joint.

Based on the reduced hallux dorsiflexion and increased forefoot supination during stance an increased loading of the lateral plantar zones of the foot was expected. This hypothesis was based on previously reported studies were reduced MTP1 joint motion due to fusion resulted in unloading of the hallux and an increased lateral loading of the foot [10]. However, PTI values in this study showed no differences in plantar loading between HR subjects and controls and thereby did not support the stated hypothesis. Nawoczenski et al. evenly presented no significant differences in plantar loading between HR subjects and controls, although a (non-significant) decreased loading of the medial metatarsal heads was detected in symptomatic feet as compared to asymptomatic feet [14]. Zammit et al reported increased peak pressures beneath the hallux and lesser toes in HR subjects, while no differences beneath the metatarsals. Peak pressures were in our opinion less informative as compared to PTI values, since peak pressures represents the maximal load in an area under the foot during one step while PTI describes the cumulative effect of pressure over time in a certain area of the foot, and thus provides a value for the total load exposure of a foot sole area during one step [27].

A possible explanation for the absence of differences in plantar pressure distribution is that there is, although limited and painful, still enough motion in the MTP1 joint left and therefore plantar loading is not affected.

Regarding temporal-spatial parameters, a significant shorter step length in HR subjects was detected, while no significant differences in stance time and gait velocity were detected between groups. Canseco et al. evaluated stride length and reported a non-statistically significant but potentially clinically relevant difference in stride length between groups (i.e. HR 1.20±0.19 vs healthy control 1.29±0.10; p=0.053). The significant lower height of HR subjects in this study, and consequent shorter leg length, is the most plausible explanation for this difference in step length, although pain while walking might also result in a shorter step length. Gait velocities between subjects and controls were comparable with values reported by Canseco et al [28].

We acknowledge that this study had some limitations. Selection of an age- and gender-matched control group would have been more appropriate, since the healthy control group contained significantly more male subjects, and there was a non-significant mean difference in age of 4.6 years. As a result, the healthy control group had a significantly greater height, and it is known that age and height affect gait velocity, which subsequently strongly influences gait kinematics [29,30]. Since no statistically difference in gait velocity was detected, it was though that the difference in height did not significantly influence our results. However, although not statistically significant, it cannot be ruled out whether a difference in gait velocity of 0.09 m/s between groups was clinically relevant. In addition, some studies show a true age effect [31,32] and gender-specific differences [30,33] independent of gait velocity, so the non-significant difference in age and significant differences in sex distribution between groups might have influenced the presented results, although this true age-effect was not seen in other studies [34]. The relative small sample size might be a potential weakness of this study since no sample size was calculated before the start of the study, although these group sizes are common in this research area due to the relative extensiveness of measurements.

Despite these limitations, this study revealed important information regarding the compensatory mechanism of the foot for the loss of MTP1 motion in HR subject. Knowledge of this compensatory mechanism seems to be highly relevant for planning of surgical intervention. For example, it is reasonable to assume that an arthrodesis is a less suitable option for a subject with less frontal forefoot motion (i.e. less compensatory reserve), since a well-functioning compensatory mechanism is mandatory to restore gait for the complete loss of MTP1 joint motion in this intervention. In this situation, a MTP1 joint preserving (cheilectomy) or replacing method (prosthesis or hemiprosthesis), in which less compensatory motion is required, might be more suitable.

CONCLUSION

The forefoot compensates for the loss of motion MTP1 joint motion by an increase in supination. Although forefoot kinematics changed, no significant differences in plantar loading were detected. These results proved that the foot has the intrinsic capacity to compensate for the loss of MTP1 joint motion in HR and knowledge of this compensatory mechanism should be used in further research. These studies should focus on the hypothesis if patients with less compensatory capacity would benefit more from joint replacing interventions (i.e. in which it is thought that less compensatory motion is necessary), than from an arthrodesis (i.e. more compensatory motion is expected to be mandatory). Subsequently it would be interesting to investigate whether this 'foot-specific treatment' will improve patient satisfaction.

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CHAPTER 4

HALLUX RIGIDUS AFFECTS LOWER LIMB KINEMATICS ASSESSED WITH THE GAIT PROFILE SCORE

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Key words

Hallux rigidus, Kinematics, Gait analysis, Lower extremity, Gait Profile Score

Abbreviations

FFI	Foot Function Index
GVS	Gait Variable Score
MCID	Minimal Clinically Important Difference
MTP1	First Metatarsophalangeal
ROM	Range of Motion
GPS	Gait Profile Score
HR	Hallux Rigidus
MOXFQ	Manchester-Oxford Foot Questionnaire
PROM	Patient-Reported Outcome Measure

ABSTRACT

Background: Previous research showed that hallux rigidus (HR) affects foot and ankle kinematics during gait. It is unclear if HR affects lower limb kinematics as well.

Research question: Does HR affect lower limb kinematics, and if so, is gait deviation correlated with patient-reported outcome?

Methods: This was a retrospective case-control study, including 15 HR patients and 15 healthy controls who underwent three-dimensional gait analysis by using the Plug-in Gait lower body model. The Gait Profile Score (GPS), a gait index score describing gait deviation and composed out of nine Gait Variable Scores (GVS), and intersegmental range of motion of lower limb joints were assessed. Patient-reported outcome was assessed with the Foot Function Index (FFI) and Manchester-Oxford Foot Questionnaire (MOXFQ). Data were analysed with Student *t*-tests and Spearman rank correlations.

Results: HR significantly affects gait, reflected by a higher GPS in HR subjects as compared to healthy controls. Gait deviation was seen in ankle flexion ($GVS_{ankle\ flexion}$) and to a lesser extent in pelvic rotation ($GVS_{pelvic\ rotation}$). Interestingly, these differences were not detected when lower limb kinematics were evaluated by comparing the intersegmental ranges of motion of these joints. Positive correlations were present between patient-reported outcomes and GPS, especially functional subdomains, were positively correlated with GPS and $GVS_{ankle\ flexion}$.

Significance: This study demonstrated that HR, next to foot kinematics, additionally affects lower limb kinematics evaluated with an objective gait index score, i.e. GPS. The positive correlation between the GPS and patient-reported outcome can be seen as the first step in defining whether objectively measured gait indices can be used in considering surgery since most of the benefit of surgery will be expected in the patients with most gait deviation.

INTRODUCTION

Hallux rigidus (HR), also known as osteoarthritis of the first metatarsophalangeal (MTP1) joint, is the most common joint affected by osteoarthritis in the foot. The cause of HR is thought to be multifactorial, with rising prevalence and severity of HR with ageing [1]. Symptoms include pain, swelling, and reduced MTP1 joint range of motion (ROM), and activities requiring dorsiflexion as walking usually cause pain [1]. As a consequence, HR is known to reduce activity levels and quality of life [2].

Several studies showed that HR alters foot kinematics. Pain and osteoarthritic changes of the MTP1 joint decrease the required dorsiflexion of MTP1 joint during push-off [3,4]. As a consequence, patients avoid MTP1 dorsiflexion by hindfoot supination [1], and forefoot abduction [3]. Kuni et al. [4] additionally showed a decreased sagittal ankle ROM, although this was not observed in a study by Smith et al. [5].

It is expected that when the foot and ankle kinematics change, kinematics of proximal joints in the lower limb will be affected as well. These joints may compensate for the deviated foot and ankle motion in order to maintain efficient gait. This mechanism, i.e. that foot abnormalities result in a number of compensatory motions in proximal joints, was clearly reported in children with hemiplegic cerebral palsy by Stebbins et al [6]. In patients with hip, knee and ankle osteoarthritis it was observed that compensatory lower limb joint motions occur regardless of the affected joint [7]. In rheumatoid arthritis patients, decreased MTP1 dorsiflexion was correlated with increased knee and hip flexion [8].

Gait deviation is regularly evaluated by using three-dimensional motion capture analysis of gait to compute segmental and/or joint motion. The Gait Profile Score (GPS) has been recently developed to provide a single measurement of quality of an individual's gait pattern, based on lower limb kinematics [9]. GPS is calculated based on nine key kinematic Gait Variable Scores (GVS) [9]. GPS thereby represents a single measure of the quality of gait, which excludes subjectivity of choosing particular parameters of interest (i.e. joints/planes) for analysis, which often occurs in three-dimensional motion capture analysis [9]. The major advantage of gait indices as the GPS is that a large amount of gait data are reduced into a single index score and provide a data summary that more simply indicates asymmetry and the relative magnitude of deviation of the kinematic variables [9,10,11,12]. The GPS has been previously used to evaluate gait in multiple neurologic disorders as well as in joint hypermobility syndrome [9,13]. Recent studies showed that GPS and GVS seemed to be appropriate outcome measures for evaluating functional limitation during gait since there were significant correlations with functional subdomains of patient-reported outcomes [13] and clinical outcome measures [11,14].

Whether HR affects proximal joint kinematics has not been investigated before. Knowledge regarding the influence of HR on proximal joint motion and loading can be relevant, i.e. in the prevention of symptoms that occur due to overload of these joints and the timing of surgery.

Therefore, this study aims to investigate whether HR affects lower limb joints kinematics, assessed with the GPS and inter-segmental range of motion and if so, how gait deviation was correlated to patient-reported outcome. We hypothesized that HR would affect lower limb kinematics, reflected in higher GPS and GVSs as compared to controls. Especially, changed ankle and hip movement were expected, due to the stiff and painful MTP1 joint which will be avoided during stance. In addition, it was hypothesized that a more deviated gait, reflected in higher GPS and GVSs, was correlated with a worse patient-reported outcome, reflected in poor results in disabilities and/or walking subdomains in the validated patient-reported outcome measures (PROMs) Foot Function Index (FFI) and Manchester Oxford Foot Questionnaire (MOXFQ). The GPS was chosen because it provides a summary measure and quantifies the relative contribution of specific joint or planes of motion to the observed gait deviation [3,12] and is proven to be sensitive in assessing differences between a group with pathology and healthy controls [12].

METHODS

Study population

Patient files of the Department of Orthopedic Surgery of our institution were screened for eligible patients, between December 2015 and February 2018. Inclusion criteria were a symptomatic, radiologically confirmed degenerative osteoarthritis of the MTP1 joint (i.e. HR) of any grade, in which conservative treatment failed, and patients were subsequently referred for surgery. Subjects were excluded if they had any of the following conditions; diabetes mellitus, rheumatoid arthritis, gout, total knee or hip replacement, arthrodesis of foot joints, were not able to walk more than 100 meters with aids, gait abnormalities due to any neurological disorder and severe knee/hip osteoarthritis, or postural deviations in feet due to fractures. Regnauld classification of HR was used to grade degenerative changes of the MTP1 joint [15].

Overall, 15 HR subjects were compared to 15 healthy controls (i.e. 30 feet) without gait altering traumas or medical conditions (see Table 1). Written informed consent was provided by all subjects. The study was accepted by the local ethics committee.

Motion analysis

Gait analysis was conducted at the Human Movement Laboratory of our University by using a Vicon System (Vicon Motion Systems, Oxford, UK), comprising 8 infrared cameras (6 MX3 and 2 T20 running at 200 Hz). Two force plates (AMTI OR6 Series, Advanced Mechanical Technology Inc, Watertown, NY, USA) running at a frequency of 1000 Hz, were embedded in the walkway. Subjects' height, weight, leg length, and knee and ankle width were measured according to Vicon Plug-in Gait Product Guide. The placement of reflective markers was conducted according to the Plug-in Gait Lower Body Model and performed by two researchers who were experienced in working with the Plug-in Gait Lower Body Model to improve the reliability of the measurements [16]. First, a static trial was completed in an anatomically neutral position for model calibration and calculation of subject-specific joint axes. Subsequently, at least 15 dynamic walking trials in which the subject was cleanly striking the force plate were recorded while subjects were walking barefoot at self-selected speed across a 10-meter walkway.

Data processing

Marker tracking and labelling were performed by using Vicon Nexus 1.8.5 and further processed with MATLAB (version R2012A, The MathWorks Inc, Natick, MA, USA).

Ground reaction force data were used to identify initial contact and toe-off. Subsequently, stance (time between heel strike and toe-off), swing (time between toe-off and consecutive initial contact), and stride time (time between consecutive initial contact of same foot) were identified and used to calculate cadence. The definitions of gait velocity, step length, and width were previously described [17]. Stride length was defined as the distance between the heel markers of two subsequent heel strikes of the foot of interest. ROM was calculated for the seven phases of gait as defined by Perry et al. after time normalization of the gait cycle [18]. These seven phases of gait were the loading response (0-12%), midstance (12-31%), terminal stance (31-50%), preswing (50-62%), initial swing (62-75%), midswing (75-87%), and terminal swing (87-100%) [18].

Intersegmental ROM was calculated for the pelvis and hip in the sagittal plane (i.e. anterior/posterior tilt and flexion/extension, respectively), frontal plane (i.e. upward/downward obliquity and abduction/adduction, respectively) and transverse plane (i.e. protraction/retraction and internal/external rotation, respectively. Sagittal intersegmental ROM was calculated for the knee and ankle (i.e. flexion/extension and dorsiflexion/plantarflexion, respectively).

The GPS consists of nine predetermined GVSs, i.e. pelvic tilt, pelvic obliquity, pelvic rotation, hip flexion, hip abduction, hip rotation, knee flexion, ankle dorsiflexion and foot progression angle [9]. The GPS was calculated from the root mean square average of nine kinematic variables (i.e. GVS) [9]. The GVS is based on the root mean square difference between the patient's values and values of healthy controls for that particular variable [9].

The measurements of both legs of healthy controls were averaged into one number in all of the variables due to their dependency. The averaging was done after calculating the GPS and GVSs.

Patient-reported outcome

Patient-reported outcome was assessed by using the validated FFI and MOXFQ [19,20]. The FFI is a self-administered questionnaire used to assess foot complaints in terms of limitations, pain and disabilities. In this study, the 'Limitations' domain was excluded since this domain did not apply to the studied population [21]. The MOXFQ is a 16-item patient-reported instrument validated outcome measure for foot pathology [20]. It contains three domains, i.e. foot pain, walking/standing problems and issues related to social interaction. For both questionnaires, raw scores were converted to metric values (0-100, where 100 represents the worst outcome).

Statistical analysis

SPSS software (version 23, IBM, Armonk, NY, USA) was used to perform statistical analysis. Normality of the distribution was tested with the Shapiro-Wilk test. A log-linear transformation was performed for not normally distributed data before *t*-tests. The unpaired Student *t*-test was used to detect statistical differences between HR and healthy controls and the paired samples t-test was used to compare both legs in healthy controls. The significance level was set at $P < .05$. Bonferroni correction was conducted on the ROM measurements because of multiple comparisons between the seven phases of gait. After Bonferroni correction, the significant P-value for ROM measurements was 0.007. Spearman rank correlation was used to assess the correlation between patient-reported outcome and GPS and GVSs, which showed a difference between HR patients and healthy controls. Correlations were interpreted as negligible (0-0.09), weak (0.1-0.39), moderate (0.4-0.69), strong (0.7-0.89) and very strong (0.9-1.0) [22]. Statistical significance was accepted at $P < .05$.

RESULTS

Subject characteristics

One of the HR subjects had a hemiprosthesis of the MTP1 joint on the contralateral side. The HR group contained more female subjects and had a significantly lower height when compared to the healthy control group (i.e. mean 166.6 vs 174.3 cm, respectively, *P* = .015). Ten subjects included were graded as grade II HR while 5 subjects were classified as grade III HR. With respect to the other subject characteristics, no statistically significant differences were detected (see Table 1).

Table 1. Subject characteristics[a].

	Hallux Rigidus		Healthy Controls		*P* Value
	Mean ±SD (Range)	**95% CI**	**Mean ±SD (Range)**	**95% CI**	
No. subjects	15	–	15	–	–
Gender (male/female)	4/11	–	9/6	–	–
Age (years)	63.7 ±10.5 (40-79)	57.9-69.6	59.1 ± 5.1 (53-70)	56.3-61.9	.137
Height (m)	1.67 ± 0.01 (1.55-1.81)	1.62-1.71	1.74 ± 0.01 (1.62-1.88)	1.70-1.79	.015*
Weight (kg)	75.1 ± 19.1 (50.5-122.0)	64.5-85.7	83.0 ± 11.9 (56.5-98.2)	76.4-89.6	.187
BMI (kg/m^2)	26.9 ± 6.0 (20.4-43.2)	23.6-30.2	27.4 ± 3.9 (20.2-33.3)	25.2-29.5	.679
HR grade	Grade II n = 10, Grade III n=15		Not applicable		

[a] Data are presented as mean values and standard deviation with ranges in parentheses. 95% CI, 95% confidence intervals.
[b] Grading system based on Regnauld [15].
* Significant difference *P* <.05

Spatio-temporal parameters

HR subjects had a significantly smaller step and stride length even after normalisation for the subjects' height (see Table 2). No significant differences were detected in gait velocity, step length and width, cadence and stance/swing time between groups.

Gait Profile Score and Gait Variable Scores

The GPS and the GVSs are presented in Figure 1. A significant higher GPS (i.e. 2.1°, *P* = .006; Figure 1A) was detected in HR as compared to healthy controls. In addition, significant higher $GVS_{pelvic\ rotation}$ (i.e. 1.0°, *P* = .047; see Figure 1D) and $GVS_{ankle\ flexion}$ (i.e. 2.6°, *P* = .029; see Figure 1I) values were found in HR subjects as compared to healthy controls. In addition, no significant differences between both legs in health controls were found.

Table 2. Spatiotemporal gait characteristics[a].

	Hallux Rigidus		Healthy Controls		*P* Value
	Mean ±SD (Range)	**95% CI**	**Mean ±SD (Range)**	**95% CI**	
Velocity (m/s)	1.04 ±0.14 (0.64-1.44)	0.96-1.11	1.14 ±0.20 (0.73-1.47)	1.06-1.11	.053
Step Length (m)	0.57 ±0.07 (0.47-0.78)	0.54-0.59	0.64 ±0.08 (0.49-0.77)	0.61-0.67	.000*
Step Length[b]	0.34 ±0.04 (0.27-0.43)	0.33-0.36	0.37 ±0.05 (0.27-0.45)	0.35-0.39	.016*
Stride Length (m)	1.16 ±0.14 (0.95-1.54)	1.11-1.22	1.29 ±0.14 (1.03-1.55)	1.25-1.34	.001*
Stride Length[b]	0.70 ±0.08 (0.57-0.86)	0.67-0.73	0.74 ±0.08 (0.58-0.87)	0.71-0.78	.032*
Step Width (m)	0.23 ±0.04 (0.16-0.32)	0.21-0.24	0.23 ±0.04 (0.18-0.30)	0.22-0.24	.671
Cadence (step/min)	105.17 ±11.99 (81.58-125.95)	100.70-109.65	102.69 ±12.18 (74.17-128.12)	98.15-107.24	.430
Swing Time (s)	0.58 ±0.07 (0.48-0.74)	0.56-0.61	0.59 ±0.09 (0.47-0.84)	0.57-0.63	.461
Stance Time (s)	0.72 ±0.09 (0.59-0.91)	0.68-0.75	0.71 ±0.11 (0.52-0.96)	0.67-0.75	.701

[a] Data are presented as mean values and standard deviation with ranges in parentheses. 95% CI, 95% confidence intervals.
[b] Normalised to subjects' height.
* Significant difference $P < .05$

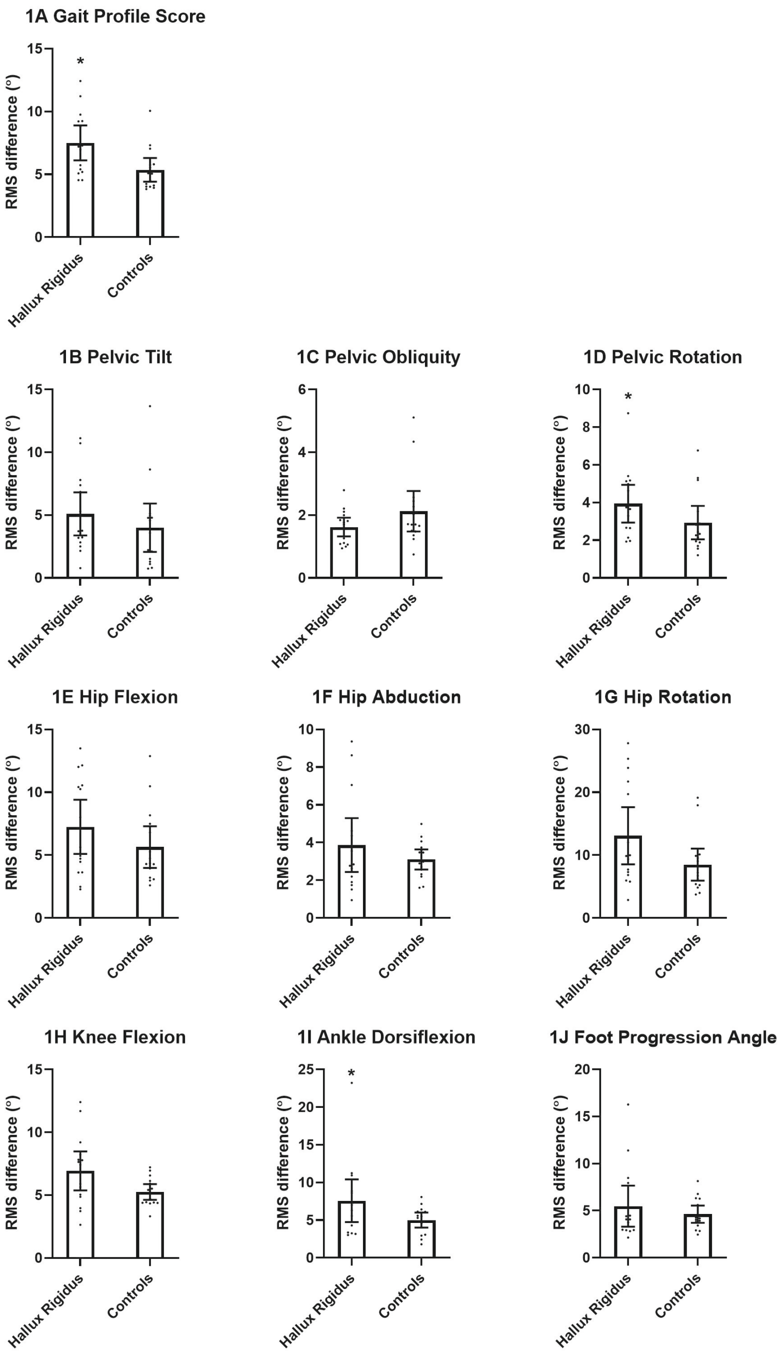

Figure 1. Gait Profile Score and Gait Variable Scores. The individual values (dots), mean values and 95% confidence intervals are presented. *Significant difference compared with controls *P* <.05.

Range of motion

Intersegmental ROM of the GVSs with a significant difference between HR and healthy controls (i.e. pelvic rotation and ankle flexion) are shown in Figure 2. No significant differences in intersegmental ROM in pelvic rotation (see Figure 2A and 2B) and ankle flexion (see Figure 2C and 2D) were detected.

