A finite-element analysis study of the metatarsophalangeal joint of the hallux rigidus


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Hallux rigidus was first described in 1887. Many aetiological factors have been postulated, but none has been supported by scientific evidence. We have examined the static and dynamic imbalances in the first metatarsophalangeal joint which we postulated could be the cause of this condition. We performed a finite-element analysis study on a male subject and calculated a mathematical model of the joint when subjected to both normal and abnormal physiological loads.

The results gave statistically significant evidence for an increase in tension of the plantar fascia as the cause of abnormal stress on the articular cartilage rather than mismatch of the articular surfaces or subclinical muscle contractures. Our study indicated a clinical potential cause of hallux rigidus and challenged the many aetiological theories. It could influence the choice of surgical procedure for the treatment of early grades of hallux rigidus.

Hallux rigidus is a common pathological problem which affects the great toe and is present in 2% of the population between the ages of 30 and 60 years.1,13 Degenerative arthritis of the first metatarsophalangeal joint (MTPJ) was first described by Davies-Colley in 1887,7 but the term hallux rigidus was first coined by Cotterill in the same year.5 Symptoms associated with hallux rigidus are well documented and include pain6-8 and stiffness.9,10 There is disagreement, however, as to the demographic factors and aetiology of the condition. A traumatic origin has been proposed by several authors.2,11 Jack12 suggested a spontaneous onset, but others have implicated poor footwear,2,10 a tight tendo-Achilles10 and metatarsus primus elevatus as described by Lambrinudi13 in 1938. There has been conflicting evidence in the literature in relation to this concept.7,12,14-17 Another view is that there is a mismatch between the head of the metatarsal and the hemispherical articular surface of the proximal phalanx. A flat or chevron-shaped distal metatarsal articular surface has been hypothesised by many authors2,18,19 and identified clinically by Coughlin and Shurnas.1 The senior author (MMS) also believes in this concept. However, there are other causes which could alter the biomechanics of the joint and we proposed three factors which may contribute to hallux rigidus:

1. A mismatch of the articular surface of the first MTPJ caused by a graded plantar displacement of the centre of rotation.
2. A tight medial band of the plantar fascia causing reduced dorsiflexion of the first MTPJ.
3. An increase in the tension in flexor hallucis longus (FHL) and flexor hallucis brevis (FHB) causing reduced dorsiflexion of the first MTPJ.

The possibility of tightening of the dynamic structures being the cause of hallux rigidus is derived from the clinical observation of a subgroup of patients with asymptomatic hallux limitus who have a reduced arc of dorsiflexion of the first MTPJ when the ankle is in equinus and neutral.

The proposed aetiology. A joint is composed of two structures lined with cartilage that allows ‘frictionless motion’ through boundary lubrication, which is controlled by both static and dynamic forces. Static force structures include the capsule, the plantar fascia and the medial and lateral ligaments and dynamic force structures consist of extensor hallucis longus (EHL), FHL, FHB, adductor hallucis and abductor hallucis.

The congruency and three-dimensional (3D) geometry of the articular surfaces result in an intrinsically established centre of rotation. While a standard human ball-and-socket joint such as the hip has a fixed and constant centre of rotation, a standard human hinge joint moves in the x, y and z axes depending on the point of contact of the articular surfaces. In most of the published literature the first MTPJ has been established as a ball-and-socket joint and this has been the basis of most designs of...
implant for arthroplasty of this joint. However, the only study which has investigated the centre of rotation of the first MTPJ was by Shereff, Bejiani and Kummer who showed in a cadaver model that the centre of rotation moved similarly to that of the knee in a path likened to an ‘up-side-down’ inverted comma, i.e. a modified hinge. We considered that there is an imbalance in this controlled environment which leads to an alteration in the centre of rotation resulting in dorsal impingement during movement.

Materials and Methods
A 25-year-old male subject was selected at random from a series of college students who did not have any congenital or acquired pathology of the foot. He underwent three tests to obtain the data to allow construction of a finite-element analysis model of the first MTPJ. Only one patient was used because we were not gathering population data, but assessing the variable changes which can occur in the single model.