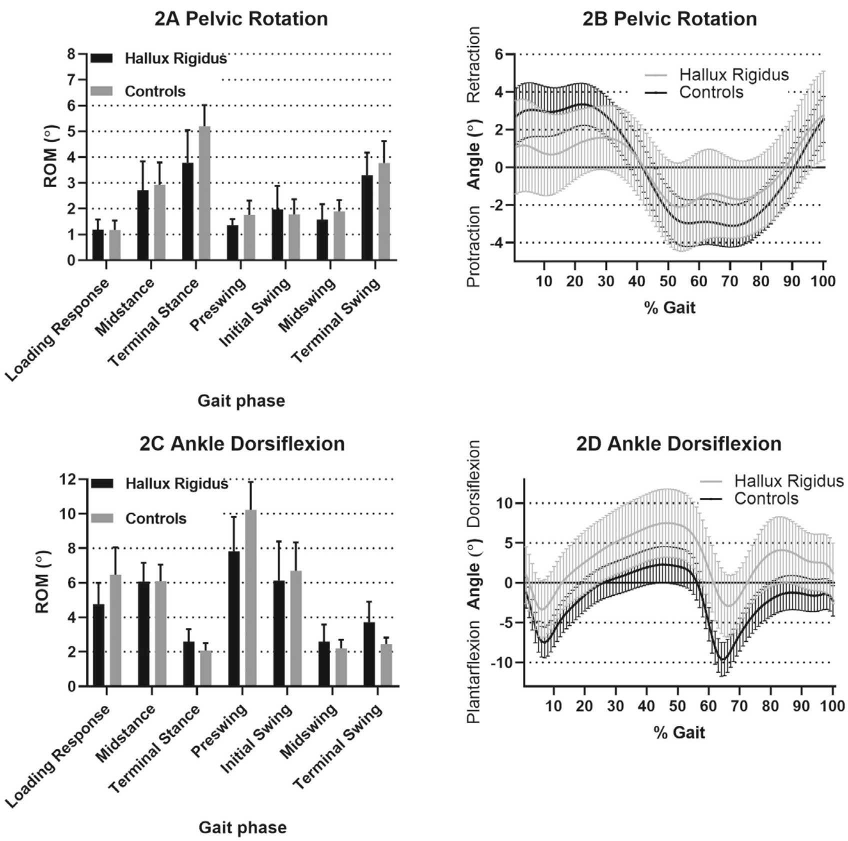

Figure 2. Range of motion with 95% confidence intervals and averaged absolute joint angles ±1 standard deviation for pelvic rotation (A-B) and ankle dorsiflexion (C-D) for hallux rigidus and healthy controls.

Intersegmental ROM and motion patterns of GVSs where no significant differences were found (i.e. pelvic tilt, pelvic obliquity, hip flexion, hip abduction, hip rotation and knee flexion) are shown in Appendix 1. A significant difference in sagittal knee ROM during midswing was detected in HR subjects (4.1°, $P = .003$) when compared to healthy controls (see Appendix 1).

Relation of patient-reported outcome and Gait Profile Score

GPS showed a significant positive, moderate level, correlation with MOXFQ score, MOXFQ 'walking/standing' domain and FFI 'disabilities' domain (see Figure 3A, 3B, and 3C, respectively).

Significant positive, moderate level, correlation was detected for $GVS_{ankle\ flexion}$ and MOXFQ domain 'walking/standing' (see Figure 3D). No statistically significant correlations for $GVS_{pelvic\ rotation}$ and PROMs were found.

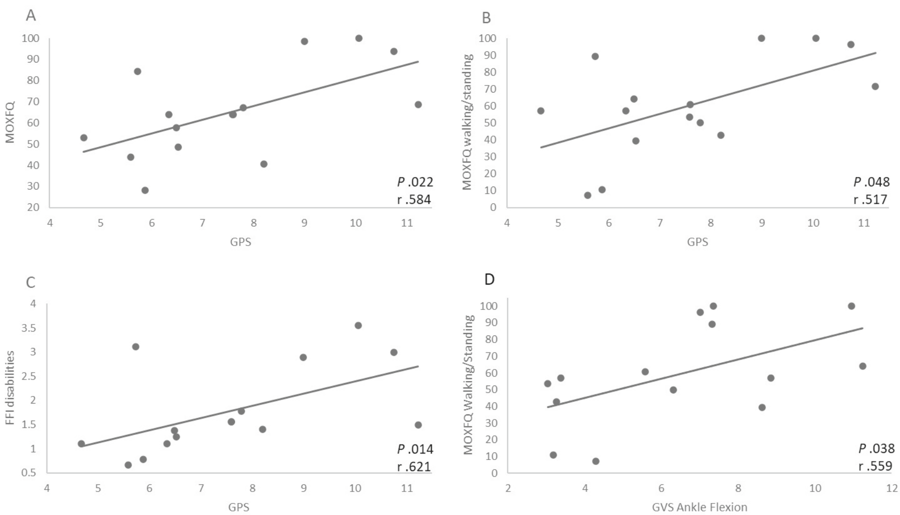

Figure 3. Correlations of patient-reported outcome measures MOXFQ and FFI, and GPS (A-C) and $GVS_{ankle\ flexion}$ (D)

DISCUSSION

This study aimed to determine if HR affects lower limb kinematics assessed by using the GPS, and if so, how gait deviation was correlated with patient-reported outcome. It was hypothesized that HR altered the gait pattern especially by a changed ankle and hip movement, due to avoidance of the stiff and painful MTP1 joint during stance, reflected by a deviated ankle and hip GVSs and altered segmental joint ROM.

Our findings support the hypothesis that HR significantly affects lower limb kinematics, reflected by a deviated GPS. Results showed that most of the deviation observed in GPS can be explained by altered sagittal ankle motion (i.e. $GVS_{ankle\ flexion}$) in HR patients, and for the minority by an altered transverse pelvic motion (i.e. $GVS_{pelvic\ rotation}$). These results support our hypothesis that HR affects lower limb kinematics, where compensation occurs at multiple levels. However, contrary to our hypothesis, the hip was not involved in this compensatory mechanism.

Although $GVS_{ankle\ flexion}$ showed a significant difference between HR patients and controls, no significant difference was detected by analysing sagittal ankle intersegmental ROM. This example shows the additional value of using GPS and GVSs next to analysing ROM since the creation of cut-off values in the latter (e.g. for gait phases) resulted in different conclusions. The offset between groups can also explain a part of the differences found, and are mainly the result of anatomical differences between groups and errors in marker placement, although the effect of the latter was minimized since two investigators, experienced with the Plug-in Gait Lower Body Model, performed marker placement in all subjects.

This was the first study evaluating lower limb kinematics in HR by using GPS. Our results showed a difference in GPS between HR patients and controls of 2.1°, which is above the minimal clinically important difference (MCID) of 1.6° reported by Baker et al. [10]. This MCID value should be applied to our patient population with caution since this MCID for GPS was determined in children with cerebral palsy, and it is known that minimal detectable changes vary per pathology [23]. Nevertheless, GPS differences detected in this study are likely to be clinically relevant, since gait deviations in HR patients are more subtle as compared to subjects with cerebral palsy, resulting in a lower MCID value for HR. In addition, GPS was reported in two other studies evaluating foot pathology, i.e. idiopathic clubfoot and idiopathic toe walking, and our GPS score (i.e. 2.1°) was in line with GPS scores in those studies of 2.4° and 1.6° respectively [12,14]. However, the next step in using the GPS in HR patients will be determining an HR specific MCID for the GPS.

As expected, significant moderate positive correlations were found for MOXFQ score, MOXFQ 'walking/standing' domain and FFI 'disabilities' domain and GPS. Besides, a positive correlation between the MOXFQ 'walking/standing' domain and $GVS_{ankle\ flexion}$ was reported. These results indicate that GPS and $GVS_{ankle\ flexion}$, i.e. objectively measured gait indices of overall gait deviation and deviated joint motion the most adjacent joint, seemed to correspond well with the disabilities and/or problems while walking, reported by HR patients themselves. On the other hand, low correlations were expected and found for the other GVSs which were affected by HR, since a major part of the gait deviation seen in HR patients reflected in the GPS was explained by $GVS_{ankle\ flexion}$, indicating that altered ankle motion is most responsible for compensating for the loss in MTP1 motion.

We acknowledge that this study had some limitations. Selection of age and gender-matched control group would have been more appropriate, since there was, although not statistically significant, a mean age difference of 4.6 years and gender distribution was not equal between groups. In addition, a significant difference in height was detected between both groups. It is known from the literature that age and height mainly affect gait velocity, and gait velocity strongly influences kinematics [24,25]. The difference in height was deemed not to have influenced our results, since no statistically significant difference in gait velocity was observed between both groups. Whether the difference in gait velocity of 0.1m/s between both groups is clinically relevant is not known. In addition, the potential influence of the non-significant difference in age between the studied groups can not be ruled out, since some studies show a true age-effect, independent of gait velocity [26,27], although this true age-effect was not seen in other studies [28]. In addition, several studies showed gender-specific differences in lower-limb kinematics independent of gait velocity, so the difference in gender distribution between groups may have influenced our results [12,24,29].

Since this was the first study evaluating lower limb kinematics in HR, the sample size was not calculated before the start of the study. Therefore, the relatively small sample size might be a potential weakness of this study, although these group sizes were common in this research area due to the relative extensiveness of measurements. Furthermore, the Foot Profile Score (FPS) has been recently developed by McCahill et al. [30]. They showed that the FPS presents gait deviations not reflected by GPS and therefore provides new information in pathologies in which foot deformity is dominant and therefore, in future studies both GPS and FPS should be presented [30].

This study showed that HR, in a group of subjects pending on a surgical intervention, influences lower limb kinematics and that the ankle is particularly affected. Therefore, proximal joint functioning should be taken into account as well in evaluating and considering surgery in foot pathology, since previous research showed that foot pathology produces compensatory mechanisms in proximal joints and reduced compensatory capacity in these joints can potentially limit the beneficial effect of surgery [6]. The positive correlation between GPS, $GVS_{ankle\ flexion}$ and PROM index scores and PROM functional subdomains seen in this study suggest that patient-reported outcome and gait pattern are associated and can possibly be used in the planning and type of surgery in patients with symptomatic HR.

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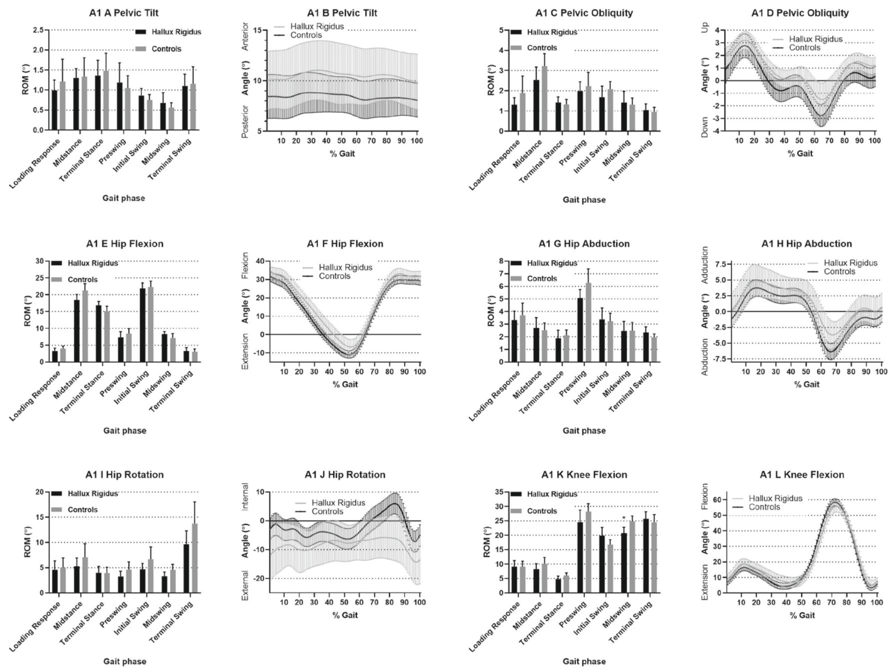
SUPPLEMENTARY FILES



Appendix 1. Range of motion with 95 % confidence intervals and averaged absolute joint angles ±1 standard deviation for pelvic tilt (A–B), pelvic obliquity (C-D), hip flexion (E-F), hip abduction (G-H), hip rotation (I-J) and knee flexion (K-L) for hallux rigidus patients and healthy controls. *Significant difference *P* <.05.

CHAPTER 5

GAIT ANALYSIS OF FOOT COMPENSATION AFTER ARTHRODESIS OF THE FIRST METATARSOPHALANGEAL JOINT

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Keywords

MTP1 arthrodesis, hallux, gait analysis, Oxford Foot Model, multisegment foot model, plantar pressure; compensatory mechanism

Abbreviations

DFA	Dorsiflexion Fusion Angle	HVA	Hallux Valgus Angle
IMA	Intermetatarsal Angle	MTP1	First Metatarsophalangeal
OA	Osteoarthritis	OFM	Oxford Foot Model
PP	Peak Pressure	PTI	Pressure Time Integral
ROM	Range of Motion		

ABSTRACT

Background: Arthrodesis of the MTP1 joint is an intervention often used in patients with severe MTP1 joint osteoarthritis and relieves pain in approximately 80% of these patients. The kinematic effects and compensatory mechanism of the foot for restoring a normal gait pattern after this intervention are unknown. The aim of this study was to clarify this compensatory mechanism, in which it was hypothesized that the hindfoot and forefoot would be responsible for compensation after an arthrodesis of the MTP1 joint.

Methods: Gait properties were evaluated in 10 feet of 8 patients with MTP1 arthrodesis and were compared with 21 feet of 12 healthy subjects. Plantar pressures and intersegmental range of motion were measured during gait by using the multisegment Oxford Foot Model. Pre- and postoperative X-rays of the foot and ankle were also evaluated.

Results: MTP1 arthrodesis caused decreased eversion of the hindfoot during midstance, followed by an increased internal rotation of the hindfoot during terminal stance, and ultimately more supination and less adduction of the forefoot during preswing. In addition, MTP1 arthrodesis resulted in a lower pressure time integral beneath the hallux and higher peak pressures beneath the lesser metatarsals. A mean dorsiflexion fusion angle of 30 ± 5.4 degrees was observed in postoperative radiographs.

Conclusion: This study demonstrated that the hindfoot and forefoot compensated for the loss of motion of the MTP1 joint after arthrodesis in order to restore a normal gait pattern. This resulted in a gait in which the rigid hallux was less loaded while the lesser metatarsals endured higher peak pressures. Further studies are needed to investigate whether this observed transfer of load or a preexistent decreased compensatory mechanism of the foot can possibly explain the disappointing results in the minority of the patients who experience persistent complaints after a MTP1 arthrodesis.

INTRODUCTION

Osteoarthritis (OA) of the first metatarsophalangeal (MTP1) joint is a common disorder of the musculoskeletal system in elderly, which progresses with age [1]. The exact etiology of MTP1 joint OA is unknown, although trauma, overuse, operations, deformations, and the length of the first metatarsal seem to be involved [2,3]. Patients usually present with pain, stiffness, and swelling of the MTP1 joint. Erythema and a limited range of motion of this joint are observed during physical examination, while conventional radiographs show degenerative changes of the MTP1 joint [4,5].

First metatarsophalangeal joint OA severely affects quality of life since patients experience chronic pain and more difficulties while performing physical tasks and daily activities [6]. An arthrodesis of the MTP1 joint is the preferred intervention to relieve pain when the articular cartilage is extensively damaged and patients have been refractory to conservative treatment. Approximately 80% of the patients were satisfied after this intervention, in which an arthrodesis alleviated pain complaints and increased function [7-12]. The reason for dissatisfaction in the remaining 20% of the patients is unknown. It is reasonable to assume that adjacent joints in the foot will compensate for the lack of motion in the MTP1 joint after an arthrodesis in order to restore foot function. An impaired ability of these adjacent joints to compensate for the motionless MTP1 joint can possibly explain the disappointing results of some MTP1 arthrodeses. However, it is not known if and how the foot compensates for restoring the gait pattern towards a normal gait pattern after this intervention.

Motion capture analysis, in which the human body is divided in several segments, allows for measurements and analysis of motion between these segments during gait. This method provides an opportunity to clarify which joints are responsible for restoring the gait pattern after a MTP1 arthrodesis. To our knowledge, only 3 studies used motion capture analysis to assess gait properties after a MTP1 arthrodesis and showed a decrease in step length and step width, although no differences in foot kinematics were detected after this intervention [13-15]. However, these studies were particularly limited by the gait models used, which presented the foot as a single segment instead of multiple segments. This would be more representative since the foot consists of 26 bones. As a result, the compensatory mechanism after a MTP1 arthrodesis remains unknown.

The goal of this study was to elucidate where the foot compensates for the loss of motion of the MTP1 joint after an arthrodesis in order to restore the gait pattern towards a normal gait pattern. Currently, there is no foot model available describing motion between all individual foot joints. Therefore, the 4-segment Oxford Foot Model (OFM) was used to evaluate foot kinematics. This foot model divided the foot and ankle in a tibial, hindfoot, forefoot, and hallux segment. Plantar peak pressures, which provided information on the maximal pressure in a plantar area at one moment during stance, and pressure-time integrals, which provided information of total loading of a plantar area during the entire stance phase, were measured to investigate the effect of a MTP1 arthrodesis on foot loading.

We hypothesized that the hindfoot and forefoot would compensate for the absence of motion in the MTP1 joint after an arthrodesis by showing less eversion and more supination, respectively, as it would be expected that the rigid hallux would be avoided during roll-off. As a result, decreased loading of the hallux and increased loading of the lesser metatarsals would be expected during the stance phase of gait.

METHODS

Study Population

This cross-sectional study was conducted at the Human Movement Laboratory of our institution. Potential candidates were identified in the patient files of the department of orthopaedics of our institution. Patients who underwent MTP1 arthrodesis for symptomatic OA of the MTP1 joint in the past 5 years, with a clinical and radiographic consolidation of the arthrodesis, and a minimum follow-up of 1 year were eligible for participation. Patients with an arthrodesis of another joint in the same foot, who required assistance when walking, or were unable to walk more than 100 metres barefoot were excluded. In addition, patients with a total knee prosthesis, a total hip prosthesis, diabetes mellitus, inflammatory joint diseases, or neurological diseases influencing gait were not eligible for participation in this study. Patients were compared to healthy subjects with no medical history resulting in an abnormal gait pattern (i.e. fractures or deformities of the lower extremities, neurological brain, or spinal cord injury). Approval for this study was obtained from the local ethics committee, and all patients provided written informed consent.

Overall, 8 patients were included, of which 6 patients underwent a unilateral MTP1 arthrodesis and 2 patients a bilateral MTP1 arthrodesis, resulting in a total of 10 feet with MTP1 arthrodesis. Twelve healthy subjects were included (9 of whom were measured bilaterally), resulting in a total of 21 control feet.

Operative Technique

All patients were operated between December 2010 and May 2014 by 2 orthopaedic surgeons. Briefly, a longitudinal dorsomedial incision was used. Socked and ball reaming of the metatarsal head and base of the proximal phalanx was applied. Fixation was established with the "HALLU-FIX Integra plate" (Integra Life Sciences, Plainsboro, NJ, USA). During the postoperative period, patients were immobilized with a non-weightbearing cast for 4 weeks, followed by a weightbearing cast for the subsequent 4 weeks. No complications of the primary surgical intervention (i.e. infection or revision surgery) were reported.

Radiographic evaluation

Two independent observers, who were blinded to the gait analysis and patient outcome, evaluated preoperative and postoperative radiographs. The following parameters were evaluated on radiographs: intermetatarsal angle (IMA), hallux valgus angle (HVA), and hallux interphalangeal angle [16]. The dorsiflexion fusion angle (DFA) was measured as described by Coughlin et al. [17]. Mean angles of both measurements were calculated. Differences between observers greater than 5 degrees were resolved by consensus. Radiographic consolidation of the MTP1 arthrodesis was confirmed in all patients.

Motion analysis

Motion capture was conducted using a Vicon system (Vicon Motion Systems, Oxford, UK), consisting of 16 infrared cameras (8 T10, 6 MX3 and 2 T20 running at 200Hz). One trained researcher placed all 42 markers (Appendix 1) according to the OFM protocol after careful identification of the bony landmarks. The OFM is a 4-segment model of the foot and divides the foot and ankle in a tibial (tibia and fibula), hindfoot (calcaneus and talus), forefoot (5 metatarsals), and hallux segment and has been validated to measure intersegmental motion in the sagittal, coronal and transverse plane [18-20]. A 10-meter runway was equipped with a forceplate (AMTI OR6 Series, Advanced Mechanical Technology Inc., Watertown, NY, USA) running at a frequency of 1000 Hz and was synchronized with the Vicon Nexus 1.8.5 software. Dynamic plantar pressures were measured using a pressure plate (High Speed Advanced Footscan System, RSscan International, Paal, Belgium), which had a sampling frequency of 253 Hz. The pressure plate was mounted on top of the forceplate and was also synchronized with Vicon Nexus 1.8.5.

The following patient characteristics were measured for running the OFM: height, weight, knee and ankle width (distance between the lateral and medial condyle of the knee and the distance between the lateral and medial malleolus of the ankle respectively), and leg length (distance between the anterior iliac spine and the medial malleolus). One trained researcher performed all measurements. Markers were calibrated, and subject-specific axes were calculated during 1 static trial, with the patients standing in an anatomically neutral position. After this static trial, 3 markers were removed according to the OFM protocol, and patients were asked to walk at a comfortable speed with their eyes focused on the wall in front of them. After the practice trials, at least 15 proper recordings with the subject cleanly striking the pressure plate were obtained while walking barefoot.

Data processing
Markers were tracked and labelled using Vicon Nexus 1.8.5. Intersegmental range of motion and spatio-temporal parameters of interest were calculated with MATLAB software (version R2012A, The MathWorks Inc, Natick, MA, USA). All trials with a gait velocity ranging between 2 standard deviations of the subjects' own average speed were used for further analysis. The pelvic segment centre of mass, which was estimated based on the pelvic markers, was used to define gait velocity. Stance time was defined as the time between heel strike and toe off of the foot of interest. Step length was calculated as the distance between both heel markers in the direction of gait, while step width was the distance between these markers in the plane perpendicular to the direction of gait. Intersegmental range of motion (ROM) was calculated for the hindfoot-tibia and forefoot-hindfoot segment in the frontal plane (i.e. inversion/eversion and pronation/supination, prospectively), sagittal plane (i.e. dorsiflexion/plantarflexion), and transverse plane (i.e. external/internal rotation and abduction/adduction, respectively) and for the hallux-forefoot segment in the sagittal plane (i.e. dorsiflexion/plantarflexion). The ROM was calculated for the 4 phases of stance as defined by Perry et al. after time normalization of the gait cycle [21]. These phases were the loading response (0-17% of stance phase), midstance (18-50%), terminal stance (51-83%), and preswing (84-100%). The ROM was defined as the difference between the minimum and maximum joint angle during each phase. Initial contact was identified as the onset of a vertical ground reaction force exceeding 20 Newtons (N), and toe off was identified as the first moment after initial contact with the vertical ground reaction force below 20N. The ROM was averaged for at least 6 trials per subject, which has proven to be a sufficient number of trials to achieve high intraclass correlation coefficients for the OFM [19].