The first test used the CODA mpx 30 system (Charnwood Dynamics Ltd, Leicester, United Kingdom) for kinetic and kinematic analysis, which contains an active marker system based on infrared light. Markers were placed on the medial aspect of the first MTPJ, the medial aspect of the calcaneum, the lateral aspect of the fifth MTPJ and the mid-point of the tibia. These markers established a simplified 3D line diagram of the shin and foot. The subject made five ‘dummy’ walks along the walkway in the laboratory and on a sixth walk was asked to walk over the force plates. This process was repeated. In the second walk of the two, gait-analysis results were obtained for the Fx, Fy, and Fz ground reaction forces. The foot is divided into three rockers for analysis of the gait cycle; the first is based on the rolling of the heel, the second is the rolling of the tibiotalar joint and the third is the rolling of the first MTPJ. From the marker system the velocity and acceleration of heel rise were calculated and the maximum angle of the third rocker was calculated (Fig. 1).

The second test used pedobarographical analysis to identify the centre of pressure for the CODA mpx 30 system. This was depicted graphically by a standardised x-y graph which consisted of an axis from the centre of the calcaneum to the centre of first MTPJ, as represented by the highest peak pressures in both of these areas, and a perpendicular axis through the second metatarsal head. The centre of pressure on the CODA system was mapped on to the centre of pressure on the pedobarography system and was graphically represented by the above x and y axes. The data on the ground reaction force were analysed and only those obtained immediately after the start of the heel rise were used. This correlated with the electromyographic findings of the activity of tibialis posterior and, therefore, initiation of loading of the first MTPJ. We assumed that the first MTPJ and surrounding muscles and ligaments were inactive until the start of heel rise.

Finally, we used MRI for the geometrical data. These images were obtained from the volunteer, who lay supine in the MRI scanner (Intera Gyroscan, 1.5T; Philips, Bothell, Washington), in the sagittal, axial and coronal planes (Fig. 2). The MR sequence was a fat-suppressed T1 gradient echo, which is the optimum for anatomical geometrical analysis. The MR scans incorporated the entire foot and ankle to the level of the mid-tibia. The feet were placed in a 90° ankle/foot orthosis to simulate the bone and soft-tissue geometry on weight-bearing, since full weight-bearing was not possible in the scanner. A total of 110 slices was obtained in each individual plane with a thickness of 0.75 mm with no gaps. Ten sagittal slices of the first MTPJ were obtained for analysis. The remainder of the MR scans were used to determine the triplanar co-ordinate geometry of the soft-tissue anatomy surrounding the joint and to measure the maximum cross-sectional area of the relevant muscle bellies.

The MR scans were processed in the DICOM (Digital Imaging and Communications in Medicine) format, using the MIMICS 8.1 software (Materialise, Leuven, Belgium). After isolating out the first MTPJ bony structure on all the scans using the MIMICS system, standard template library files were formatted. Using the same software, the co-ordinate geometry of all the soft-tissue structures was
obtained. The standard template library file meshes were subsequently developed and were smoothed using algorithms to ten iterations.

**Centre of rotation of the first MTPJ.** This was obtained using affine transformational matrices. This method uses matrices mathematical analysis to calculate the centre of rotation based on two points on each surface of the metatarsal head and the proximal phalanx. As the latter dorsiflexes relative to the first metatarsal per degree, the centre point of the parallelogram formed from the four points is mapped and translated. This method was calculated from the sagittal MR scans and gave an extremely accurate calculation. It mapped a centre of rotation similar to that described by Shereff et al\(^{20}\) in the cadaver model (Fig. 3).