Since it is known that bilateral disease can influence compensatory mechanisms, motion patterns of the segments of interest and the pelvis, hip and knee of bilateral and unilateral treated patients were compared to assess this influence. In addition, left and right feet of healthy subjects were compared to assess if analysis of both feet influences outcome.

For analysis of dynamic plantar pressure, the foot was automatically divided in 10 anatomical areas (i.e. the hallux (Toe_1), lesser toes (Toe_{2-5}), metatarsal heads

($Meta_1$-$Meta_5$), midfoot, medial heel and lateral heel) by the Footscan® 7.0 Gait 2nd Generation software. Trials with inconsistencies in the automatic masking procedure were manually adjusted. An ASCII output was generated in which peak pressures (PP), force-time integrals and contact areas were obtained. PP was defined as the highest magnitude measured by any sensor in an area and reflects the highest value in a peak pressure-time curve of a particular area. The force-time integral and contact area were used for calculating the pressure-time integral (PTI) as described by Melai et al [22]. This alternative calculation of the PTI described the cumulative effect of pressure on a plantar area over time (i.e. area under the peak pressure-time curve), instead of summing the PP per timeframe for an entire trial. It thereby provided a more representative value of the total load exposure of a plantar area during stance. Both PP and PTI were calculated for the 10 described areas.

Statistical analysis

Statistical analyses were performed with SPSS software (version 23; IBM, Armonk, NY, USA). The Shapiro-Wilk test was performed to assess whether gait parameters were normally distributed. Log linear transformations were used for not normally distributed data. The unpaired Student *t* test was used to detect differences in patient characteristics, spatio-temporal parameters, intersegmental ROM, and plantar pressure data between patients and healthy subjects. Differences in radiographic angles between pre- and postoperative radiographs and differences in intersegmental ROM in both feet of bilateral evaluated healthy controls were tested with the paired *t* test. A *P* value less than .05 was considered to be statistical significant for patient characteristics, spatio-temporal parameters and plantar pressure data. To adjust for multiple tests over the 4 phases of stance, a Bonferroni correction was applied to achieve an overall error rate of 5%. Therefore, a *P* value less than .0125 was considered to be statistically significant for differences in intersegmental ROM.

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RESULTS

Patient characteristics

Baseline patient characteristics are presented in Table 1 and depict differences between both groups. Healthy subjects were significantly younger ($P = .003$), had a greater height ($P = .002$), and lower body mass index ($P = .05$), and contained more male participants compared to the MTP1 arthrodesis group. Radiographic angles are presented in Table 2, showing a significant decrease in IMA and HVA ($P = .02$ and $P = .03$ respectively) after MTP1 arthrodesis. The mean postoperative DFA was 30.0 ± 5.4 (range, 21-35) degrees.

Table 1. Patient Characteristics.[a]

	MTP 1 Arthrodesis	Healthy Control	*P* Value
No. of subjects (No. of feet)	8 (10)	12 (21)	-
Age[b] (y)	59.4 ± 8.3 (50-69)	43.1 ± 18.2 (20-65)	.003
No. (% of subjects) male	2 (25)	9 (75)	-
No. (% of feet) right side	5 (50.0)	11 (52.4)	-
Weight (kg)	78.1 ± 21.0 (55.0-108.3)	75.3 ± 9.7 (62.0-91.0)	.731
Height[b] (cm)	168.2 ± 9.45 (157.0-184.0)	179.6 ± 5.01 (168.5-185.0)	.002
Body mass index[b] (kg/m^2)	27.1 ± 4.4 (22.3-33.6)	23.3 ± 2.5 (19.4-26.9)	.050
Leg length (cm)	89.80 ± 5.55 (80.0-99.0)	93.43 ± 23.3 (78.0-97.0)	.068
Knee width (cm)	10.48 ± 1.05 (9.5-12.2)	10.41 ± 0.66 (9.3- 12.0)	.819
Ankle width (cm)	6.94 ± 0.49 (6.4-7.7)	6.92 ± 0.47 (6.1- 7.7)	.721

[a] Mean values and standard deviations with the range in parentheses are presented. MTP1, first metatarsophalangeal joint.
[b] Significant difference between first metatarsophalangeal arthrodesis and healthy control $P < .05$

Table 2. Radiographic Evaluation of Preoperative and Postoperative Radiographs.

Radiographic Evaluation	Preoperative	Postoperative	*P* Value
IMA (degrees)[a]	10.8 ± 3.4	8.7 ± 2.4	.02
HVA (degrees)[a]	16.4 ± 7.8	10.7 ± 5.5	.03
IPA (degrees)	12.1 ± 4.7	12.8 ± 2.8	.59
DFA (degrees)	-	30.0 ± 5.4	-

Abbreviations: DFA, dorsiflexion fusion angle; HVA, hallux valgus angle; IMA, intermetatarsal angle; IPA, inter phalangeal angle.
[a]Significant difference between first metatarsophalangeal joint arthrodesis and healthy control $P < .05$

Gait analysis

Gait analysis took place at a median follow-up of 27 months (range, 18-60 months) postoperatively. With the numbers available, no significant differences in gait velocity, stance time and step length were detected between both groups, as is shown in Table 3. Step width was significantly smaller in the MTP1 arthrodesis group compared to the healthy controls ($P = .001$).

Table 3. Spatio-Temporal Parameters of Gait for the MTP1 Arthrodesis and Healthy Control Group.[a]

	MTP1 Arthrodesis	Healthy Control	*P* Value
Gait velocity (m/s)	1.18 ± 0.25	1.17 ± 0.19	.867
Stance time (s)	0.70 ± 0.11	0.70 ± 0.08	.946
Step length (m)	0.61 ± 0.08	0.57 ± 0.05	.168
Step width (m)[b]	0.08 ± 0.03	0.13 ± 0.04	.001

[a] Data are presented as mean values and standard deviation. MTP1, first metatarsophalangeal joint.
[b] Significant difference between MTP1 arthrodesis and healthy control P < .05

Kinematic results are presented in Figure 1 and Figure 2. The MTP1 arthrodesis group showed a significantly increased ROM in the terminal stance phase in the transverse plane in the hindfoot-tibia segment (*P* = .002, Figure 1A), which was the result of a more internally rotated hindfoot (Figure 2A). A significant decreased ROM was observed after a MTP1 arthrodesis in the frontal plane during midstance in this segment (*P*= .001, Figure 1C), due to diminished eversion of the hindfoot (Figure 2C). No significant differences could be detected in sagittal plane motion in the hindfoot-tibia segment (Figure 1B and Figure 2B).

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Transverse plane motion showed a significantly reduced ROM after a MTP1 arthrodesis in the forefoot-hindfoot segment during preswing (*P* = .003, Figure 1D), due to diminished adduction of the forefoot in this phase (Figure 2D). In addition, significantly less plantar flexion was observed during midstance (*P* < .001, Figure 2E) and terminal stance (*P* = .001, Figure 2E) in this segment, which resulted in a significantly reduced ROM in the sagittal plane in the MTP1 arthrodesis group (Figure 1E). A significant increase in ROM after a MTP1 arthrodesis, as a result of increased supination of the forefoot (*P* < .001, Figure 1F and Figure 2F) was detected in the frontal plane during preswing in the forefoot-hindfoot segment.

Decreased ROM of the hallux was observed in the loading response (*P* < .001, Figure 1F) and terminal stance phase (*P* = .001, Figure 1F) in the MTP1 arthrodesis group, which was the result of less plantarflexion of the hallux during loading response and less dorsiflexion of the hallux during terminal stance (Figure 2G).

Evaluation of motion patterns of the segments of interest (Figure 3), and proximal joints (Appendix 2) showed no major differences between unilateral and bilateral treated patients. Differences in joint angles were below 5 degrees for all joints, except sagittal hip and knee joint motion, showing a maximum difference in joint angle of 7 degrees between those patients. Evaluation of healthy controls showed no significant differences in ROM and joint motion patterns between left and right feet (Appendix 3), which justified the usage of both left and right feet in this study.

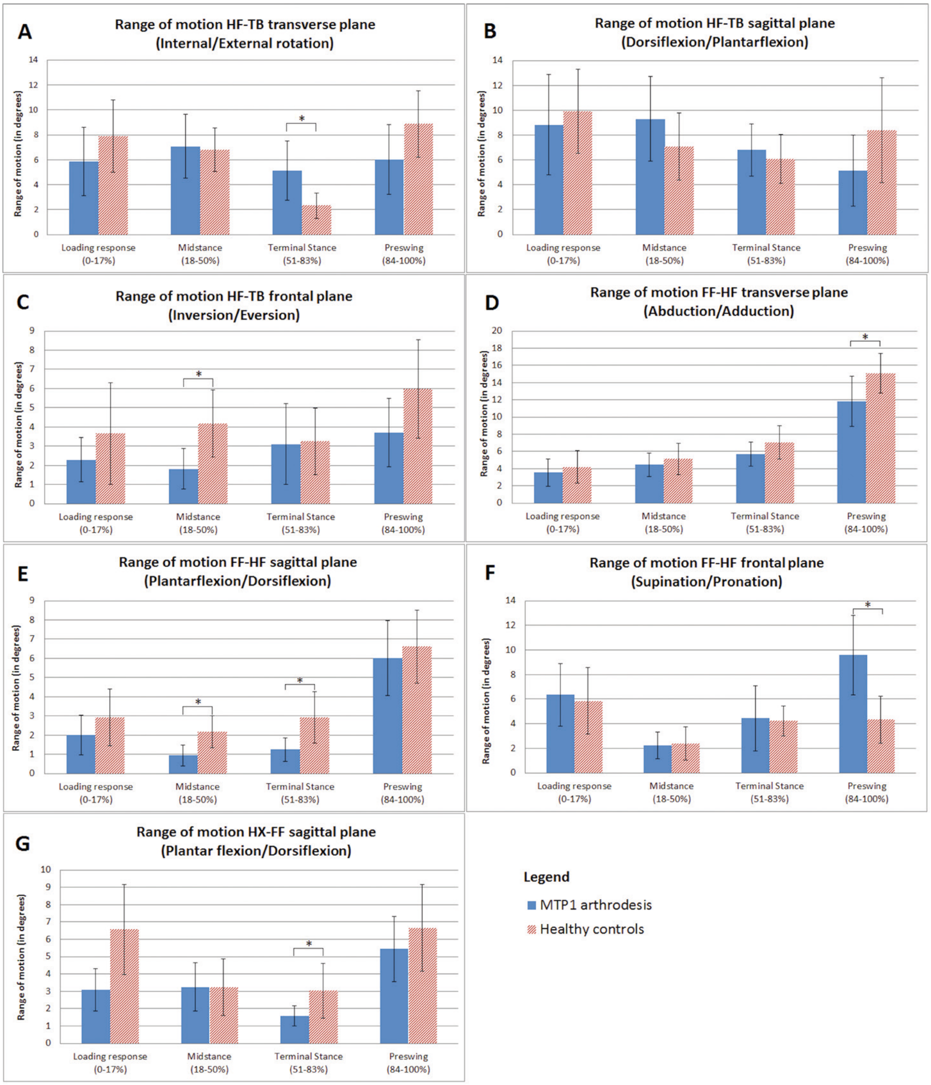

Figure 1. Range of motion in the hindfoot-tibia segment (A-C), forefoot-hindfoot segment (D-F) and hallux-forefoot (G) segment in the transverse, sagittal and frontal plane during stance for the first metatarsophalangeal joint arthrodesis group and healthy controls.

** Indicates a significant difference in ROM (P* <0.0125).

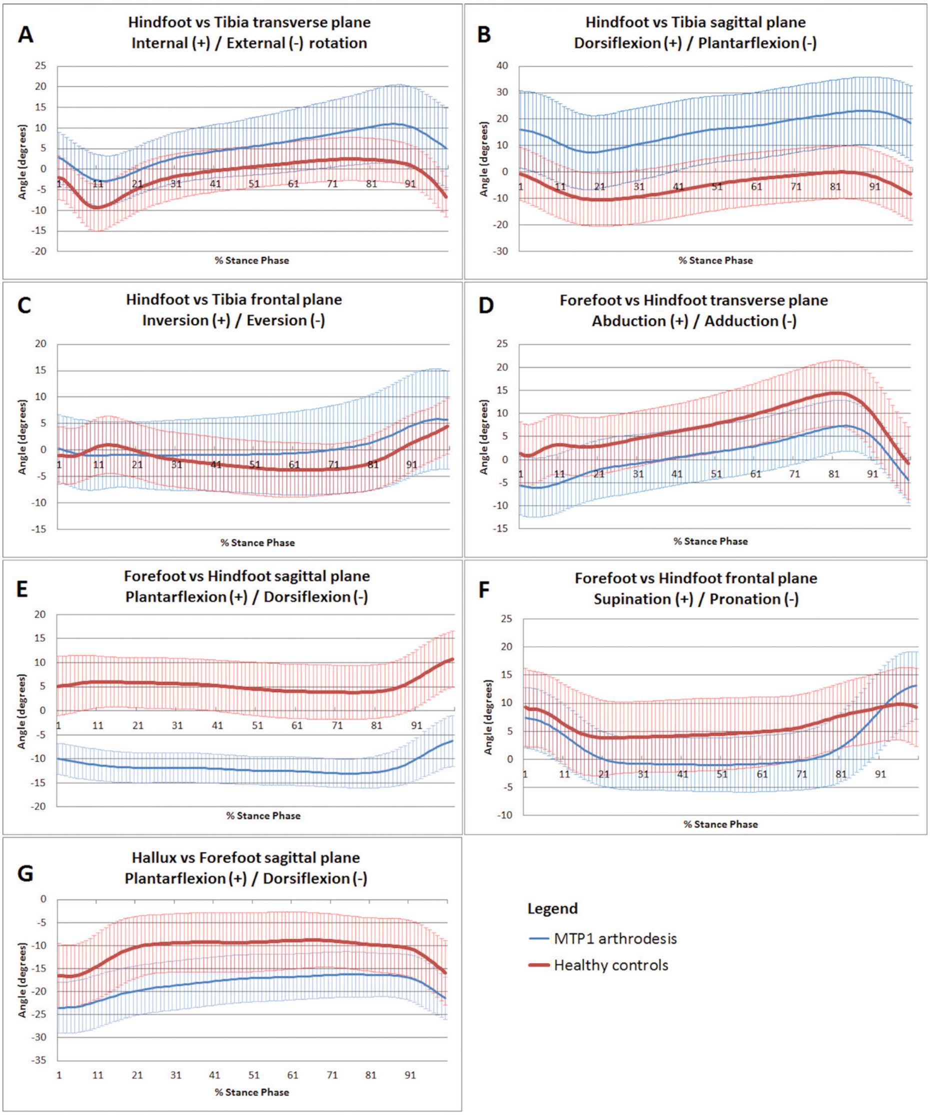

Figure 2. Averaged absolute joint angles in the hindfoot-tibia segment (A-C), forefoot-hindfoot segment (D-F) and hallux-forefoot (G) segment in the transverse, sagittal and frontal plane during stance for the first metatarsophalangeal joint arthrodesis group and healthy controls.

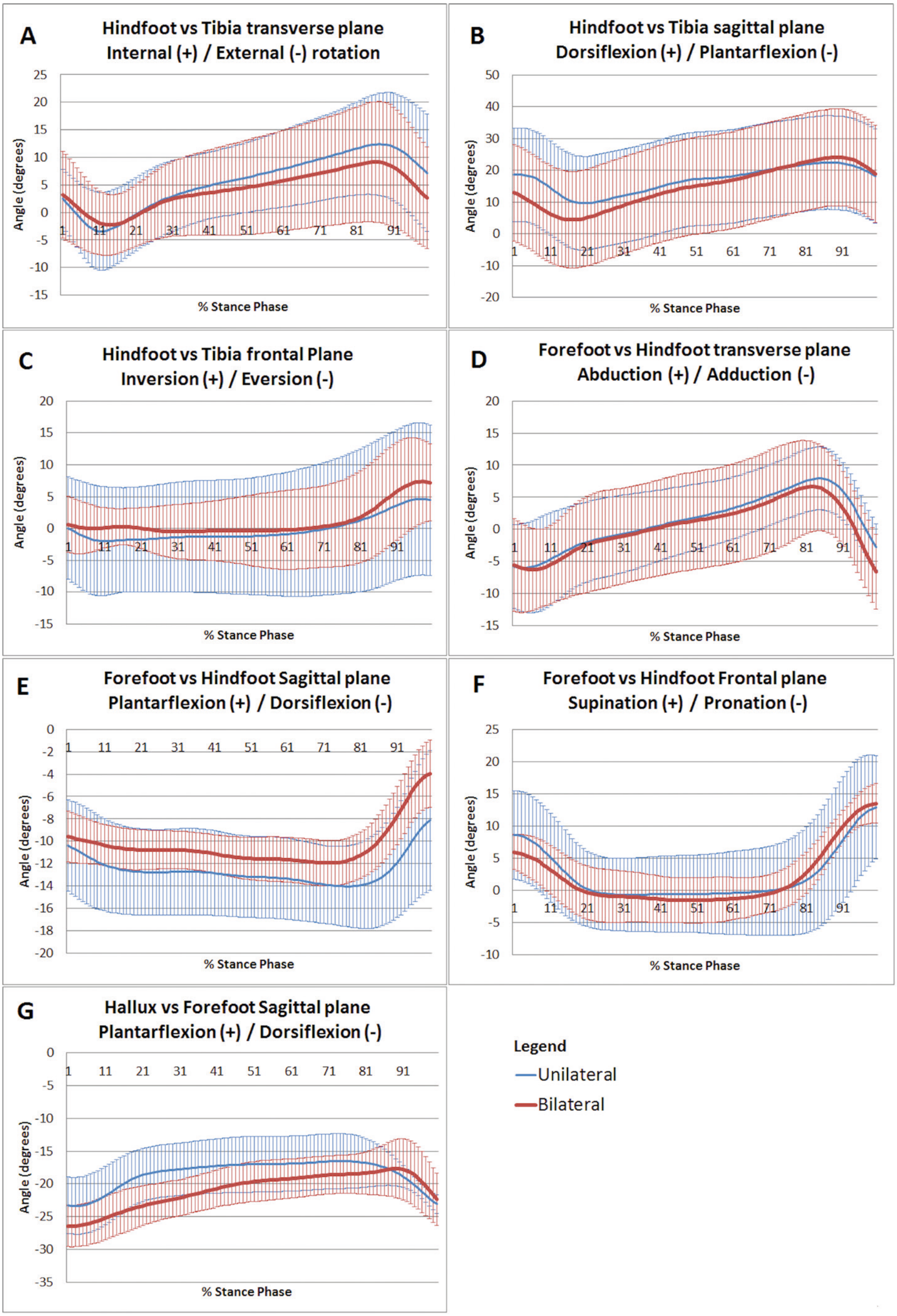

Figure 3. Averaged absolute joint angles in the hindfoot-tibia segment (A-C), forefoot-hindfoot segment (D-F) and hallux-forefoot (G) segment in the transverse, sagittal and frontal plane during stance for patients with a unilateral and bilateral first metatarsophalangeal joint arthrodesis.

Plantar pressure

Significantly higher PPs were observed beneath the lesser toes (Toe 2-5, $P = .013$), second, third, fourth, and fifth metatarsal head areas ($P = .025$, $P = .038$, $P = .003$ and $P = .05$ respectively) and midfoot ($P = .017$) in the MTP1 arthrodesis group, as is shown in Figure 4. Evaluation of the PTI showed a significantly lower PTI in the hallux area (Toe1, $P < .001$), while a higher PTI was observed in the fourth metatarsal ($P = .03$) and midfoot area ($P = .003$) in the MTP1 arthrodesis group.

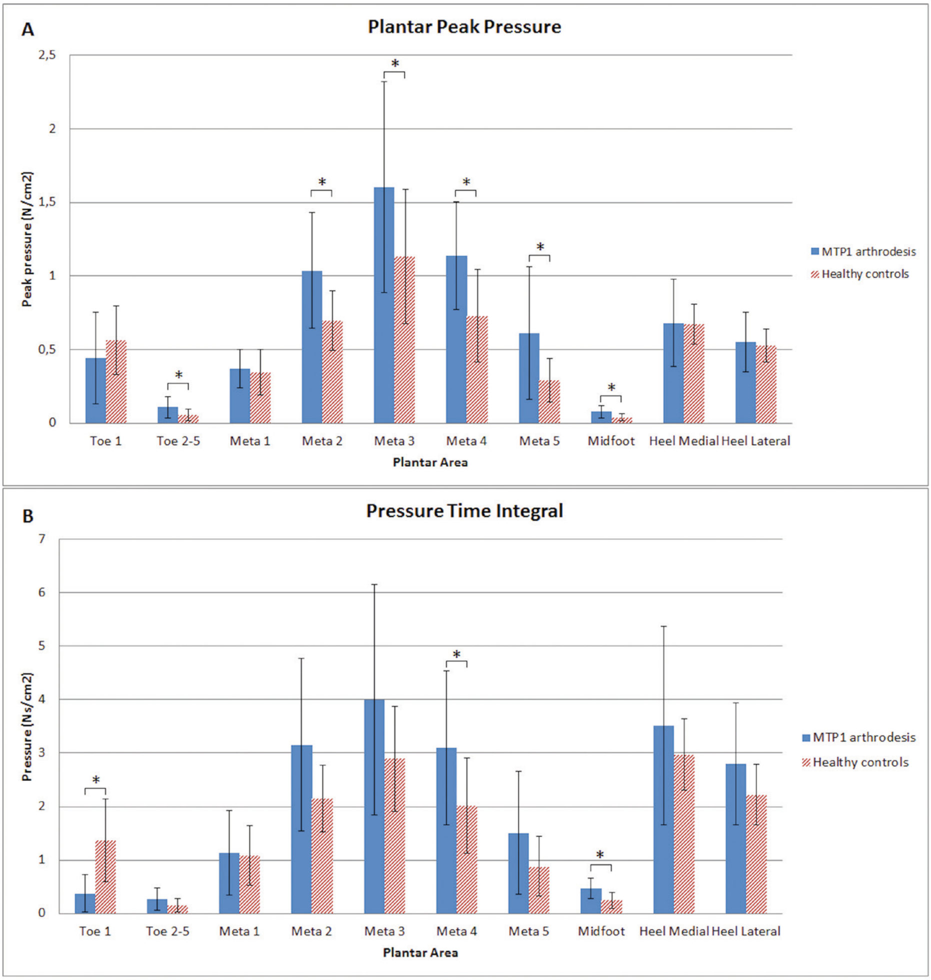

Figure 4. Plantar peak pressure (A) and pressure time integrals (B) for the ten anatomical areas of the foot for the MTP1 arthrodesis group and healthy controls.
** Indicates a significant difference between both groups (P <.05).*

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DISCUSSION

In this study, biomechanical gait properties, plantar pressures, and radiographs were evaluated in patients who underwent an arthrodesis of the MTP1 joint for symptomatic OA of this joint. This was the first study investigating the compensatory mechanism of the foot after this intervention in order to restore the gait pattern. We hypothesized that the hindfoot and forefoot would compensate due to less eversion of the hindfoot, followed by an increased supination of the forefoot. This compensatory mechanism subsequently results in decreased loading of the hallux and increased loading of the lesser metatarsals during stance.

As expected, our findings demonstrated an altered motion pattern in the forefoot and hindfoot after MTP1 arthrodesis. This motion pattern consisted of decreased eversion of the hindfoot during midstance, followed by increased internal rotation of the hindfoot in terminal stance, and ultimately increased supination and decreased adduction of the forefoot during preswing. In addition, decreased PTI beneath the hallux together with higher PTIs and PPs beneath the lesser metatarsals were observed. This consecutive altered motion pattern served as a compensatory mechanism in which the rigid hallux was avoided during roll-off. This was confirmed by the plantar pressure results showing a load transfer from the first ray towards the lesser metatarsals. These findings support our hypothesis that the hindfoot and forefoot are responsible for restoring the gait pattern after MTP1 arthrodesis.

To our knowledge, this was the first study evaluating foot and ankle kinematics after MTP1 arthrodesis with a multi-segment foot model. The validated OFM was used to assess foot and ankle kinematics in our study [18-20,23,24]. This foot model has been progressively used to gain more insight in the biomechanical consequences of foot and ankle pathologies on gait [25,26]. The high reliability of the OFM for measuring joint kinematics during gait has been proved in several studies. The highest repeatability was reported in the sagittal plane, followed by the frontal and transverse plane [18-20,23]. Previous studies evaluating gait properties after MTP1 arthrodesis are scarce and show a decrease in step length and step width [13-15]. A decrease in step width was observed in this study, which is consistent with a previous study of Brodsky et al, who suggested that this resulted in increased stability during gait [15]. However, we suggest that this is due to the higher number of women in the MTP1 arthrodesis group since it is known that step width is smaller in women [27,28]. As described before, none of these previous performed studies were able to evaluate the effects of MTP1 arthrodesis on foot and ankle kinematics as the models used in these studies were not suited for assessing foot and ankle kinematics. Therefore, the compensatory mechanism remained unclear.

From a kinematic point of view, the compensatory mechanism of the foot and ankle as shown in our study suggests a decreased loading of the hallux with subsequently increased loading of the lateral plantar areas of the foot. As stated, the results support our hypothesis as a decreased PTI beneath the hallux together with higher PPs beneath the second, third, fourth and fifth metatarsal heads and a higher PTI beneath the fourth metatarsal head were observed. This is contradictory to previous studies, which showed an increased PP beneath the hallux. Therefore, it was concluded that fusion of the MTP1 joint restored the weight-bearing function of the first ray due to pain relief and mechanical stabilisation of the medial column [8,14,17,29,30].

A possible explanation for the differences in results between our study and previous pressure studies is the nature of measuring plantar pressures, which was performed dynamically in this study while assessed statically in most previously reported studies [8,17,29,30]. In addition, previous studies were limited since they only reported PP, which gives information about the maximal pressure in an area during one timeframe but provides no information concerning the pressure load during the rest of the stance phase [14,31,32]. Our results perfectly demonstrate the additive value of assessing the PTI since this value showed that the hallux was less loaded during stance after MTP1 arthrodesis. If PP was used as our single pressure measurement outcome, this would have resulted in the incorrect conclusion that MTP1 arthrodesis restores the weight-bearing function of the hallux as no differences in PP beneath the hallux were observed between both groups.

Based on the observed compensatory mechanism, we expected to observe unloading of the first metatarsal head. This effect of a MTP1 arthrodesis was not observed. It is known from the literature that the optimal DFA of the hallux ranges between 20 and 25 degrees, with higher DFAs causing higher pressures beneath the first metatarsal [33,34]. In our opinion, decreased PP or PTI beneath the first metatarsal head was not observed since patients included in this study had an average DFA of 30 degrees.

This was the first study investigating the compensatory mechanism of the foot with a multisegment foot model and assessing PTIs of plantar areas in patients with MTP1 arthrodesis. Despite the described findings, we acknowledge that this study had some limitations. Selection of a gender- and age-matched control group would have been more appropriate as significant differences in gender and age distribution were detected between the groups. Besides, a significant difference in height was detected between both groups. The number of studies evaluating the effect of age, height, and gender on gait parameters is limited. It is known that age and height mainly affects gait velocity and gait velocity subsequently strongly influences foot kinematics [27,28,35-39]. Since gait velocity was comparable between both groups, the difference in age was deemed not to have influenced our results. In addition, the effect of gender on foot and ankle kinematics has not been defined yet, although some studies suggest a true gender effect in ankle motion in the sagittal plane [28,36,40] .Therefore, the effect of gender cannot be completely ruled out. In addition, it is known that a bilateral intervention or disease can influence gait characteristics since the limbs do not act independently during gait. Kinematics of unilateral and bilateral treated patients were compared to assess this potential effect. Kinematics at the knee, hip, and pelvic levels were visually compared in order to elucidate whether compensation appeared at a distal level (i.e. the foot) or at a more proximal level as well. Our data showed no major differences in segmental motion patterns, and maximum differences in joint angles were below 5 degrees for all motions (except sagittal hip and knee motion) at these proximal levels, resulting in the conclusion that compensation mainly occured in the foot. Subsequently, foot kinematics of these patients were visually compared, showing small differences in joint angles (ranging between 2 degrees and 5 degrees) between those patients. Therefore, it was concluded that inclusion of bilaterally treated patients did not significantly influence our data. However, we were only able to assess this visually as the number of feet that were unilaterally and bilaterally treated was too small for statistical evaluation.

Although both limbs do not act independently during gait, inclusion of both left and right feet of bilaterally evaluated healthy subjects was justified since no significant differences in ROM and joint motion patterns were observed between left and right feet.

Furthermore, small errors in marker placement could result in variability despite the acceptable to good reproducibility of the OFM [19,20,41]. To minimize this effect, one experienced researcher placed all markers. In addition, as this was the first study evaluating foot and ankle kinematics after MTP1 arthrodesis, sample size was not calculated before the start of the study. This study was therefore limited due to the number of included patients. As a result, inclusion of a patient with a more deviated gait pattern had a major influence on the presented results, as can be seen in the large variability in the presented joint motion patterns. Although variation in ROM and joint motion patterns existed between individuals, no major inconsistencies (i.e. phase shifts) were detected between subjects.

CONCLUSION

This was the first study demonstrating that the hindfoot and forefoot compensate for the loss of motion after MTP1 arthrodesis, thereby resulting in a gait pattern in which the lesser metatarsals endured higher peak pressures while the hallux was less loaded during the stance phase of gait. These results indicate that the foot had the intrinsic capacity to compensate for the loss of motion of the hallux after MTP1 arthrodesis. We suggest that a pre-existing reduced compensatory mechanism of the forefoot or hindfoot or the transfer of load from the first ray to the lesser metatarsals could result in persistence of symptoms in the minority of the patients who were dissatisfied after MTP1 arthrodesis. Prospective studies are necessary to demonstrate which of these explanations are the cause of the persistent complaints in the minority of the patients treated with an arthrodesis of the MTP1 joint.

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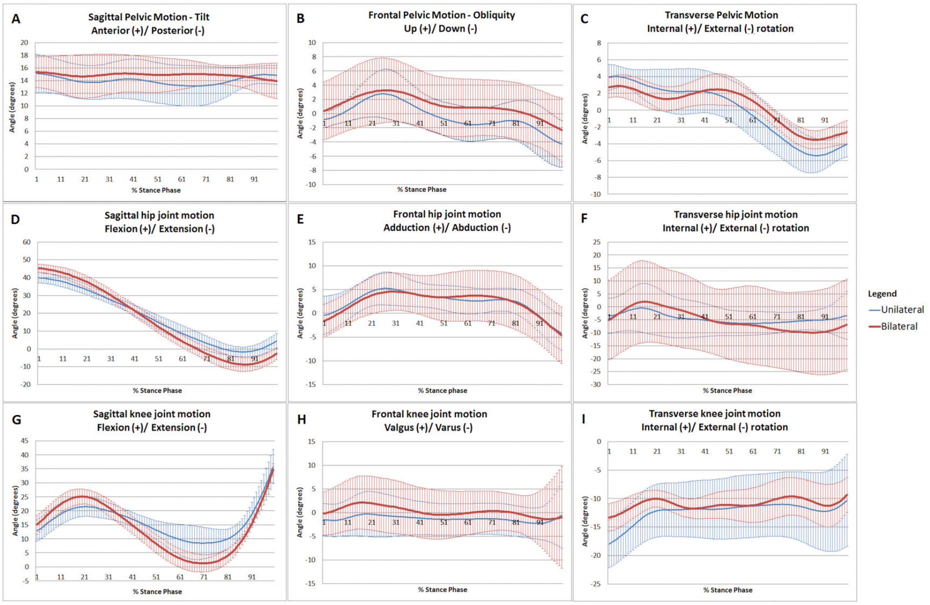
SUPPLEMENTARY FILES

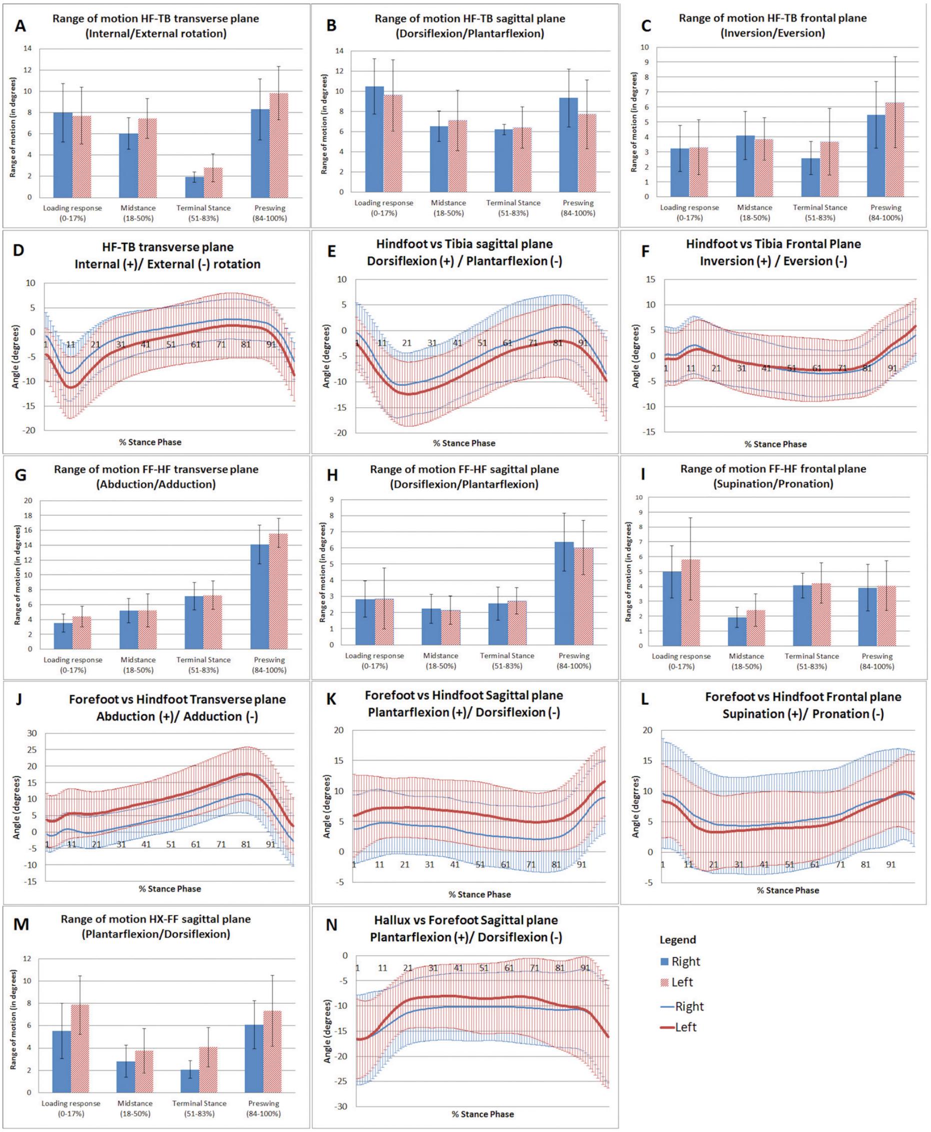
Appendix 1 – Marker placement protocol for the Oxford Foot Model.

Marker Name*	Placement
RPSI, LPSI	Posterior iliac spine
RTHI, LTHI (thigh)	The midway point of a straight line between the major trochanter and the knee
RASI, LASI	Anterior iliac spine
RKNE, LKNE (knee)	Lateral joint space of the knee
RHFB, LHFB (head of the fibula)	Directly on the proximal head of the fibula
RTUB, LTUB (tuberosity)	Tuberosity of the tibia
RTIB, LTIB (tibia)	Laterally on a straight line between the marker for the knee and for the ankle
RSHN, LSHN (shin)	Anteriorly on the middle of the tibia
RPCA, LPCA	Posterior calcaneus, static trial only
RANK, LANK (ankle)	Lateral malleolus
RMMA, LMMA (medial malleolus)	Medial aspect of the malleolus, static trial only
RCPEG, LCPEG	Wand marker on the heel pointing in cranial direction
RHEE, LHEE (heel)	The most distal aspect of the heel
RSTAL, LSTAL	Sustentaculum tali
RLCA, LLCA	Lateral calcaneus
RP5M, LP5M (proximal 5th metatarsal)	Lateral aspect of the proximal 5th metatarsal
RD5M, LD5M (distal 5th metatarsal)	Lateral aspect of the distal 5th metatarsal
RTOE, LTOE	Dorsum of the foot between phalanges 2 and 3
RHLX, LHLX (hallux)	Base of the hallux
RD1M, LD1M (distal 1st metatarsal)	Medial aspect of the distal 1st metatarsal, static trial only
RP1M, RP1M (proximal 1st metatarsal)	Medial aspect of the proximal 1st metatarsal

*A total of forty-two markers, each measuring 15 mm in diameter. R = right and L = left in the marker name.



Appendix 2. Averaged absolute joint angles for the pelvis (A-C), hip (D-F) and knee (G-I) in the sagittal, frontal and transverse plane during stance for patients with a unilateral and bilateral MTP1 arthrodesis.



Appendix 3. Range of motion and averaged absolute joint angles for the hindfoot-tibia segment (A-F), forefoot-hindfoot segment (G-L) and hallux-forefoot (M-N) segment in the transverse, sagittal and frontal plane during stance for left and right feet of bilaterally evaluated healthy controls.

* Indicates a significant difference in ROM (*P* <.0125).

CHAPTER 6

LONG-TERM EFFECTS OF CHEILECTOMY, KELLER'S ARTHROPLASTY, AND ARTHRODESIS FOR SYMPTOMATIC HALLUX RIGIDUS ON PATIENT-REPORTED AND RADIOLOGICAL OUTCOME

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Keywords

Hallux rigidus, cheilectomy, Keller's arthroplasty, arthrodesis, patient-reported outcome measure

Abbreviations

ANOVA	Analysis of Variances	ROM	Range of Motion
AOFAS-HMI	American Orthopaedic Foot & Ankle Society-Hallux Metatarsophalangeal Interphalangeal	FJS	Forgotten Joint Score
DFA	Dorsiflexion Fusion Angle	IMA	Intermetatarsal Angle
HVA	Hallux Valgus Angle	MOXFQ	Manchester-Oxford Foot Questionnaire
IP	Interphalangeal	PROM	Patient-Reported Outcome Measure
MTP1	First Metatarsophalangeal	VAS	Visual Analog Scale

ABSTRACT

Background: Several surgical interventions are available to alleviate pain in hallux rigidus, and the optimal operative technique is still a topic of debate among surgeons. Three of these are arthrodesis, cheilectomy, and Keller's arthroplasty. Currently, it is unclear which intervention yields the best long-term result. The aim of this study was to assess which of these interventions performed best in terms of patient-reported outcome, pain scores and disease recurrence at long-term follow-up.

Methods: These data are the follow-up to the initial study published in 2006. In the original study, 73 patients (n = 89 toes) with symptomatic hallux rigidus were recruited and underwent first metatarsophalangeal joint arthrodesis (n = 33 toes), cheilectomy (n = 28 toes) or Keller's arthroplasty (n = 28 toes). Outcome measures were AOFAS hallux metatarsophalangeal-interphalangeal (HMI) score, and pain was assessed with a visual analogue scale (VAS) at a mean follow-up period of 7-years. Patients of the original study were identified and invited to participate in the current study. Data were collected in the form of AOFAS-HMI score, VAS pain score, Manchester-Oxford Foot Questionnaire (MOXFQ), and Forgotten Joint Score (FJS-12). In addition, a clinical examination was performed and radiographs were gained. Data were available for 37 patients (n = 45 toes), with a mean follow-up period over 22-years.

Results: AOFAS-HMI and VAS pain score improved during follow-up only in arthrodesis patients. Furthermore, no statistically significant differences in clinical and patient-reported outcome were detected between groups based on AOFAS-HMI, VAS pain, MOXFQ or FJS-12. However, clinically important differences in patient-reported outcomes and pain scores were detected, favoring arthrodesis. Radiographic disease progression was more evident after cheilectomy compared with Keller's arthroplasty.

Conclusion: Arthrodesis, cheilectomy, and Keller's arthroplasty are 3 successful operative interventions to treat symptomatic hallux rigidus. Because clinically important differences were detected and symptoms still diminish many years after surgery, a slight preference was awarded for arthrodesis.

INTRODUCTION

Osteoarthritis (OA) of the first metatarsophalangeal (MTP1) joint, also known as hallux rigidus (HR), is a common disorder of the musculoskeletal system in middle-aged people and progresses with age. The exact etiology of HR is believed to be multifactorial because anatomic variation, trauma, surgery, deformations (eg, hallux valgus) and the length of the first metatarsal seem to be involved in the development of HR [1,2]. The prevalence is estimated at approximately 30% at an age of 50 years, and increases toward 40% for men and 55% for women at an age of 65 years [3]. HR is a major cause of chronic pain and disability and severely affects the experienced quality of life [4,5]. The osteoarthritic process results in loss of range of motion of the MTP1 joint and can be observed on conventional radiographs, although the grade of OA seen on radiographs poorly correlates with the experienced functional impairment [4-7].

Three widely used operative techniques for HR are cheilectomy, Keller's arthroplasty, and arthrodesis of the MTP1 joint [8]. Of these interventions, Keller's arthroplasty was originally reserved for low-demand, older patients, since it may result in a nonfunctional, unstable hallux and high incidence of metatarsalgia [8]. Cheilectomy is predominantly recommended for patients with mild to moderate HR resulting in high satisfaction rates at short term [8,9]. Arthrodesis is mainly performed in patients with severe HR and as a salvage procedure after prior HR surgery, resulting in high satisfaction rates but a stiff, motionless MTP1 joint [9].

6

In 2006, Beertema et al. published a study in which the outcome after these 3 interventions was assessed by using the AOFAS-HMI score and VAS pain score in HR patients. Cheilectomy and Keller's arthroplasty showed better outcome in low-grade HR (ie, Regnauld classification grade I or II), whereas the best outcome was after Keller's arthroplasty in grade III HR. Furthermore, pain scores were higher after arthrodesis in low-grade HR (ie, grade I HR). Therefore, it was concluded that cheilectomy should be considered in low-grade HR (ie, grade I or II) and Keller's arthroplasty in patients with any grade of HR (ie, grade I to III) [10].

Despite these valuable findings at 7 years of follow-up, no long-term comparative studies are available describing outcome of these operative interventions. In the literature, several studies described outcome after MTP1 arthrodesis or cheilectomy for HR, where only a few studies evaluated outcome after Keller's arthroplasty [10-14]. At the moment, only 2 studies have investigated the outcome after one of these interventions with a follow-up duration longer than 10 years [14,15].

The aim of this comparative follow-up study was to assess clinical and radiographic outcome after cheilectomy, Keller's arthroplasty, and arthrodesis in patients treated for HR after a very long follow-up period. We hypothesized that arthrodesis would perform better compared with cheilectomy due to disease progression in the latter group. Comparable outcomes for Keller's arthroplasty and the arthrodesis group were expected. In addition, an overview of the literature was provided.

METHODS

Study population

The present retrospective comparative cohort study was performed at the department of orthopedics of our institution and was a follow-up study to one by Beertema et al [10]. Patients were eligible for inclusion in the original study when they were treated for symptomatic hallux rigidus or hallux valgus/rigidus. All patients had pain and loss of motion of the MTP1 joint. Ninety-four feet (n = 77 patients) were included and treated with cheilectomy (n = 32), Keller's arthroplasty (n = 28), or arthrodesis (n = 34). Type of surgery was based on surgeon preference. Eventually, 89 feet (n = 73 patients) were included in the outcome analysis in the original study [10]. These subjects were eligible for inclusion in this follow-up study. Patients were invited to visit our outpatient clinic for a clinical examination (ie, patient anthropometrics, MTP1 joint and interphalangeal (IP) motion) and were independently examined by 2 investigators who were not involved in the primary operative procedure. Approval for this study was obtained from the local ethics committee, and all patients provided written informed consent.

Twenty-eight cheilectomy toes together with 33 arthrodesis toes and 28 Keller's arthroplasty toes were included in the original study (Figure 1) [10]. Of the cheilectomy group, 5 patients (6 toes) were deceased, 2 patients (2 toes) were lost to follow-up, and 7 patients (9 toes) were not able or not willing to participate, resulting in a total of 10 cheilectomy patients (11 toes) in this study. Regarding the arthrodesis group, 5 patients died (7 toes), 3 patients (3 toes) were untraceable at the time of this study, and 5 patients (7 toes) were not able or willing to participate, yielding a total of 12 arthrodesis patients (16 toes). In the Keller's arthroplasty group, 6 patients (7 toes) died, 1 patient was lost to follow-up (1 toe), and 2 patients (2 toes) were not willing or able to participate. As a result, 15 patients (18 toes) treated with a Keller's arthroplasty were included.

Demographic data of included subjects are shown in Table 1. No statistically significant differences between groups were observed for age at surgery, age at follow-up, follow-up duration, weight, length and BMI.