**The finite-element analysis model.** Using the standard template library geometrical data, the gait-analysis data and the centre-of-rotation formula, a finite-element analysis model of the first MTPJ was calculated (Fig. 4). Initially, this was derived as a rudimentary ball-and-socket model, but using acoustic pressure software (ABAQUS, Simulia, Providence, Rhode Island) we were able to apply these forces to the geometrical model. The model consisted of 204 006 3D tetrahedral elements and 291 980 nodes. The material properties of all the structures were used to produce an accurate finite-element analysis model. Density, Young's modulus and Poisson's ratio were used for the metatarsal head and proximal phalanx (1900 kg/m\(^3\), 1600 MPa and 0.28, respectively)\(^{23}\) and the articular cartilage overlying these structures (1100 kg/m\(^3\), 2100 MPa and 0.1, respectively)\(^{22}\). All the soft-tissue structures were analysed as binodal beam structures and only in their elastic phase. The density, Young's modulus and Poisson's ratio used for the muscles (110 kg/m\(^3\), 126 MPa and 0.485, respectively), ligaments and capsule (1100 kg/m\(^3\), 260 MPa and 0.4, respectively), tendons (1100 kg/m\(^3\), 2700 MPa and 0.47, respectively) and plantar fascia (1100 kg/m\(^3\), 200 MPa and 0.4, respectively)\(^{21,22}\) were imported into the model, and the metatarsal head was rotated about the proximal phalanx to simulate normal gait. Therefore, the proximal phalanx and sesamoids were fixed boundary points and the metatarsal was rotated at the calculated rate of heel rise (Fig. 1).

The finite-element analysis model was applied to six environmental conditions as follows: (1) the normal environment of physiological loading; (2) an increase of 30% in the tension of FHB; (3) an increase of 40% in the tension of FHB; (4) an increase of 100% in the tension of FHB; (5) an increase of 30% in the medial band of the plantar fascia; and (6) a static inferior displacement of 0.5 mm, 1.0 mm, 2.0 mm and 4.0 mm in the centre of rotation of the first MTPJ to mimic a static mismatch of the articular surface.

The middle four conditions simulated dynamic imbalances, with normal static geometrical matching, while the last had normal dynamic balancing but abnormal static geometrical matching. In tightening the dynamic structures, the muscles and the plantar fascia, the initial static position of the first MTPJ was congruent. However, as the toe dorsiflexed during the gait cycle the joint became incongruent, but the centre of rotation remained within its normal pathway.

**Results**

When the finite-element analysis model was applied to normal physiological loads, the articular cartilage underwent...
normal stress loads (maximum stress 3.6 MPa) in the full arc of movement and demonstrated no difference through this (Fig. 5). With regard to the dynamic misbalancing conditions, the increase of 30%, 40% and 100% in the tension of FHB produced a mean maximum articular cartilage stress of 4.34 MPa (4.32 to 4.39) on the dorsal aspect of the metatarsal head under the same cycle conditions (Fig. 6). This non-significant increase in the joint stress did not cause an abnormal stress environment within the joint (paired t-test, p = 0.6477). Similar results were found with increasing tension of the FHL. An increase of 30% in the tension of the medial band of the plantar fascia resulted in significantly abnormal joint stress with the maximum stress of the articular cartilage on the dorsal aspect of the metatarsal head. This increased to 7.3 MPa (paired t-test, p = 0.0015), resulting in doubling of the load through the first MTPJ compared with the normal physiological state (Figs 7 and 8). In this model there was a similar increase in the sesamoid-metatarsal joint with stress, increasing to 6.8 MPa. With regard to the static mismatch of the articular surface with inferior displacement of the centre of rotation of 0.5 mm to 4 mm, the finite-element analysis model was unable to achieve one complete cycle, indicating unrealistic conditions of loading and, therefore, an impossible environment for movement of the joint.

**Discussion**

Although various studies have investigated the anatomy, clinical findings and radiological determinants of both the normal and abnormal first MTPJ, little is known about the kinetics and kinematics of this joint.20,24 The normal sagittal arc of movement is 90° of dorsiflexion to 30° of plantar flexion.24 This was confirmed by Shereff et al20 in a movement analysis study of the first MTPJ in a fresh-frozen cadaver model using lateral radiographs. They calculated the surface movement, the instant centre of rotation and the range of movement of the first MTPJ in normal feet and in those with hallux valgus and hallus rigidus. In normal feet the instant centres of rotation had a constant arc of movement through the range of movement, which lay within the metatarsal head, parallel to its articular surface. In abnormal feet the instant centres of rotation were scattered within and outside the first metatarsal head in a random fashion. Shereff et al20 postulated that the scattering was
due to the dorsal exostosis, articular degeneration and scarring of the juxta-articular soft-tissue structures. A limitation of the study was that all movement analysis was performed only with passive movement of the first MTPJ, therefore ignoring the muscle tension of the flexors and extensors which play an important role in the movement analysis of all joints. In addition, the study had a small number of cadaver feet and did not identify the basic demographics of the cadavers.