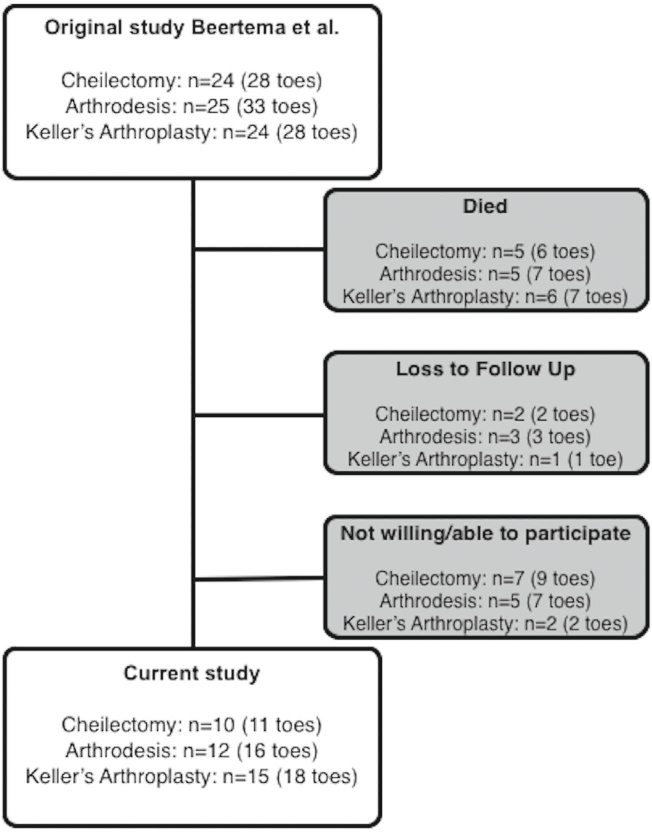

Figure 1. Study Population

Table 1. Patient Characteristics.[a]

	Keller's Arthroplasty (1)	Arthrodesis (2)	Cheilectomy (3)	*P* value 1-2	*P* value 1-3	*P* value 2-3
Patients (toes)	15 (18)	12 (16)	10 (11)	-	-	-
Man/female	9:6	4:8	6:4	-	-	-
Age Surgery, y	53.4 ± 7.5 (31-63)	49.5 ± 9.9 (34-68)	51.4 ± 7.0 (39-62)	.433	.882	.918
Age follow-up, y	75.1 ± 7.2 (57-87)	73.0 ± 8.2 (61-89)	74.1 ± 7.8 (62-86)	.865	.985	.982
Follow-up, y	22.4 ± 2.7 (19-27)	23.0 ± 3.8 (18-29)	22.6 ± 3.1 (19-28)	.926	.999	.977
Weight, kg	79.6 ± 12.1 (58-94)	79.4 ± 13.9 (58-94)	81.3 ± 7.4 (73-92)	.999	.985	.985
Length, m	1.69 ± 0.08 (1.50-1.77)	1.64 ± 0.13 (1.47-1.82)	1.72 ± 0.09 (1.63-1.86)	.634	.887	.350
BMI	27.9 ± 3.7 (22.1-34.8)	30.1 ± 7.6 (17.5-41.2)	27.6 ± 2.2 (23.1-29.6)	.700	.999	.710
MTP1 ROM, degrees	60.0 ± 13.3 (40-90)	0 ± 0 (0-0)	43.1 ± 18.7 (25-65)	-	.046[b]	-
Dorsiflexion, degrees	43.2 ± 14.4 (15-65)	0 ± 0 (0-0)	24.6 ± 19.0 (10-55)	-	.017[b]	-
IP motion, degrees	29.6 ± 21.5 (5-75)	23.2 ± 12.8 (5-50)	36.9 ± 14.6 (15-60)	.758	.727	.294

Abbreviations: BMI, body mass index; IP, interphalangeal; MTP1, first metatarsophalangeal joint; ROM, range of motion.

[a] Data are presented as mean with standard deviation and the range in parentheses.

[b] Statistically significant difference between groups in which a *P* value ≤.05 was considered as statistically significant.

Patient-reported outcomes

Patient-reported outcomes (PROs) were assessed by using the validated Manchester-Oxford Foot Questionnaire (MOXFQ) and Forgotten Joint Score (FJS) [16,17]. The MOXFQ is a 16-item instrument answered on a 5-point scale concerning walking/standing problems (7 items), foot pain (5 items), and issues related to social interaction (4 items) [16,18]. MOXFQ scores were presented on a 100-point scale, with 0 representing the best outcome and 100 the poorest outcome. The FJS is a 12-item questionnaire answered on a 5-point scale, which focuses on the awareness of having an affected joint during daily life and daily activities, and higher scores correspond with lower awareness (ie, 0 represents poorest outcome and awareness during all daily activities and 100 represents the best outcome and no awareness) [17].

Clinical outcome was assessed with the American Orthopaedic Foot & Ankle Society (AOFAS) rating system for the hallux metatarsophalangeal-interphalangeal (AOFAS-HMI) modified by Roukis et al [19,20]. This modified AOFAS-HMI allows 40 possible points for pain, 40 points for function, and 20 points for alignment, with higher scores corresponding with better outcomes. The AOFAS scores for the arthrodesis group were adjusted to eliminate 10 points devoted to range of motion, and scores were therefore calculated by dividing the subtotal by 90.

Current pain perception was assessed by using the visual analogue scale (VAS), where 0 corresponds with no pain and 10 with the most intense pain [21,22].

Radiographic evaluation

Weightbearing anterior-posterior and lateral radiographs were evaluated by 2 independent observers, who were blinded to clinical outcomes. The following parameters were evaluated on radiographs: intermetatarsal angle (IMA), hallux valgus angle (HVA), and dorsiflexion fusion angle (DFA) for the arthrodesis group [23]. The DFA was measured as described by Coughlin [24]. Mean angles of both measurements were calculated. Differences between observers greater than 5 degrees were resolved by consensus. As in the original study, Regnauld radiographic classification of HR was used to grade degenerative changes of the MTP1 joint in the cheilectomy and Keller's arthroplasty group [25].

Statistical analysis

Statistical analyses were performed with SPSS software (version 26; IBM, Armonk, NY). Analysis of variances (ANOVA), with post-hoc Gabriel correction, was used to detect differences in patient characteristics, outcomes of clinical questionnaires, IP ROM and radiographic angles between the 3 groups. Welch's *F* test was used to test for homogeneity of variance. The unpaired Student *t* test was used to test differences in MTP1 ROM and MTP1 dorsiflexion between the Keller's arthroplasty and cheilectomy group. Differences in AOFAS-HMI score between the original study and the present study were tested with the paired Student *t* test. A *P* value comparable to or less than .05 was considered to be statistically significant.

To evaluate the power of the study, effect sizes (Cohen *d*) were calculated for the patient-reported outcome measures (PROMs) as the standardized difference between 2 means divided by the standard deviation of either group. An effect size of 1.0 is equivalent to a change of 1 SD in the sample, which is considered to be a very large change, and an effect size of 0.8 is considered to be large, 0.5 is moderate, and 0.3 is small [26]. A large effect size subsequently corresponds with a high power, a small effect size with a low power.

RESULTS

Patient-reported outcome measures

After 22 years of follow-up, no statistically significant differences between groups in AOFAS-HMI score were detected (Table 2). However, AOFAS-HMI scores significantly improved during follow-up in the arthrodesis group (ie, 82.2 to 91.0; *P* = .022, Figure 2B). This improvement in outcome was not detected in the Keller's arthroplasty (ie, 86.1 to 83.9; *P* = .657) and cheilectomy group (ie, 79.8 to 77.1; *P* = .703). Although higher pain scores were reported in the cheilectomy group at long-term follow-up (ie, VAS 1.8 vs 0.7 and 0.7 in the arthrodesis and Keller's arthroplasty group, respectively), no statistically significant differences were detected between groups. VAS pain score significantly decreased in the arthrodesis group (ie, 1.9 to 0.7; *P* = .026, Figure 2A) during follow-up. This change in VAS pain score over time was not seen in the Keller's arthroplasty (ie, 1.2 to 0.7; *P* = .311) and cheilectomy group (ie, 2.0 to 1.8; *P* = .823). Comparable results in MOXFQ index score and 3 MOXFQ domain scores were seen at follow-up in the 3 groups. No statistically significant differences between groups were observed in terms of awareness of the operated joint, as assessed with the FJS, although lowest score (ie, highest awareness) was present in the cheilectomy group. Calculated effect sizes were small (≤0.3) for all the PROMs.

Table 2. Clinical Outcome Assessed with Patient-Reported Outcome Measures.[a]

	Keller's Arthroplasty (1)	**Arthrodesis (2)**	**Cheilectomy (3)**	***P*-value 1-2**	***P*-value 1-3**	***P*-value 2-3**
AOFAS-HMI[b]	83.9 ± 16.7 (54-100)	91.0 ± 6.8 (78-100)	77.1 ± 27.2 (24-100)	.704	.774	.335
VAS Pain	0.72 ± 1.23 (0-4.6)	0.66 ± 1.02 (0-3.9)	1.81 ± 2.28 (0-7.1)	.999	.171	.151
FJS-12 (in %)	82.6 ± 24.8 (8-100)	83.1 ± 22.1 (40-100)	71.8 ± 30.7 (25-100)	.999	.606	.590
MOXFQ index score	27.9 ± 33.6 (0-90.6)	19.6 ± 21.5 (0-62.5)	26 ± 24.9 (0-70.3)	.764	.997	.907
Standing/ Walking	27.8 ± 37.9 (0-96.4)	20.8 ± 27.7 (0-71.4)	24.4 ± 26.5 (0-64.3)	.888	.989	.988
Pain	23.3 ± 28.1 (0-75)	14.4 ± 17.1 (0-50)	20.9 ± 21.5 (0-65)	.586	.989	.845
Social Interaction	33.7 ± 36.1 (0-100)	23.9 ± 22 (0-68.8)	35.2 ± 31.9 (0-100)	.722	.999	.706

Abbreviations: AOFAS-HMI, American Orthopaedic Foot & Ankle Society (AOFAS) rating system for the Hallux Metatarsophalangeal-Interphalangeal (HMI); VAS, visual analogue scale; FJS, forgotten joint score; MOXFQ, Manchester-Oxford Foot Questionnaire.

[a] Data are presented as mean with standard deviation and the range in parentheses. $P \leq .05$ was considered as statistically significant.

[b] The adapted AOFAS-HMI score was used with a maximum achievable amount of points of 100.

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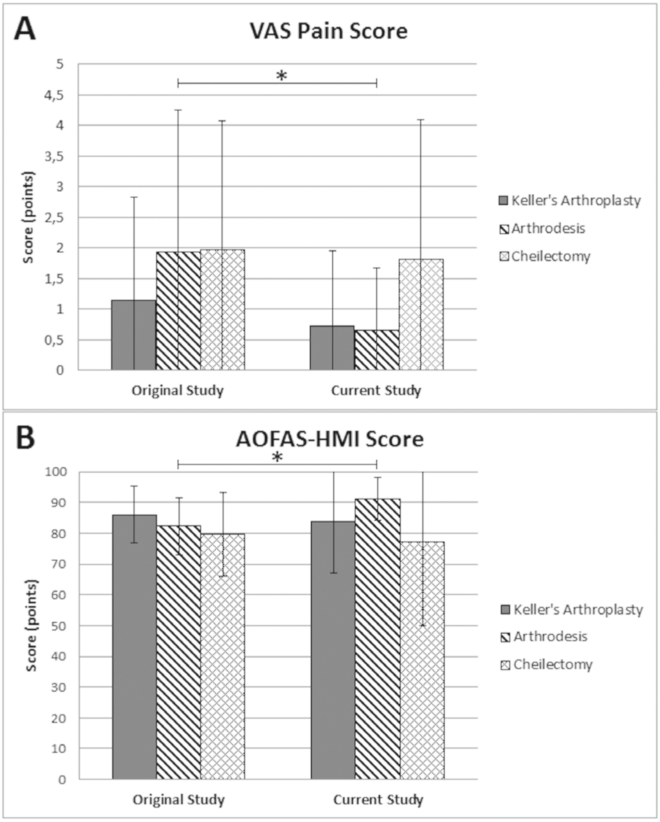

Figure 2. AOFAS-HMI scores and VAS pain scores for the Keller's arthroplasty, arthrodesis and cheilectomy groups of patients included in the original study and current study.
* *P* value ≤0.05 was considered as a statistically significant difference.

Radiographic evaluation and MTP1 Joint Motion

No statistically significant differences in IMA and HVA were detected between groups (Table 3). The highest degree of OA, assessed with Regnauld classification system, was seen in the Keller's arthroplasty groups as compared to the cheilectomy group (ie, 2.15 and 1.75, respectively). However the progression of OA over time was higher in the cheilectomy group (ie, 0.5 vs 0.15 degree in the Keller's arthroplasty group).

A statistically significant larger MTP1 ROM and MTP1 dorsiflexion was observed in the Keller's arthroplasty group as compared to the cheilectomy group (ie, 60.0 vs 43.1 degrees; *P* = .046 and 43.2 vs 24.6 degrees; *P* = 0.17, respectively). As expected, no motion in the MTP1 joint was detected after arthrodesis. No significant differences in IP ROM were observed between groups.

Table 3. Radiographic Evaluation of Keller's Arthroplasty, Arthrodesis and Cheilectomy at Follow-up.

	Keller's Arthroplasty (1)	Arthrodesis (2)	Cheilectomy (3)	*P* value 1-2	*P* value 1-3	*P* value 2-3
Patients (toes)	12 (14)	8 (10)	7 (8)	-	-	-
IMA, degrees	8.9 ± 3.0 (5.3-13.8)	10.4 ± 4.5 (6.4-19.5)	9.5 ± 2.5 (5.1-13.4)	.665	.969	.935
HVA, degrees	9.8 ± 8.0 (-3.4-24.8)	13.6 ± 10.0 (3.1-29.9)	15.9 ± 6.3 (7.1-26.9)	.617	.911	.278
DFA, degrees	NA	26.2 ± 8.0 (11.3-39.6)	NA	-	-	-
HR grade[b]	Gr I n = 2, Gr II n = 8, Gr III n = 4 Initial study: Gr 2 Current study: 2.15	NA	Gr I n = 3, Gr II n = 4, Gr III n = 1 Initial study: Gr 1.25 Current study: Gr 1.75	-	-	-

Abbreviations: DFA, dorsiflexion fusion angle; HVA, hallux valgus angle; IMA, intermetatarsal angle; IPA, interphalangeal angle; NA, not applicable;
[b]Grading system based on Regnauld [25].

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Overview of literature

An overview of the studies which assessed clinical outcome, patient-reported outcome or pain with the VAS or numeric rating scale (NRS) after cheilectomy (Appendix 1), Keller's arthroplasty (Appendix 2) and arthrodesis (Appendix 3) for symptomatic OA of the MTP1 joint were provided.

DISCUSSION

This study aimed to evaluate long-term patient-reported and radiographic outcome in patients who were treated with Keller's arthroplasty, arthrodesis or cheilectomy for HR [10]. Best outcomes were reported after cheilectomy and Keller's arthroplasty in low-grade HR and after Keller's arthroplasty in high-grade HR by using VAS pain and AOFAS-HMI score in the initial study, where patients had a mean follow-up duration of 7-years. In the present study, we hypothesized that the arthrodesis group and Keller's arthroplasty group would perform better as compared to cheilectomy, because of disease progression in the latter group.

As hypothesized, no significant differences between arthrodesis and Keller's arthroplasty were detected based on AOFAS-HMI score. Surprisingly, cheilectomy showed a comparable outcome, despite the disease progression that was detected on radiographs. Although differences in AOFAS-HMI scores between groups were not statistically significant, there was a clinically relevant difference between groups. In hallux surgery, a difference larger than 7.9 points in AOFAS score is considered as a minimal clinical important difference (MCID), that is, the smallest difference that is important for a patient or the smallest improvement considered worthwhile by a patient [27]. As a result, arthrodesis had a better outcome as compared to cheilectomy 22 years postoperatively.

Most arthrodesis studies published in the literature showed AOFAS-HMI scores ranging between 72 and 83 points [28-35], except for 3 other studies showing higher AOFAS-HMI scores (ie, 90 points) [9,32,36], and 1 study reporting a lower outcome (ie, 53 points) [37]. These studies had a mean follow-up period ranging between 28 months and 8.6 years. The results presented in this study showed that the AOFAS-HMI at long term was comparable with these studies, but also significantly improved over time. Based on our results and the literature, it can be concluded that an arthrodesis is an excellent intervention at very long term, with a positive time effect and longevity [15,28].

In cheilectomy studies, AOFAS-HMI scores ranged between 76 and 85 points after 1.1 to 5.4 years of follow-up [8,38-43]. Only Coughlin and Shurnas showed a better outcome after a longer follow-up period (ie, 90 points at 9.6 years post-surgery) [9]. The present results are consistent with the initial study at the 7-year follow-up and the outcome remained stable over years. Thus, the deterioration of the MTP-1 joint seen on radiographs did not significantly affect clinical outcome. This finding, that radiographic severity of OA is not necessarily inversely correlated with PROM, is more frequently observed in orthopedic surgery [44]. Keller's arthroplasty for HR is less well described in literature. Only 3 studies reported AOFAS-HMI scores ranging between 83 to 89 points with a wide spread in follow-up period from 14-months to 23-years [11-14]. Our results are consistent with these studies, which showed that the good mid-term results of a Keller's arthroplasty remain stable over a long time. In addition, the fear of having a nonfunctional first ray resulting in limitations and/or pain was not proved with these results.

In terms of pain, no significant differences between groups were detected in VAS-pain score. However, VAS-pain score significantly improved in the arthrodesis patients during follow-up. Unsurprisingly, results for the VAS-pain score were consistent with the AOFAS-HMI score, because a major part of the points in the AOFAS-HMI score were allocated for pain [19,20]. Arthrodesis is a highly effective intervention to reduce pain in HR, because fusion of the first metatarsal and proximal phalanx eliminates the motion between the osteoarthritic surfaces of these bones which causes pain. Previous studies showed a significant decrease in VAS-pain scores from values ranging between 6.2 and 8.7 preoperatively to 0.4 and 2.7 postoperatively, with in general lower VAS-pain scores in studies with a longer follow-up period [9,10,15,28,31,34,37,45-48]. The results presented in this study were in line with the literature and also demonstrate a further improvement in pain relief over time after arthrodesis of the MTP1 joint. This pain-reducing effect in HR is also reported for cheilectomy, reducing pain scores from values between 7.1 and 8.1 preoperatively to values 1.1 and 2.2 postoperatively [9,10,41,49-52]; no other study except the study of Beertema et al previously reported VAS-pain scores after Keller's arthroplasty [10]. Contrary to arthrodesis, no further decreases in VAS-pain scores were detected in these 2 groups. This might be due to disease recurrence and/or progression detected in follow-up radiographs. Although not statistically significant, a difference larger than 1.0, which is considered as an MCID for VAS pain scores, was present between the arthrodesis and Keller's arthroplasty group (ie, 1.2 points and 1.1, respectively) as compared to cheilectomy group [53]. Therefore, our results indicate that both arthrodesis and Keller's arthroplasty perform better as a pain-reducing intervention as compared to cheilectomy after very long follow-up.

No statistically significant differences between groups were identified by using the foot specific PROM MOXFQ, which is often used to assess outcome in hallux surgery [12,54,55]. Significant lower MOXFQ scores were expected in the arthrodesis group as compared to the cheilectomy group, especially in the pain domain due to disease progression in the cheilectomy group, and the Keller's arthroplasty group, because of biomechanical limitations due to the nature of the latter intervention. Also, there were no statistically significant differences; neither clinically important differences were identified because differences between groups were below the MCID values of 16, 12 and 24 for the walking/standing, pain and social interaction domain of MOXFQ [18]. The absence of statistically significant and clinically relevant differences might indicate that there were no true differences between groups. Other explanations were the lack of sensitivity to capture change of these scores, or the lack of power to detect changes due to the design of this study. The former explanation seems unlikely since the MOXFQ is an extensively tested PROM that is highly responsive for hallux surgery [18], whereas the latter could be present because of the relatively high number of dropouts due to the long period of follow-up.

In the literature, only 4 studies previously investigated the 3 studied interventions at 6 to 50 months by using the MOXFQ, and compared to our results showed better outcomes in MOXFQ for Keller's arthroplasty at short-term [12], comparable to cheilectomy studies [52,55], whereas better outcomes were presented in this study with respect to a previous arthrodesis study [54]. This is consistent with the results seen in the original article, in which it was stated that cheilectomy and Keller's arthroplasty yields best outcomes in the short term [10], but arthrodesis improves over time as shown in our results.

To our knowledge, this was the first study reporting the FJS-12 in HR surgery in order to evaluate joint awareness after HR surgery during normal daily activities. Although the FJS-12 is not validated for hallux surgery [17], it was thought that it had an added value on evaluating long-term outcome after hallux surgery, because it assesses how joint surgery affects normal daily activities and/or tasks and is therefore more specific than questionnaires assessing general quality of life, which were expected to be more influenced by major comorbidities. It was expected that disease progression after cheilectomy, which was expected and observed in radiographs, would have resulted in more joint awareness in daily living. However, no statistically significant differences in FJS-12 scores were detected between groups, which implies that radiographic disease progression does not necessarily corresponds with poorer patient-reported functioning during daily life. Nevertheless, a difference greater than 10 points was detected between the cheilectomy group and both the Keller's arthroplasty and arthrodesis groups. It is unclear if this relatively large difference is clinically relevant, since MCID values of FJS-12 are not known yet in foot surgery and are not available for evaluating the outcome of hip or knee surgery in which the FJS-12 is often applied.

The biggest strength of this study was the very long follow-up period of more than 22-years, evaluating 3 of the most commonly used interventions for symptomatic HR, that is, cheilectomy, Keller's arthroplasty, and arthrodesis.

Despite the very long follow-up period, the use of several clinical and patient-reported outcomes, radiological evaluation, and the comparison of the presented results with the results gained in the initial study, we acknowledge that this study had some limitations. There was a high dropout rate, since only 37 of the 73 subjects who participated in the initial study were able to participate in this study. This was inherent to the studied pathology that in general develops during aging, and the study design with a long follow-up duration. This study was therefore limited because of the number of patients. As a result, relatively large differences in PROMs detected in this study (eg, FJS-12 between arthrodesis and cheilectomy group) that were not statistically significant would probably be statistically significant with higher numbers of subjects, that is, the relative large dropout of patients in this study may have resulted in non-significant results because of chance. In addition, calculated effect sizes showed that this study was underpowered.

Lastly, randomization of patients in the original study would have been more appropriate. For example, cheilectomy was only performed in low-grade HR and arthrodesis predominantly in high-grade HR, which may have caused significant differences in clinical and patient-reported outcomes between groups before surgery. Assuming that the latter subjects had more worse preoperative scores, greater improvements after surgery would be expected in this group. As a result, arthrodesis would be favored, although this difference might be based on baseline difference in groups (ie, selection base). In our opinion, the lack of preoperative scores did not influence our results, because the original study already showed better outcomes after Keller's arthroplasty and cheilectomy for low-grade and high-grade HR respectively, as compared to arthrodesis. That arthrodesis yields better PROMs in the long term as compared to cheilectomy therefore seems to be a real effect.

CONCLUSION

The present study showed clinical, patient-reported, and radiological outcome at a follow-up of more than 22-years after arthrodesis, cheilectomy and Keller's arthroplasty for symptomatic HR. A significant further improvement in clinical outcome and pain reduction was seen after follow-up in the arthrodesis group, but not in the Keller's arthroplasty and cheilectomy group, indicating that symptoms can still diminish many years after surgery. Clinically important differences in outcome between arthrodesis and cheilectomy group were detected in the AOFAS-HMI and VAS-pain score, favoring arthrodesis. In addition, a clinically relevant lower pain score was also seen after Keller's arthroplasty as compared to cheilectomy 22 years after surgery. In addition, the greatest radiologic disease progression was observed in the cheilectomy group. The findings in this study, together with the presented previously performed studies, show that arthrodesis, cheilectomy and Keller's arthroplasty are 3 proper methods to treat symptomatic HR with good to excellent clinical and patient-reported outcome after a very long period after surgery. We did find a slightly better outcome for arthrodesis for treatment of HR base on clinical and patient-reported outcome.

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SUPPLEMENTARY FILES

Appendix 1. Previous Studies Evaluating Clinical Outcome with Questionnaires, Visual Analogue Scale for Pain, and First Metatarsophalangeal Joint Motion after Cheilectomy in Hallux Rigidus.

Author (y)	Study Design	Patients (Toes)	Age (y)†	Follow-up†	Stage of Disease	Clinical Outcomes	First Metatarsophalangeal Joint Motion
Easley et al. (1999)[38]	Retrospective case serie	57 (75)[a]	51 (36-70)	63 (37-92) months	Gr I n=2, Gr II n=24, Gr III n=42[c]	**AOFAS** 45 ± 13 to 85 ± 14*	**Dorsiflexion** 20° ± 7 to 39° ± 14* **ROM** 34° ± 9 to 64° ± 18*
Lau et al. (2001)[41]	Retrospective cohort study	19 (24)[b]	51.9 ± 7.9	2.0 ± 1.0 years	Gr II n=20, Gr III n=4[c]	**AOFAS** post: 78 ± 13.0, **FFI** post: 21.0 ± 24.5 **VAS** 8.1 ± 1.6 to 2.9 ± 2.2*	**Dorsiflexion** 14.1° ± 7.4 to 30.9° ± 7.7*
Feltham et al. (2001)[39]	Retrospective cohort study	67 (67)[a]	54.5 (23-80)	65 (28-117) months	Gr I n=4, Gr II n=37, Gr III n=16[d]	**AOFAS** post: 79.9	**ROM** 13° to 59°*
Coughlin and Shurnas (2003)[9]	Retrospective cohort study	80 (93)[a]	50 (16-76)	9.6 (2.3-20.3) years	Gr I n=6, Gr II n=32, Gr III n=34, Gr IV n=8[e]	**AOFAS** 45 (24-70) to 90 (67-100)* **VAS** 8 (6-10) to 1.5 (0-8)*	**Dorsiflexion** 14.5° (0-45) to 39° (10-65)* **ROM** 39° (5-80°) to 64° (15-110°)*
Keiserman (2005)[8]	Retrospective case serie	17 (8[a], 9[b])	55.5	34.2 (12-83) months	Gr II n=12, Gr III n=2[c]	**AOFAS** 61.2 to 85.5*	NA
Beertema et al (2006)[10]	Retrospective cohort study	24 (28)	49 (22-72)	8 (2-12) years	Gr I n=16, Gr II n=7, NA n=5[a]	**AOFAS** post:79.8 ± 13.6 (65-100) **VAS** post: 1.98 ± 2.09 (0-6.8)	**Dorsiflexion** 44° ± 16.0 (0-80) **ROM** 54.6° ± 20.3 (0-100)
Nawoczenski et al. (2008)[49]	Prospective case serie	20 (20)[a]	49 (34-63)	6.2 (4.6-8.9) years	NA	**VAS** 7.1 (2-10) to 1.7 (0-5)*	**ROM** 13.3° ± 12.7 to 21.7° ± 14.7*
Canseco et al. (2009)[56]	Prospective case serie	19 (19)[a]	50.5 (34-75)	1.5 years	NA	**AOFAS** significant increase (no values)	**ROM** significant increase (no values reported)
Lin and Murphy (2009)[42]	Retrospective case serie	20 (20)[a]	53.8 (29-69)	2.8 years	Gr I n=1, Gr II n=9, Gr III n=4[d]	**AOFAS** 53.5 to 84*	**ROM** 44.8° to 57.5*
Harrison et al. (2010)[55]	Prospective case serie	25 (25)[a]	62 (39-80)	17 (9-27) months	NA	**MOXFQ index** 33/64 to 9.6/64*[f] Walking/Standing ↓ 41.1 Pain ↓ 31.6 Social interaction ↓ 34.4	NA

Appendix 1. (Continued)

Author (y)	Study Design	Patients (Toes)	Age (y)†	Follow-up†	Stage of Disease	Clinical Outcomes	First Metatarsophalangeal Joint Motion
Smith et al. (2012)[43]	Prospective cohort study	17 (17)[a]	47.4 (37-64)	1.8 (1.0-3.6) years	NA	**AOFAS** 62 ± 7.7 to 81 ± 6.4*	**ROM** 33.9° ± 11.1 to 50.6° ± 11.3*
Kuni et al. (2014)[40]	Prospective case serie	8 (8)[a]	59.1 ± 6.4	1.1 ± 0.3 years	NA	**AOFAS** 56.9 ± 19.9 to 75.9 ± 13.9*	**ROM** 37.4° ± 8.3 to 34.8° ± 9.7
Nicolosi et al. (2015)[50]	Retrospective case serie	58 (58)[a]	55.7 ± 9.5	7.1 (0.8-14.9) years	NA	**VAS** post: 1.1 ± 1.6	NA
Ruff et al. (2018)[51]	Retrospective case serie	57 (57)[a]	56.7 (29-74)	49.2 (24-96) weeks	NA	**VAS** 6.5 (3-10) to 1.3 (0-6)*	**Dorsiflexion** 5.8° (0-10°) to 50.9° (32-72)*
Teoh et al. (2019)[52]	Prospective case serie	89 (98)[a]	54 (29-71)	50 (12-84) months	Gr I n=33, Gr II n=54, Gr III n=11[e]	**VAS** 8.0 (6-10) to 3 (0-10)* **MOXFQ index** 58.6 (30-94) to 30.5 (0-92)[g] Walking/Standing ↓32.4 Pain ↓ 31.5 Social interaction ↓ 26.1	

† Data are presented as mean with standard deviation and the range in parentheses.
* Significant difference in outcome after surgery; NA: not available;
[a] Cheilectomy
[b] Cheilectomy plus Kessel Bone Osteotomy
[c] Grading system based on Hattrup and Johnson
[d] Grading system based on Regnauld
[e] Grading system based on Coughlin and Shurnas
[f] A total of 64 was the maximum score in MOXFQ score
[g] A total of 100 was the maximum score in MOXFQ score

Appendix 2. Previous Studies Evaluating Clinical Outcome with Questionnaires, Visual Analogue Scale for Pain and First Metatarsophalangeal Joint Motion after Keller's Arthroplasty in Hallux Rigidus

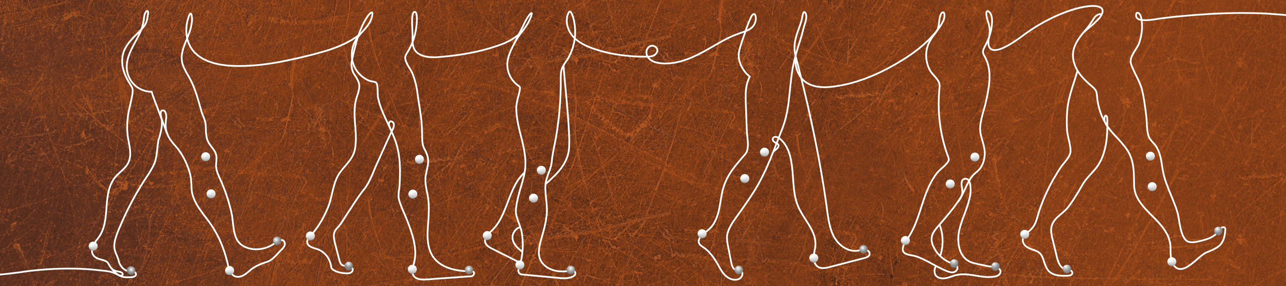
Author (y)	Study Design	Patients (Toes)	Age (y)†	Follow-up†	Stage of Disease	Clinical Outcome	First Metatarsophalangeal Joint Motion
Beertema et al (2006)[10]	Retrospective cohort study	24 (28)	58 (31-77)	6 (2-12) years	Gr I n=6, Gr II n=14, Gr III n=4, NA n=4[a]	**AOFAS** post: 86.1 ± 9.2 (72-100) **VAS** post: 1.15 ± 1.68 (0-5.7)	**Dorsiflexion** post: 44.6°±11.1 (30-65) **ROM** post: 59.4°±16.1 (20-85)
Schenk et al. (2009)[13]	Retrospective cohort study	22 (30)	57.8 (43.5-75.6)	14.1 (6-27) months	NA	**AOFAS** 50 to 88 ± 21.6*	**ROM** 28.2°±15.2 to52.2°±15.7*
Schneider et al. (2011)[14]	Retrospective case serie	78 (87)	50	23 (20-33) years	Mean Gr1.7[a]	**AOFAS** post: 83 (15-100)	**Dorsiflexion** post: 15°±16 **ROM** post: 30°±14
Coutts et al. (2012)[11]	Retrospective case serie	32 (42)	NA (42-78)	92 (36-154) months	Gr II n=42[a]	**AOFAS** 38 to 89*	**ROM** post: 59.5°
Maher et al. (2017)[12]	Retrospective cohort study	48 (53)	NA (45-89)	6 months	NA	**MOXFQ domain**[b] **Walking/Standing** 59.5 ± 25.4 to 21.8 ± 25.8* **Pain** 58.4 ± 16.6 to 23.1 ± 22.8* **Social interaction** 48.8 ± 23.6 to 14.6 ± 19.8*	NA

† Data are presented as mean with standard deviation and the range in parentheses.
* Significant increase in outcome after surgery; NA: not available;
[a]Grading system based on Regnauld
[b]A total of 100 was the maximum score in MOXFQ score

Appendix 3. Previous Studies Evaluating Clinical Outcome with Questionnaires, Visual Analogue Scale for Pain and First Metatarsophalangel Joint Motion after Arthrodesis in Hallux Rigidus

Author (y)	Study Design	Patients (Toes)	Age (y)†	Follow-up†	Stage of Disease	Clinical Outcome
Lombardi et al. (2001)[33]	Retrospective case series	17 (21)	53.2 (36-77)	28.1 (10-66) months	Gr II n=9, Gr III n=5, Gr IV n=4[a]	**AOFAS** 39.1 (10-70) to 75.6 (22-90)*
DeFrino et al. (2002)[36]	Prospective case series	9 (10)	56 (38-72)	34 (26-44) months	NA	**AOFAS** 38 (20-62) to 90 (74-100)*
Ettl et al. (2003)[37]	Retrospective case series	34 (38)	52 (24-71)	54 (18-116) months	Gr III n=38[a]	**AOFAS** post: 53 (5-84) **VAS** 8.0 to 2.7*
Coughlin and Shurnas (2003)[9]	Retrospective cohort study	30 (34)	50 (16-76)	6.7 (2.1-12.2) years	Gr III n=10, Gr IV n=20[b]	**AOFAS** 38 (24-60) to 89 (72-90)* **VAS** 8.7 (6.0-10) to 0.4 (0-5.0)*
Gibson et al. (2005)[46]	Randomized controlled trial	22 (38)	55 (34-77)	24 months	Gr I n=3, Gr II n=10, Gr III n=10, Gr IV n=15[b]	**VAS** 6.2±1.8 to 1.1±1.6*
Beertema et al. (2006)[10]	Retrospective cohort study	25 (34)	54 (31-68)	7 (2-13) years	Gr I n=4, Gr II n=18, Gr III n=7, NA n=5[a]	**AOFAS** post: 82.2±9.2 (67-100) **VAS** post: 1.93±2.32 (0-8)
Raikin et al. (2007)[34]	Retrospective cohort study	26 (27)	54.1 (32-73)	30 (13-67) months	NA	**AOFAS** 36.1 (19-62) to 83.8* **VAS** post: 0.7
Aas et al. (2008)[28]	Retrospective case series	35 (39)	52 (34-69)	8 (2-15) years	NA	**AOFAS** post: 74±15 (23-90) **VAS** post: 1.0±2.3 (0-8.4)
Wassink and van den Oever (2009)[57]	Retrospective case series	89 (109)	59 ± 10 (41-82)	69 (7-114) months	NA	**AOFAS** post: 50±12 (10-60)[d]
van Doeselaar et al. (2010)[48]	Prospective case series	27 (27)	58 (42-72)	37 (14-54) months	NA	**VAS** post: 0.5 (0-7.9)
Kim et al. (2012)[32]	Retrospective cohort study	51 (51)	60.5 ± 9.7 (36-84)	194 weeks	NA	**AOFAS** post: 90
Erdil et al. (2013)[31]	Retrospective cohort study	12 (12)	58.2 ± 8.5	35.33 (24-66) months	Gr III n=1, Gr IV n=11[b]	**AOFAS** 33.6 ± 3.8 to 76.1 ± 5.7* **VAS** 8.0 ± 0.7 to 0.5 ± 0.7*
Fanous et al. (2014)[54]	Prospective case serie	25 (26)	59 (38-75)	10 (4-10) months	Gr IV n=26[b]	**MOXFQ** 42/64 (21-54) to 18/64 (8-40)[c]
Simons et al. (2015)[47]	Retrospective cohort study	132 (132)	59.6 ± 9.5	39.5 (12-96) months	NA	**VAS** post: 1 (0-10)
Voskuijl (2015)[35]	Retrospective cohort study	50 (58)	63 ± 7.1 (47-78)	4.4 (1.3-7.0) years	NA	**AOFAS** post: 77±18
Baumhauer et al. (2016)[45]	Randomized controlled trial	50 (50)	54.9 ± 10.5 (32.4-78.2)	24 months	Gr II n=18, Gr III n=23, Gr IV n=19[b]	**VAS** 6.9 ± 1.4 (3.8-9.8) to 0.6 ± 1.2 (0-7.0)*
Chraim et al. (2016)[30]	Retrospective case series	60 (61)	68.5 (55-81)	47.3 (39-56) months	NA	**AOFAS** 40.9 ± 18.8 to 79.3 ± 11.2*
Stone et al. (2017)[15] i.e. follow-up study Gibson et al. (2005)[46]	Randomized controlled trial	30 (30)	NA	15.2 (13.8-17.2) years	NA	**VAS** 6.2 ± 1.8 to 0.5 (0-40)
Beekhuizen et al. (2018)[29] i.e. follow-up study Voskuijl et al. (2015)[35]	Retrospective cohort study	39 (47)	62.3 ± 7.7 (47-78)	103.2 ± 25.9 (61-141) months	NA	**AOFAS** post: 72.8 ± 14.5

† Data are presented as mean with standard deviation and the range in parentheses.
* Significant increase in outcome after surgery; NA: not available;
[a]Grading system based on Regnauld
[b]Grading system based on Coughlin and Shurnas
[c]A total of 100 was the maximum score in MOXFQ score
[d]Maximum achievable amount of points of 60



CHAPTER 7

GENERAL DISCUSSION

Hallux rigidus (HR) is a foot disorder with a high prevalence in elderly and an evident negative impact on daily life. To date, it is not clarified how HR affects one of the most basal activities, i.e. normal walking. The main objective of this thesis was to describe where the lower limb compensates for the loss of hallux motion in HR and subsequent MTP1 arthrodesis, to facilitate normal walking. Furthermore, this thesis aimed to discover which surgical intervention yields the best patient-reported outcome after treatment for symptomatic HR, refractory to conservative treatment.

OVERVIEW OF FINDINGS

Five studies were performed to achieve these objectives. Firstly, MTP1 arthrodesis is superior to total joint replacement in terms of pain reduction, clinical outcome, complication rate and revision rate based on results of our systematic review of the literature (**Chapter 2**). Next, three-dimensional gait analysis of HR subjects were performed by using the multi-segment Oxford Foot Model (OFM). Results demonstrated a decreased step length and increased forefoot supination in pre-swing as compensatory mechanism for the loss of hallux motion. Plantar pressure distributions were identical to healthy controls. This study provided a first insight in the compensatory mechanism of the foot in HR patients (**Chapter 3**). Then, lower limb kinematics of HR subjects were acquired by using the Plug-in Gait lower body model and gait deviation was defined with the Gait Profile Score (GPS). Intriguingly, HR caused a significantly altered GPS, which was positively correlated with patient-reported outcome (**Chapter 4**). Subsequently, subjects treated with a MTP1 arthrodesis were studied and exhibited compensatory forefoot and hindfoot motion during stance to facilitate walking. A decreased hindfoot eversion during midstance, followed by an increased hindfoot internal rotation in terminal stance and subsequent increased forefoot supination in pre-swing were observed. These results clearly illustrate the compensatory mechanism of the foot, thereby avoiding the stiff hallux during push-off. This altered motion pattern resulted in increased planter pressures underneath the lateral areas of the foot and decreased plantar pressures underneath the hallux (**Chapter 5**). Finally, outcome was recorded in subjects with a follow-up period over 22 years after surgery. No significant differences were found between subjects treated with cheilectomy, Keller's arthroplasty and arthrodesis on pain score, clinical and patient-reported outcome. However, a significant improvement in clinical outcome and pain reduction was seen in the arthrodesis group many years after surgery, and clinically relevant differences were present, leading to the conclusion that this is the most beneficial intervention in HR (**Chapter 6**).

GAIT ALTERNATIONS IN PATIENTS WITH HALLUX RIGIDUS

Adequate motion of the hallux, especially dorsiflexion in terminal stance and pre-swing, is crucial to facilitate normal walking. Restrictions in hallux motion can severely affect foot function, lead to alternations in gait pattern and induce pathological changes in the MTP1 joint [1]. HR is characterized by a limitation in MTP1 joint motion, where dorsiflexion is affected earlier and to a greater extent [2,3]. As a result, walking and other functional weight-bearing activities are problematic [4]. Although gait abnormalities have been described in HR [5,6], a thorough understanding of gait alterations and compensatory foot motion in HR and after MTP1 arthrodesis is lacking.

Spatiotemporal parameters are changed in hallux rigidus

Three-dimensional gait analysis demonstrated a shorter step and stride length in HR subjects as compared to healthy controls, while no significant differences in gait velocity, step width and stance time were present (**Chapter 3** & **Chapter 4**). These findings partly corroborate results from previous studies, where similar gait velocities were reported in one study [5], whereas a second study showed a significant lower walking speed in HR subjects as compared to controls [6]. An altered gait pattern to avoid weight-bearing of the painful hallux during toe-off is a proposed explanation for the observed shorter step length. When pain would be the major reason, shorter step length should also be present in other painful hallux pathologies. An example of such a painful disease, often affecting the MTP1 joint, is chronic gout. Subjects with chronic gout display a decrease in step length [7], together with a decrease in gait velocity and cadence [7,8], supporting this hypothesis. Another explanation for the decreased step length is mechanical impingement of the hallux and subsequent reduced push-off power generation [9,10]. Theoretically, a decreased step length would then also be seen in patient with an arthrodesis of the MTP1 joint. This effect was prescribed by Defrino et al. [11], but was not observed in this thesis (**Chapter 5)**, leaving the role of mechanical impingement unclear. Although these findings strengthen the idea that pain and hallux stiffness both play a role in the smaller step length present in HR subjects, their exact contribution remain not fully known and should be further explored, since this was not the main topic of this thesis.

Foot and ankle motion in hallux rigidus measured with a multi-segment foot model

Proper hallux dorsiflexion during terminal stance and pre-swing is mandatory for normal walking. The mean dorsiflexion angle of the MTP1 joint necessary for normal walking is approximately 45 degrees [1]. Results in this thesis illustrate that compensatory motion for the significantly limited hallux dorsiflexion in pre-swing occurs in the forefoot. An increased forefoot supination was observed in subjects with HR analyzed with the OFM (**Chapter 3**). This finding was not described in previously reported studies evaluating foot and ankle motion in HR [5,6]. This mechanism is presumably specific for HR, since distinct motion patterns were found in foot joints of hallux valgus patients [12]. The compensatory mechanism in subjects treated with MTP1 arthrodesis was more encompassing. A decreased eversion of the hindfoot in midstance, followed by an increased internal rotation of the hindfoot during terminal stance and ultimately more supination and less adduction of the forefoot during pre-swing was seen (**Chapter 5**). No previous studies studied foot and ankle kinematics after a MTP1 arthrodesis using a multi-segment foot model [11,13,14]. The presented novel findings provided a first step towards a better understanding of foot and ankle motion in patients with HR and subsequent treatment with a MTP1 arthrodesis.

Numerous multi-segment foot models (MFMs) are developed and successfully applied in clinical populations for analyzing foot and ankle motion [15,16]. These MFMs differ in the number of segments, segment definition, repeatability, and equipment required. To date, the most comprehensive model described is the Glasgow-Maastricht Foot Model, enabling evaluation of motion of all 26 bones of the foot [17,18]. Selection of the correct MFM should be based upon the clinical or biomechanical hypothesis. To achieve the objectives postulated in this thesis, the MFM must (i) contain a hallux segment, (ii) should be validated and (iii) must be applicable for use in clinical practice. Here, the Oxford Foot Model (OFM) was chosen since it includes a hallux segment [19], is extensively validated [20-26] and is often used in clinical research in foot and hallux pathology [12,27,28]. True MTP1 joint motion is measured in the OFM due to placement of the hallux marker on the proximal phalanx, thereby excluding first interphalangeal joint motion [19]. Other frequently applied MFMs containing a hallux segment are the DuPont Foot Model [29], Rizzoli Foot Model [30], Milwaukee Foot Model [31] and Heidelberg Foot Measurement Method [32]. Although all MFMs had clinically acceptable reliability, studies comparing those MFMs illustrated that caution should be taken when comparing results gained with different MFMs, since relevant differences between models exist [33,34]. For example, Schallig et al. illustrated significant differences in static and dynamic joint angles between the OFM and the Rizzoli Foot Model (RFM). In general, tibia-hindfoot range of motion was greater for the OFM, while range of motion was greater in the hindfoot-forefoot and forefoot-hallux segment for the RFM [35,36]. Repeatability of the RFM was slightly better as compared to the OFM in a study comparing several MFMs [37]. Both models were comparably sensitive to marker misplacement [38]. Especially misplacement of markers which define an axis of a segment coordinate system (e.g. the heel marker in the OFM) can introduce segment orientation errors larger than 5°, which are considered clinically relevant [38,39]. With the differences between and limitations of MFMs in mind, the OFM was considered a suitable MFM to reach the proposed objectives in this thesis.

Lower limb motion evaluated with the Gait Profile Score

Three-dimensional gait analysis generates a wide range of kinematic variables across the gait cycle. Clinical decisions were often based on interpretation of this complex information. This can lead to relevant differences in decisions between interpreters. Studies in children with cerebral palsy [40], subjects with rheumatoid arthritis [41], or subjects with hip, knee or ankle osteoarthritis [42], showed that foot abnormalities cause compensatory motion in proximal joint (i.e. ankle, knee, hip or pelvic motion). This mechanism, i.e. that a foot problem alters proximal joint motion, was also detected in HR subjects (**Chapter 4**). This insinuates that clinicians should thoroughly consider motion of lower limb joints when assessing a foot problem, leading to a larger amount of information to interpret. The Gait Profile Score (GPS) was used in this study to elucidate proximal joint motion. GPS provides a single measure of the 'quality' of a gait pattern and reduces the large amount of gait data into one index score. Subjectivity of choosing parameters of interest in data analysis (i.e. joints/planes) is thereby excluded. GPS can minimize differences in interpretations between clinicians since results are more easy to interpret [43]. GPS is proven to be a valid measure to gait deviation, since clinical rating of gait deviation is strongly correlated with GPS [43,44].

Results in this thesis proved that gait was significantly deviated in subjects with HR, reflected in a higher GPS. Gait Variable Scores (GVSs) $GVS_{ankle\ flexion}$ and $GVS_{pelvic\ rotation}$ contributed to the deviated GPS (**Chapter 4**), where especially $GVS_{ankle\ motion}$ substantially contributed. It seems logical that most compensatory motion for the diminished hallux motion took place in this adjacent joint. The additive value of using GPS as compared to particular joints or planes of interest was obvious, since no difference in sagittal range of motion of the hindfoot-tibia (i.e. the ankle) segment was detected (**Chapter 3** & **Chapter 4**), while $GVS_{ankle\ motion}$ was significantly different in HR subjects.

From literature, it is known that positive correlations between GPS and functional domains of patient-reported or clinical outcome measures exist (i.e. poorer outcome in patients with higher GPS) in subjects with clubfeet [45]. In this thesis, a positive correlation was discovered between GPS and patient-reported outcome (**Chapter 4**), especially between GPS and functional domains of questionnaires, clearly indicating that subjects with a more altered gait pattern experience more problems due to their foot problem. Simultaneously with performing this study, the Foot Profile Score (FPS) was presented by McCahill et al [46]. The FPS provides a gait index score in which detailed foot and ankle motion is represented, since GPS includes the traditional measurement of the foot as a single segment. Six key kinematic variables or Foot Variable Scores (FVS), (i.e. hindfoot dorsiflexion, forefoot dorsiflexion, hindfoot inversion, forefoot supination, forefoot adduction) are measured with the OFM and used in calculating FPS. FPS offers more information than gained with the GPS, since it reveals gait deviations not reflected by GPS [46]. It can be especially worthwhile to use in subjects with foot pathology as the dominant problem, where motion of proximal joints (or GPS) are relatively unaffected [46,47]. Therefore, it would be of interest to calculate FPS in subjects with HR.

Effects of compensatory motions on plantar pressure distribution

Numerous pedobarographic studies reported plantar pressure distribution in subjects with symptomatic HR. Studies showed an increased loading of the lesser metatarsal heads, most likely to avoid the painful hallux during push-off [48,49]. Most studies in literature used peak pressures as outcome measure [50]. Peak pressures are in our opinion less suitable, since they represent the maximal loading in an area under the foot, thereby not considering submaximal values. PTI describes the cumulative effect of pressure over time, giving the total load experienced by a plantar zone during stance [51]. Based on the observed increased forefoot supination in pre-swing, a lower PTI value underneath the hallux was expected. Surprisingly, this effect was not detected. It was thought that subjects, although their MTP1 joint motion is limited and painful, still have enough MTP1 joint motion not to affect plantar pressure distribution (**Chapter 3**). This hypothesis was supported by the results found in subjects treated with an arthrodesis for HR in which MTP1 joint motion was eliminated. Increased peak pressures and PTI underneath the lesser metatarsals and midfoot were present, while PTI underneath the hallux was less in these subjects, showing that elimination of MTP1 joint motion does affect plantar pressure distribution (**Chapter 5**). These results were contrary to previous studies, demonstrating an increased peak pressure beneath the hallux after MTP1 joint fusion [11,52-54]. Our study demonstrated the additive value of assessing plantar pressure with PTI, since this value showed less hallux loading after MTP1 arthrodesis while peak pressures were comparable between HR subjects and healthy controls. Based on the results presented in this thesis, we can conclude that hallux rigidus does not affect plantar pressure loading, while subsequent treatment with an arthrodesis does. After an arthrodesis, the hallux is less loaded while higher pressures were found in lateral plantar zones.

CLINICAL OUTCOME AFTER SURGERY FOR HALLUX RIGIDUS

Two of the most performed interventions in severe HR are MTP1 arthrodesis and total joint replacement (TJR). Until recently, it was not known which intervention performs best. Previous reviews were unable to fully answer this question, because a broad indication for TJR was used [55], only one outcome measure was used [56], and fair to poor quality studies where included [57]. To answer which intervention performs best, a systematic review of methodologically good-quality studies was performed. Results illustrated that arthrodesis is superior to TJR in terms of clinical outcome (i.e. American Orthopaedic Foot & Ankle Society (AOFAS) rating system for the Hallux Metatarsophalangeal-Interphalangeal; AOFAS-HMI), pain relief (i.e. Visual Analogue Score; VAS pain score), intervention-related complications and revision rates (**Chapter 2**). Remarkably, the number of randomized controlled studies comparing both interventions was low and most included studies were pro- or retrospective cohort studies or case-series. Although all included studies in this review were considered as having a low risk of bias, randomized controlled trials obviously have a higher level of evidence as compared to cohort studies and case-series [58].

Longest follow-up duration in an included study was eight years after an arthrodesis [59], which is a relatively short follow-up duration. Hence, a follow-up study was performed 22 years after an arthrodesis, Keller's arthroplasty or cheilectomy for HR (**Chapter 6**). To date this study has the longest follow-up duration evaluating outcome after these interventions. Interestingly, all three interventions performed comparable in terms of reported pain scores (VAS pain score), clinical- (AOFAS-HMI score) and patient-reported outcome (Forgotten Joint Score and Manchester-Oxford Foot Questionnaire). However, a noticeable further increase in clinical outcome and decrease in experienced pain during follow-up was solely observed in the arthrodesis group. In addition, clinically relevant differences detected were in favor of an arthrodesis. Based on the results presented in this thesis, arthrodesis can be considered as the best intervention for HR based on pain reducing effect and improvement in clinical and patient-reported outcome.

LIMITATIONS

Some limitations should be acknowledged when interpreting results of this thesis. This thesis elucidated the mechanism of the foot and lower limb to compensate for the decline in MTP1 joint motion in subjects with HR and subsequent MTP1 arthrodesis, thereby using the multi-segment OFM. Evaluating foot motion with MFMs has two intrinsic limitations, (i) simplification of the foot in rigid segments which are not rigid [60], and (ii) soft tissue artifacts (STA) [61]. STA are predominantly caused by three factors, i.e. skin deformation, bone motion beneath the skin and inertia of the markers during impact [62]. Bone pin studies can overcome both limitations and provide more accurate measures of joint motion, but are invasive [63,64]. Schallig et al. described the influence of STA in the OFM. Most STA was seen in the proximal heel marker (i.e. 9.3mm) and proximal malleolus marker (11.5mm). STA affect multi-segment joint kinematics with a mean joint angle error of 3.9°, and most in forefoot and hindfoot transverse plane motion [65]. As a consequence, errors based on STA can result in differences in segmental motion exceeding the limit of 5° which is considered as a clinically relevant difference [39]. Most notable changes in HR subjects were seen in forefoot frontal plane motion in pre-swing (i.e. increased forefoot supination), where changes exceed the mean joint angle error due to STA of 2.3°.

Moreover, knowledge and experience with marker placement according to the used MFM is essential to prevent errors due to marker misplacement, because every segment in the OFM has at least one marker with a placement sensitivity of ≥1°/mm [38]. However, studies address good intra- and interobserver repeatability of the tibia-hindfoot and hindfoot-forefoot segment, although repeatability of the hallux-forefoot segment is not studied before [19,21-23,66]. Most of these above mentioned limitations are inherent to MFMs and not completely avoidable. Attempts should be made to reduce the amount of error caused by STA and marker misplacements. Recently, the Amsterdam Foot Model (AFM) was developed and proven to be more robust to marker misplacements and showed smaller effects of STA as compared to the OFM and RFM [67]. This MFM was not available when studies in this thesis were conducted. Although the use of e.g. the AFM can reduce the errors generated by STA and marker misplacement in future studies, the limitations of measuring joint angles with MFMs should be taken into account when interpreting results from MFMs studies.

The GPS was computed to identify how HR affects lower limb kinematics in this thesis. The minimal clinically important difference (MCID) of the GPS is defined in children with cerebral palsy (value 1.6°), and it is known that MCID values vary per pathology [68,69]. To date, the MCID for HR subjects is not known. Nevertheless, GPS values found in this thesis are likely to be clinically relevant. Gait deviation in HR is expected to be less extensive as compared to cerebral palsy, resulting in a lower MCID for HR. Assessing gait deviation with FPS could potentially reveal additional relevant information. Unfortunately, FPS was not available at the time of conduction of this thesis.

The most reported outcome measure to assess outcome after surgery for HR in literature is the AOFAS-HMI score [70]. An outcome measurement must be reliable, valid and responsive to change [71]. The AOFAS-HMI scoring system is reliable and responsive [72,73], although only parts seem to be valid, which results in uncertainty about the validity of the entire scoring system [73-75]. Other patient-reported outcome measures, as the Foot Function Index (FFI), Manchester Oxford Foot Questionnaire (MOXFQ) and Short Form (SF)-36 are validated, reliable and responsive to assess foot related problems and general health in subjects with foot and ankle complaints [72,75,76]. In addition, the AOFAS-HMI score assigned points to MTP1 range of motion, which makes the use of this outcome measure less suitable for evaluation of MTP1 arthrodesis subjects [70]. The AOFAS-HMI score modified by Roukis et al. can be used to overcome this problem and was subsequently used in the follow-up study in this thesis [77]. With these limitations in mind, AOFAS-HMI score was included as outcome measure in this thesis since it is the far most commonly used scoring system. Due to the limitations of the AOFAS-HMI score, the use of the FFI, MOXFQ or SF-36, solely or together with the AOFAS-HMI score, are highly recommended in future studies to investigate patient-reported outcome.

RECOMMENDATIONS FOR FURTHER RESEARCH AND CLINICAL PRACTICE

While this thesis provides a first insight in gait characteristics in patients with HR, several important questions remain to be investigated. Subjects with HR demonstrate compensatory motions in foot, ankle and lower limb kinematics. Moreover, results in this thesis illustrate that gait deviation, represented with GPS, is correlated with patient-reported outcome, and especially functional and limitation subdomains.

A study in cerebral palsy patients demonstrated that pre-operative GPS value can be used to predict which patients benefit most from surgery [78]. It would be highly interesting and clinically relevant if pre-operative FPS can serve the same function in treatment of HR patients. Hence, future studies should first investigate the presence of a relationship between the compensatory mechanism in foot, evaluated with kinematic data of the foot (i.e. FPS and FVSs) and foot-specific validated patient-reported outcome measures (e.g. FFI, MOXFQ or SF-36).

Subsequently, subjects should be analyzed after surgical intervention to study whether surgery improved gait deviation and patient-reported outcome. These studies can reveal which compensatory motion patterns are needed to benefit most from a particular surgical intervention. In this way, these studies identify which gait parameters can be used to predict treatment outcome and help clinicians in deciding how to treat patients.

As MFM, we suggest to use both the AFM and OFM in these future studies. The AFM because it is more robust to marker misplacement and STA as compared to the OFM, but OFM as well since this is the only MFM available to create FPS to date. However, theoretically FPS can also be applied with the AFM. In our opinion, there is a minor role for plantar pressure analysis in predicting how subjects should be treated, since no differences in plantar loading were observed in this thesis in HR subjects.

Ultimately, after relevant gait parameters are identified, studies should ideally focus on studying if these parameters can be obtained with less extensive measurements than a three-dimensional gait analysis with a MFM in a gait laboratory. Although this can be time consuming, a recent study presented and validated a platform to compute movement dynamics using videos derived from smartphones. We acknowledge that several important steps have to be taken before this can be used in clinical practice, but clearly shows the potential of further implementing gait analysis in clinical practice in the near future. Although these recommendations for further research are focused on HR, the approach presented here is also suitable for other foot and ankle pathologies.

CONCLUDING REMARKS

This thesis clearly demonstrated that the foot, ankle and lower limb of patients with HR have compensatory mechanisms to facilitate efficient walking, despite the limitation in hallux motion. Biomechanics were measured with the OFM and Plug in Gait lower-body model. The forefoot compensates for the impaired hallux motion in HR, while the forefoot and hindfoot compensate for the loss of hallux motion after an arthrodesis. Besides, gait deviation observed in HR subjects was found to be correlated with patient-reported outcome and especially functional and limitation domains. Based on pain scores, clinical outcome and patient-reported outcome, patients with severe HR benefits most from an arthrodesis of the MTP1 joint. Decisions on how to treat patients are nowadays made based on patient characteristics, severity of HR and surgeon preference. The results in this thesis provide a first step in improving the treatment of HR, and future studies should focus on the applicability of MFMs in predicting treatment effect, thereby ultimately providing a subject-specific advise for treatment based on subject- and gait characteristics of an individual patient.

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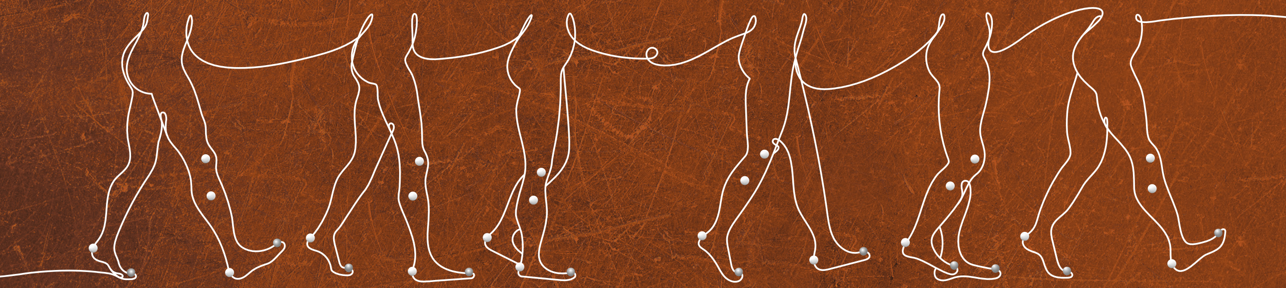


CHAPTER 8

IMPACT PARAGRAPH

AIMS, RESULTS AND CONCLUSIONS OF THE STUDIES

Hallux rigidus (HR) is a disease in which the joint of the great toe (hallux) is painful and stiff due to osteoarthritis. Hallux rigidus is the most prevalent form of osteoarthritis in the foot and the occurrence of HR is expected to increase due to aging of the population. The hallux is of major importance in human walking. Diseases of the hallux such as HR are known to have a severe impact on walking and other daily activities, thereby negatively influencing the experienced quality of life. In which way HR influences gait and how the foot and lower limb compensate for this limited motion of the hallux is not known. Several surgical options are available to treat patients in whom conservative treatment failed. Although numerous studies have reported outcome after surgery, it is not known which intervention is superior in treating HR. This thesis describes several scientific studies to broaden our knowledge of gait characteristics and patient-reported outcome of patients with hallux rigidus (HR). In this chapter, these studies and their outcome are positioned in a broader context to transfer the scientific knowledge described into clinical practice and social impact.

A literature study was performed in **Chapter 2**, to examine whether a fusion of the great toe joint (or MTP1 arthrodesis) or replacement of the joint resulted in the best outcome. A MTP1 arthrodesis tend to be superior in reducing pain, improving clinical outcome and had less intervention-related complications and revisions illustrated by the results of this study.

In **Chapter 3**, gait and foot motion of patients with HR was investigated. As expected, diminished motion in the great toe was present. Increased motion of the forefoot was seen during push-off, to facilitate normal walking, while no difference in plantar loading was detected. Hence, this study illustrated that the foot itself has the capacity to compensate for the loss of motion in the hallux in patients with HR.

Whether this also influenced other joints in the lower limb was investigated in **Chapter 4**. Results revealed that patients with HR had a different gait pattern as compared to healthy subjects. Especially the ankle and pelvis are contributing to this altered gait pattern. Notably, there was a relation between the extent of gait deviation and the degree of well-being of patients, reported by themselves. The existence of such a relation between objective measured gait deviation and patient-reported outcome was not previously reported in HR patients.

The effect of fusion of the MTP1 joint, also known as an arthrodesis, on foot motion was studied in **Chapter 5**. Results illustrated that compensatory motion in the hindfoot and forefoot enables the subject to walk efficiently, avoiding the rigid hallux while pushing-off. This resulted in a decreased pressure underneath the hallux and higher pressures under the outer plantar zones of the foot. This was the first study describing this compensatory mechanism after a MTP1 arthrodesis for HR.

Most studies reporting patient-reported outcome after HR have a follow-up period of months to a maximum of several years after surgery. In **Chapter 6**, the outcome after three surgical interventions (i.e. arthrodesis, cheilectomy and Keller's arthroplasty) for HR were evaluated more than 22 years after surgery. Results showed comparable pain scores, clinical outcomes and patient-reported outcomes among these three interventions. However, only subjects with MTP1 arthrodesis showed a further decrease in experienced pain and improvement in clinical outcome. Moreover, a clinically relevant better outcome was detected after arthrodesis as compared to cheilectomy and clinically relevant lower pain scores were seen after arthrodesis and Keller's arthroplasty as compared to cheilectomy. This led to the conclusion that based on these outcome measures, arthrodesis is the favorable intervention to treat patients with HR.

RELEVANCE

Aging is a major social challenge, due to increased risk of diseases which influence quality of life and health care costs. HR is an example of such a disease, since it is the most prevalent form of osteoarthritis in the foot and prevalence increases with aging.

Results of this thesis highly contribute to a further understanding of the effects of HR and treatment on walking, since no previous studies described the effects of HR on foot, ankle and lower limb motion in subjects with HR and after treatment with a MTP1 arthrodesis. This is the most performed intervention, because it tends to be the best choice based on patient-reported outcome and pain reducing effect. Previous studies in other diseases such as cerebral palsy showed that gait patterns can be used to predict outcome after surgery. Results in this thesis can form a starting point for future studies, to see whether this is also applicable for HR. Predicting outcome prior to surgery based on a person's walking pattern enables clinicians to give a better personalized advise for treatment. At patient-level, this will improve post-operative self-reliance, and will counteract inactivity with conjoined negative health effects. At health-care level, it will reduce hospital visits and revision surgeries needed. At sociopolitical-level these factors will contribute to keep the general health cost, which are already rising for years, affordable and improve 'healthy' aging.

ACTIVITIES AND PRODUCTS

The findings of this thesis have led to several activities in the field of expertise. The results of this thesis have been presented at various symposia and congresses, including the Northern Orthopaedic Federation Congress in 2016 (Linköping, Sweden), Nederlandse Orthopaedische Vereniging (NOV) congress in 2016 (Utrecht, The Netherlands), Gruijter symposium in 2016 (Alkmaar, The Netherlands), European Orthopedic Research Society (EORS) Annual Meeting in 2016 (Bologna, Italy) and 2017 (Munich, Germany). Furthermore, the findings have been translated into original manuscripts which were published in international scientific journals. Moreover, a summary of results were described in the most read medical journal in The Netherlands (Nederlands Tijdschrift voor Geneeskunde; NTVG 2018;162:D2547).

In addition, results have been presented at different meetings at Maastricht University, Maastricht University Medical Centre, Zuyderland Medical Centre (location Sittard), Amsterdam University Medical Centre (location Vrije Universiteit Amsterdam) and Noordwest Ziekenhuisgroep (location Alkmaar). In addition, results were presented at the Department of Mechanical and Manufacturing Engineering, Aalborg University, during a short internship to enlarge knowledge of foot modelling. Furthermore, a collaboration between the Department of Orthopedic Surgery of the Maastricht University Medical Centre, Department of Orthopedic Surgery of the Noordwest Ziekenhuisgroep (Alkmaar) and Department of Rehabilitation Medicine of Amsterdam UMC was set-up during this PhD-trajectory. This collaboration resulted in a research period in the Amsterdam UMC, to gain more expertise in gait analysis. In addition, results presented in this thesis were used for educational purposes for student at Maastricht University. At last, this thesis may inspire future research in understanding gait in patients with HR and determining methods to improve treatment of subjects with HR.

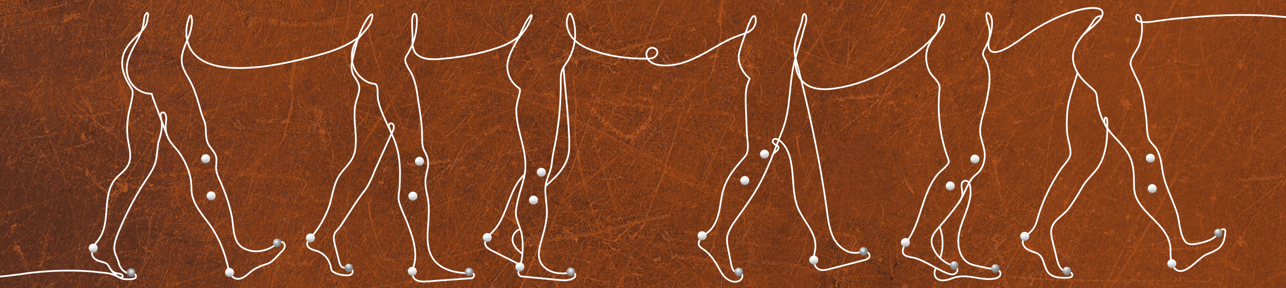
TARGET GROUPS

Health care professionals

The results of this thesis are primarily important for health care providers, such as orthopedic surgeons, general practitioners and physiotherapists. Orthopedic surgeons can use results described in this thesis in deciding which intervention to perform. For example, it is reasonable to assume that subjects with osteoarthritic changes in the forefoot and hindfoot will benefit less from and should not be treated with a MTP1 arthrodesis, since these are the major compensatory segments after surgery. General practitioners and physiotherapists can use the information from this thesis to give a thorough explanation to patients, when they visit them and report complaints in adjacent, compensating joints. Furthermore, results obtained in this thesis can be used for the development of a uniform guideline for clinicians who will treat patients with HR at different stages of disease. At the moment, such guideline is not available for foot and ankle problems, while it is available for wrist and hand problems (i.e. NHG-standaard M91; Hand- en polsklachten – February 2021).

Patients with Hallux Rigidus

This thesis shed light on gait characteristics and compensatory joint motion in HR subjects. On the long term, patients may benefit from a better understanding of gait impairments in HR. If future studies are able to develop a method in which personalized treatment is optimized based on evaluation of gait and subsequently guidelines are developed, patients will definitely benefit.



APPENDICES

SUMMARY

SAMENVATTING

ABOUT THE AUTHOR

PUBLICATIONS

DANKWOORD

SUMMARY

The first metatarsophalangeal (MTP1) joint is the most often affected joint by osteoarthritis in human feet, a condition known as hallux rigidus (HR). The prevalence of HR is higher than hip OA and equivalent to knee OA. The hallux is an essential structure in human locomotion and HR is known to have a major detrimental effect on quality of life, since it causes pain and major limitations during normal daily tasks. Conservative therapy (i.e. pain killers, foot orthoses or shoe wear modifications) is initially recommended, while surgical interventions will be considered when conservative treatment fails. Multiple joint preserving and joint destructive methods are described in literature to treat symptomatic HR. Finding the correct therapy for a specific patient is not trivial. Ideally, an intervention reduces pain, restores joint motion, and maintains hallux alignment and length to make normal daily activities possible. All available methods have their advantages in terms of pain relief and return to activities, but also have their surgical difficulties and intervention-related complications.

Besides, each intervention will influence gait, and in particular foot and ankle motion, in a specific manner. It is reasonable to assume that an intervention which requires compensatory motion in adjacent foot joints is not or less suitable in a subject with osteoarthritic changes in those joints as well. In this situation, it is crucial for a surgeon to have knowledge about the compensatory mechanism of the foot for the altered motion of the affected joint. However, before we can provide a personalized advice, it is essential to have a thorough understanding of how the disease HR affects gait characteristics and foot, ankle and lower limb kinematics. To date, this is not sufficiently known.

Three-dimensional gait analysis with a multi-segment foot model can provide this essential information. Therefore, the goals of this thesis were: 1) to get a better understanding of how HR affect gait characteristics before and after treatment, 2) understand which intervention yields the best patient-reported outcome and 3) to investigate whether there is a correlation between gait deviations and patient-reported outcome.

Chapter 2 demonstrated the results from a systematic review of the literature, with the objective to assess whether a MTP1 arthrodesis or total joint replacement is superior in reducing pain and improving clinical outcome in subjects with HR. Results illustrated that MTP1 arthrodesis is superior to total joint replacement (TJR) in reducing pain, obtained with the visual analogue scale (VAS), and improves clinical outcome, measured with the American Orthopaedic Foot & Ankle Society-Hallux Metatarsophalangeal

Interphalangeal (AOFAS-HMI) scoring system. However, both techniques significantly reduced pain and improved clinical outcome. Furthermore, significantly higher rates of intervention-related complications were reported after TJR as compared to MTP1 arthrodesis, with prosthetic loosening being the most reported complication after TJR and pain requiring hardware removal after MTP1 arthrodesis. Subsequently, revision rate after TJR was high. This literature study led to the conclusion that arthrodesis was superior to TJR based on clinical outcomes, complication rate and revision rate.

Based on results described in **Chapter 2**, it cannot be assumed that an arthrodesis is the best intervention for every patient, and it is possible that specific patients will benefit more from a TJR than from an arthrodesis. We hypothesize that limitations in foot and ankle joint motion may play a major role in the (un)successiveness of an intervention since adjacent joints must compensate for the limited or altered motion in HR or the treated MTP1 joint.

Before testing this hypothesis, foot and ankle motion should be clarified in detail in HR subjects. Gait characteristics of subjects with symptomatic HR prior to surgery were compared to healthy controls with three-dimensional gait analysis by using the multi-segment Oxford Foot Model (**Chapter 3**). Step length was significantly shorter in the HR group, while no difference in gait velocity was detected. As expected, HR significantly affects sagittal hallux motion, where a reduced hallux dorsiflexion was detected during push-off. Moreover, an increased forefoot supination was observed during pre-swing. This led to the conclusion that the forefoot compensates for the loss of MTP1 joint in HR by increased supination, to avoid the rigid and painful hallux during push-off. Based on these kinematic changes in hallux and forefoot, increased plantar pressure beneath the lateral plantar zones of the foot were expected, but not detected after analyzing plantar pressure. This study elucidated the compensatory mechanism in the foot to facilitate efficient walking in patients with HR.

The compensatory mechanism in the forefoot for the loss of MTP1 joint in HR as revealed in **Chapter 3**, may not be the only compensatory mechanism. It is conceivable that proximal joints (i.e. the ankle, knee, hip and pelvis) contribute as well. The effects of HR on lower limb joint kinematics were investigated by calculation of the Gait Profile Score (GPS) in **Chapter 4**. GPS provides a single measurement of quality of an individual's gait pattern based on nine key kinematic Gait Variable Scores (GVS), with higher values representing a more deviated gait pattern. These parameters exclude subjectivity of choosing parameters of interest (i.e. joint/planes) for analysis and are proven to be appropriate outcome measures for evaluating functional limitations during gait. Significant higher GPS, $GVS_{pelvic\ rotation}$ and $GVS_{ankle\ flexion}$ were detected in the HR group as compared to healthy controls. The altered sagittal ankle motion (i.e. $GVS_{ankle\ flexion}$) explained most of the deviation observed in GPS. Next, the correlation between gait deviation and patient-reported outcome was determined. The Manchester Oxford Foot Questionnaire (MOXFQ), a patient-reported validated outcome measure for foot pathology, containing a 'foot-pain', 'walking/standing problems' and 'issues related to social interactions' domain and Foot Function Index (FFI), a self-administered questionnaire used to assess foot complaints in terms of limitations, pain and disabilities were obtained. Significant correlations of GPS with the MOXFQ and between GPS and $GVS_{ankle\ flexion}$ with the MOXFQ 'walking/standing' domain were detected. In addition, a significant correlation between GPS and the FFI 'disabilities' domain was found. These results indicate that subjects with a more deviated gait (i.e. higher GPS and $GVS_{ankle\ flexion}$ values) experienced more disabilities and/or problems while walking. Next to altering foot kinematics (**Chapter 3**), HR also affects lower limb kinematics (**Chapter 4**), where a correlation between objective measures of gait (i.e. GPS and GVS) and patient-reported outcome was found.

A thorough understanding of the influence of HR gait parameters and kinematics on foot and ankle level (**Chapter 3**) and lower limb kinematics (**Chapter 4**) was gained. The influences of treatment with the "golden standard", i.e. a MTP1 arthrodesis, on gait characteristics was subsequently investigated and described in **Chapter 5**. Gait parameters of subjects treated with a MTP1 arthrodesis were compared to healthy controls. Step width was significantly smaller in the MTP1 arthrodesis group while other studied spatio-temporal parameters were comparable between groups. Kinematic analysis showed a significantly decreased hindfoot eversion in midstance, followed by an increased hindfoot internal rotation during terminal stance and subsequent increased forefoot supination in pre-swing after MTP1 arthrodesis. As expected, less hallux plantar flexion in loading response and less hallux dorsiflexion in terminal stance were detected. These compensatory motion patterns suggest unloading of the hallux during stance, which was confirmed with plantar pressure analysis. Higher peak pressures were detected between toe 2-5 and the lesser metatarsals during stance, while total pressure measured with pressure-time integrals was significant lower underneath the hallux and increased under metatarsal 4 and the midfoot. This study showed the compensatory mechanism of the foot after a MTP1 arthrodesis, what subsequently leaded to an altered loading pattern of the foot.

In **Chapter 6**, patient-reported outcome, clinical outcome, pain score and disease recurrence were described after MTP1 arthrodesis, cheilectomy and Keller's arthroplasty for HR. Participants in this study were initially evaluated 7 years after surgery, while this study had a follow-up period of 22 years. No statistically significant differences in AOFAS-HMI score, pain scores, or patient-reported outcome, measured with the MOXFQ and Forgotten Joint Score, were reported between groups after this follow-up period. However, AOFAS-HMI score improved and pain score decreased in the arthrodesis group during follow-up. In addition, although not statistically significant, a clinically relevant difference in AOFAS-HMI score was found where arthrodesis had a better outcome compared to cheilectomy. In addition, a clinically relevant lower VAS pain score was present after arthrodesis and Keller's arthroplasty as compared to cheilectomy after 22 years follow-up. Highest degrees of MTP1 OA were detected in the Keller's arthroplasty group, although progression of OA over time was highest after a cheilectomy. Based on these results, a slightly better outcome after arthrodesis for HR was found.

In **Chapter 7**, the main findings of this thesis were discussed in light of current literature. This thesis showed that the foot, ankle and lower body are able to compensate for the limited hallux motion in HR and absent hallux motion after an arthrodesis of the MTP1 joint. The forefoot, ankle and pelvis are responsible for this compensatory mechanism in HR, with the forefoot and hindfoot being responsible after an arthrodesis. Furthermore, an arthrodesis is the preferred method in the treatment of HR based on a review of the literature and based on a comparative study with a very long follow-up period. The current thesis therefore provides a basis for further research studying gait alterations in HR. These findings provide a first insight in the effect of HR and subsequent treatment on gait, which is important in order to determine whether gait analysis can be applied as a predictive tool for treatment. In addition, the limitations of the thesis and recommendations for further research were described in this chapter. In our opinion, future studies should identify the relationship between gait characteristics and patient-reported outcome prior and after multiple interventions for HR, in order to determine the feasibility of gait analysis as a prognostic tool for optimalisation of treatment of patients with HR.

SAMENVATTING

In de voet van de mens komt artrose het meeste voor in het eerste metatarsophalangeale (MTP1) gewricht, een aandoening genaamd hallux rigidus (HR). De prevalentie van HR is hoger vergeleken met heupartrose en gelijk aan knieartrose. De grote teen, of hallux, is een belangrijke structuur tijdens het lopen. Het is bekend dat HR een negatieve invloed heeft op kwaliteit van leven, aangezien het pijn veroorzaakt en beperkingen oplevert in het uitvoeren van normale dagelijkse bezigheden. Conservatieve behandeling (waaronder pijnstillers, inlegzolen en schoenaanpassingen) wordt initieel geadviseerd aan patiënten met HR, waarbij chirurgische behandeling overwogen zal worden wanneer conservatieve behandeling onvoldoende heeft geholpen. Verscheidene operatieve methodes waarin het MTP1 gewricht wordt behouden of wordt opgeofferd, zijn beschreven in de literatuur. Het vinden van de juiste methode voor iedere individuele patiënt is niet eenvoudig. Idealiter resulteert een behandeling in afname van pijn, herstelt het de beweeglijkheid van het gewricht, blijft de lengte en vorm van de teen behouden en zijn normale dagelijkse bezigheden weer mogelijk. Alle beschreven methodes hebben hun eigen voordelen voor wat betreft afname van pijn en het mogelijk maken van dagelijkse activiteiten, maar hebben ook hun eigen chirurgische moeilijkheden en complicaties.

Iedere ingreep zal invloed hebben op het looppatroon en meer specifiek op de bewegingen in de voet en enkel tijdens het lopen. Het is voor te stellen dat een ingreep waarbij compensatoire beweeglijkheid in omliggende voetgewrichten noodzakelijk is minder geschikt is voor patiënten waarbij deze gewrichten ook artrose bevatten. Derhalve is het voor chirurgen van belang om kennis te hebben van het compensatiemechanisme van de voet, wat de gevolgen van behandeling van het aangedane MTP1 gewricht moet opvangen. Voordat er een gepersonaliseerd advies voor de behandeling van HR gegeven kan worden is het essentieel om meer kennis te hebben van de invloed van HR op kinematica van de voet, enkel en het gehele been. Deze invloeden zijn op dit moment nog grotendeels onbekend.

Door middel van drie-dimensionele gangbeeldanalyse kan deze informatie verkregen worden, waarbij gebruik gemaakt wordt van een voetmodel bestaande uit meerdere segmenten. De drie doelen van dit proefschrift waren als volgt: 1) meer kennis verkrijgen over de effecten van HR op het looppatroon voor en na behandeling, 2) te weten komen welke interventie de beste patiënt-gerapporteerde uitkomst oplevert en 3) te onderzoeken of er een correlatie bestaat tussen afwijkingen in het looppatroon en patiënt-gerapporteerde uitkomst.

In **Hoofdstuk 2** wordt de beschikbare literatuur bestudeerd, met als doel te achterhalen of een MTP1 artrodese of totale gewrichtsprothese beter is in het reduceren van pijn en verbeteren van klinische uitkomst in patiënten met HR. Resultaten tonen dat een MTP1 artrodese pijn beter reduceert, beoordeeld met de VAS pijn score, en klinische uitkomst verder verbeterd, bepaald middels het American Orthopaedic Foot & Ankle Society-Hallux Metatarsophalangeal Interphalangeal (AOFAS-HMI) meetinstrument, vergeleken met een totale gewrichtsprothese. Hoewel een MTP1 artrodese als beste werd beoordeeld, resulteerde beide technieken tot een significante daling in pijn en verbetering in klinische uitkomst. Daarnaast werden er significant meer complicaties gezien na een totale gewrichtsvervanging vergeleken met een MTP1 artrodese. Loslating van de prothese was de meest voorkomende complicatie in de groep met totale gewrichtsprotheses, terwijl pijn waarvoor verwijdering van het artrodese materiaal noodzakelijk was de meest gerapporteerde complicatie na een MTP1 artrodese was. De hoeveelheid revisies na een totale gewrichtsvervanging was groter vergeleken met een MTP1 artrodese. Op basis van deze literatuur studie werd geconcludeerd dat een artrodese superieur was ten opzichte van een totale gewrichtsvervanging gebaseerd op klinische uitkomst, pijn reductie en de hoeveelheid complicaties en revisies.

Ondanks de resultaten beschreven in **Hoofdstuk 2**, kan niet aangenomen worden dat een artrodese de beste methode is voor iedere patiënt en zullen er waarschijnlijk patiënten zijn die meer voordeel hebben van een totale gewrichtsvervanging. Wij veronderstellen dat beperkingen in beweeglijkheid van de voet en enkel een belangrijke rol spelen in het (on)succesvol zijn van een ingreep, aangezien gewrichten rondom het MTP1 gewricht zullen moeten compenseren voor de verminderde of opgeheven beweeglijkheid van het MTP1 gewricht in HR en na artrodese respectievelijk.

Voordat deze hypothese getest kan worden zal de beweeglijkheid van de voet en enkel in patiënten met HR beter in kaart gebracht moeten worden. Karakteristieken van het gangbeeld van symptomatische HR patiënten werden vergeleken met gezonde controles. Hiervoor werd gebruik gemaakt van drie-dimensionale gangbeeld analyse middels het Oxford Voet Model. Dit voetmodel bestaat uit meerdere segmenten (**Hoofdstuk 3**). De staplengte was significant korter in patiënten met HR, terwijl er geen verschil was in loopsnelheid. Zoals verwacht was de beweeglijkheid van de hallux in het sagittale vlak significant aangedaan in patiënten met HR, waarbij er een verminderde dorsaalflexie van de hallux werd gezien tijdens het afzetten van de voet. Daarnaast werd er een toegenomen voorvoet supinatie gezien tijdens 'pre-swing'. Deze resultaten leidde tot de conclusie dat de voorvoet compenseert voor de verminderde beweeglijkheid van het MTP1 gewricht in HR door meer te supineren. Op deze manier wordt de stijve en pijnlijke hallux vermeden tijdens het afzetten. Op basis van deze kinematische veranderingen werden verhoogde plantaire drukken onder de laterale gebieden van de voet verwacht, maar niet gezien. In deze studie werd het compensatiemechanisme van de voet in patiënten met HR ontdekt en beschreven.

Het compensatiemechanisme in de voorvoet van patiënten met HR zoals beschreven in **Hoofdstuk 3** is echter mogelijk niet het enige compensatiemechanisme. Het is aannemelijk dat proximale gewrichten (zoals de enkel, knie, heup en het bekken) ook bijdragen. De effecten van HR op kinematica van het been werden onderzocht in **Hoofdstuk 4**, waarbij de Gait Profile Score (GPS) werd berekend. GPS is een uitkomstmaat waarbij de kwaliteit van het looppatroon van een persoon wordt weergegeven in één cijfer, gebaseerd op negen relevante kinematische parameters, de Gait Variable Scores (GVS). Een hogere GPS correspondeert met een gangbeeld wat meer afwijkt van een normaal gangbeeld. De subjectiviteit van het beoordelen van voorkeursparameters (bijvoorbeeld bepaalde vlakken of gewrichten) wordt door gebruik van deze parameters uitgesloten. Daarnaast is bewezen dat het adequate uitkomstmaten zijn om functionele beperkingen tijdens lopen weer te geven. Significante hogere scores in GPS, $GVS_{bekken\ rotatie}$ en $GVS_{enkel\ flexie}$ werden gezien in patiënten met HR. De flexie van de enkel ($GVS_{enkel\ flexie}$) droeg het meest bij aan de afwijkende GPS. Vervolgens werd bekeken of er een correlatie tussen de afwijking in het gangbeeld en de patient-gerapporteerde uitkomst aanwezig was. Hiervoor werd de Manchester Oxford Foot Questionnaire (MOXFQ) gebruikt. MOXFQ is een gevalideerde patiënt-gerapporteerde uitkomstmaat voor voet pathologie, bestaande uit een 'pijn', 'problemen met staan/lopen' en 'problemen op sociaal gebied' domein. Daarnaast werd de Foot Function Index (FFI), een vragenlijst die door patiënten wordt ingevuld, gebruikt om beperkingen en pijn in kaart te brengen. Significante correlaties werden vastgesteld tussen GPS en MOXFQ en tussen GPS en $GVS_{ankle\ flexion}$ en het MOXFQ 'wandelen/staan' domein. Daarnaast werd er een correlatie tussen GPS en het 'beperkingen' domein van de FFI gevonden. Deze resultaten tonen dat er een verband bestaat tussen een afwijkend gangbeeld (weergegeven door hogere GPS en $GVS_{ankle\ flexion}$ scores) en beperkingen en/of problemen tijdens wandelen. Deze studie liet zien dat HR naast de voet (**Hoofdstuk 3**) ook de kinematica van het been beïnvloedt (**Hoofdstuk 4**), waarbij er een correlatie bestaat tussen objectieve uitkomstmaten van het gangbeeld (de GPS en GVS) en patiënt-gerapporteerde uitkomst.

De effecten van MTP1 artrodese, de 'gouden standaard' behandeling voor HR, op het gangbeeld werd vervolgens onderzocht in **Hoofdstuk 5**. Gangbeeld karakteristieken van patiënten behandeld met een MTP1 artrodese werden vergeleken met gezonde controles. Behoudens een smallere stapbreedte in patiënten behandeld met een MTP1 artrodese waren er geen verschillen in spatiotemporele parameters. Analyse van kinematische data toonde een verminderde eversie van de achtervoet in 'midstance', gevolgd door een toegenomen endorotatie van de achtervoet in 'terminal stance' en vervolgens toegenomen supinatie van de voorvoet in 'pre-swing'. Zoals verwacht werd er minder plantairflexie van de hallux gezien in 'loading response' en minder dorsaalflexie van de hallux in 'terminal stance' gezien. Deze bewegingspatronen suggereren dat de hallux minder wordt belast tijdens de standfase, wat werd bevestigd met plantaire druk data. Hogere piekdrukken onder de kleine tenen en laterale metatarsalia, en hogere totale drukken onder metatarsaal 4 en de middenvoet werden waargenomen, terwijl de totale druk onder de hallux lager was. Deze studie toonde het compensatiemechanisme van de voet na een MTP1 artrodese, wat leidde tot een veranderd patroon van belasting van de voet.

Patiënt-gerapporteerde uitkomst, klinische uitkomst, pijn scores en terugkeer van ziekte werden vergeleken na een MTP1 artrodese, cheilectomie en Keller artroplastiek en beschreven in **Hoofdstuk 6**. Deelnemers in deze studie werden initieel onderzocht 7 jaar na hun operatie, waarbij analyse in deze studie 22 jaar na de operatie plaatsvond. Geen statistisch significante verschillen in AOFAS-HMI score, pijnscores of patiënt-gerapporteerde uitkomst, gemeten met de MOXFQ en Forgotten Joint Score werden gezien tussen de groepen. Echter, de AOFAS-HMI score verbeterde en de pijnscore verlaagde in de artrodese groep gedurende de follow-up periode. Daarnaast was er, hoewel niet statistisch significant, een klinisch relevant betere uitkomst in de artrodese groep ten opzichte van de cheilectomie groep op basis van de AOFAS-HMI score. Een klinisch relevante lagere pijnscore werd gezien in de artrodese en Keller's artroplastiek groep vergeleken met de cheilectomie groep 22 jaar na de uitgevoerde operaties. De hoogste graderingen van MTP1 artrose werden gezien op röntgenfoto's van de Keller's artroplastiek patiënten, hoewel de meeste progressie van artrose op röntgenfoto's gezien werd in de cheilectomie groep. Op basis van deze resultaten werd er een lichte voorkeur voor artrodese als behandelmethode voor HR gegeven.

In **Hoofdstuk 7** werden de belangrijkste bevindingen van het proefschrift besproken in het licht van de huidige literatuur. Dit proefschrift laat zien dat de voet, enkel en het been in staat zijn te compenseren voor de afgenomen of afwezige, beweeglijkheid van het MTP1 gewricht in HR en na behandeling met een artrodese. De voorvoet, enkel en het bekken zijn verantwoordelijk voor dit compensatiemechanisme in HR, terwijl de voorvoet en achtervoet dit zijn na een artrodese. Daarnaast werd aangetoond dat een artrodese de beste behandelmethode voor HR is gebaseerd op een beoordeling van de beschikbare literatuur en een studie waarin drie behandelmethodes werden vergeleken een lange tijd na de ingreep. Deze bevindingen geven een eerste inzicht in de effecten van HR en behandeling op het gangbeeld van patiënten, wat van belang is om verder te kunnen onderzoeken of gangbeeld analyse als een voorspellend hulpmiddel gebruikt kan worden in de behandeling van HR. Daarnaast worden de beperkingen van dit proefschrift en de aanbevelingen voor toekomstig onderzoek beschreven in dit hoofdstuk. Naar onze mening zouden toekomstige studies de relatie tussen gangbeeld en patiënt-gerapporteerde uitkomst voor en na verscheidene ingrepen voor HR moeten bestuderen. Op deze manier kan bepaald worden of gangbeeldanalyse gebruikt kan worden als prognostisch hulpmiddel om de behandeling van patiënten met HR te optimaliseren.

ABOUT THE AUTHOR

Jasper Stevens is op 26 juli 1991 geboren te Roermond. Hij volgde zijn voortgezet onderwijs aan het Bisschoppelijk College Schöndeln te Roermond, waaraan hij in 2009 afstudeerde. Hierna startte hij de bachelor studie Biomedische Wetenschappen aan de Universiteit Maastricht, welke hij in 2012 cum laude afrondde. Vervolgens startte hij in 2012 aan de master studie Arts-Klinisch onderzoeker aan de Universiteit Maastricht, welke in 2016 cum laude werd afgerond.

Van 2016 tot 2018 heeft Jasper als arts-klinisch onderzoeker gewerkt bij de afdeling Orthopedie in het Maastricht Universitair Medisch Centrum, waarin periodes van wetenschappelijk onderzoek werden afgewisseld met klinische taken als arts-assistent niet in opleiding (ANIOS). In deze periode werd onder supervisie van Prof. Dr. L. van Rhijn, Dr. K. Meijer en Dr. M.A. Witlox gestart met het promotieonderzoek waar dit proefschrift het resultaat van is.

In 2018 startte hij met de opleiding tot huisarts, waarin hij twee opleidingsjaren in een huisartsenpraktijk heeft gewerkt in Maastricht, onder supervisie van drs. L. Nijst, en in Montfort, onder supervisie van drs. Y. Smeets. Tussen beide opleidingsjaren werden stages gevolgd op de Spoed Eisende Hulp te Roermond, Psychiatrie te Maastricht en Klinische Geriatrie te Sittard.

Na afronding van de huisartsopleiding in 2021 is hij gaan werken als huisarts in Huisartsenpraktijk Melick en Groepspraktijk de Bres te Roermond. Vanaf 2022 werkt hij in Groepspraktijk de Bres te Roermond en Huisartsenpraktijk Herkenbosch in Herkenbosch.

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A

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