Ahn et al. demonstrated a shift in the distribution of contact on the articular surface of the metatarsal with increasing dorsiflexion of the great toe. Their study concluded that their data matched the dorsal chondral erosions present in hallux rigidus. However, this study also used a small number of fresh-frozen cadaver feet with simulated dynamic loading of the tendons and was limited by using a non-physiological environment.

In our study the instant centre of rotation was calculated at multiple points within the arc of movement using MR scans in the sagittal plane which gave a more accurate assessment of the congruency of the articular surface relative to plain radiographs. Analysis of the congruency of the articular surface on plain radiographs can give a false line of congruency because of the potential for overlap of the medial and lateral condyles of the proximal phalanx. In addition, the instant centres of rotation were calculated using four fixed points on the articular surface and rotational matrices.

Because of the similarities between the first MTPJ and the knee in regard to the rolling/glide movement and the presence of sesamoid bones, we postulated that the centre of rotation in the first MTPJ would follow a similar configuration to that mapped in the knee. On this basis we used affine transformational matrices to calculate the instant centres of rotation at multiple points in the arc of movement.

A number of orthotic and surgical treatments have been advocated for hallux rigidus, but there is no consensus on the best management in its early stages. Surgical methods can be divided into joint-preserving, joint-destructive procedures or a combination of both. The surgical procedures can be categorised into five groups, namely replacement arthroplasty, cheilectomy, osteotomy and soft-tissue release, excisional arthroplasty and arthrodysis.

Total joint arthroplasty was advocated in the late 1980s to overcome the loss of the power and flexibility when using hemi-implants, but similar problems remained with a failure rate of over 50% in the first four years in most studies. Lewis and Alva used two-dimensional finite-element analysis to calculate the stresses generated in two models of a flexible, one-piece, double-stemmed first MTPJ implant under loading. They advised modification of the geometry of the implant and reappraisal of the materials used. As a result of this study five total joint implants were introduced, including the Koenig (Biomet, Warsaw, Indiana) zirconium ceramic implants. Olms and Dietze found poor results in small numbers of patients with these prostheses. Their early failure can be explained by abnormal loading as a result of the tight medial band causing loosening of the prosthesis on the dorsal aspect of the joint.

Cheilectomy was first described by Bonney and MacNab in 1952 and is indicated in young patients with a low grade of hallux rigidus. A successful outcome is directly associated with the achievement of 90° of passive dorsiflexion at operation. The procedure gives an early improvement in movement and a rapid decrease in clinical symptoms. Mixed results have been obtained with some studies showing excellent results over periods of two to five years with others demonstrating a high rate of revision surgery. We have shown that a tight plantar fascia could be the cause of hallux rigidus which would explain the success rates of cheilectomy. Our study showed that the repetitive cyclical loading of the dorsal aspect of the metatarsal head caused a higher concentration of stress forces. This resulted in an ulcerated lesion which evolved into an osteophyte in conjunction with a tight medial band of the plantar fascia. By excising 30% of the dorsal aspect of the metatarsal head in a dorsal cheilectomy, the barrier to dorsiflexion is removed, giving an increase in dorsiflexion and reduced symptoms. The abnormal biomechanical imbalance of the joint has not been addressed, but the osseous barrier has been excised, creating geometry of the joint compatible with the abnormal biomechanical imbalance.
Cadaver biomechanical studies have assessed the effects of cheilectomy on dorsiflexion of the first MTPJ. Heller and Brage\textsuperscript{31} showed that it significantly increased dorsiflexion but in an abnormal pattern because of the normal gliding being replaced by a pivot movement. As a result the kinematics of the first MTPJ were disrupted. This may explain why the rates of patient satisfaction are high regardless of the grade of the condition.\textsuperscript{28}

Mismatch of the articular surface has gained popularity as a cause of hallux rigidus. Coughlin and Shurnas\textsuperscript{1} considered that a chevron/spherical articular surface was a possible cause of the condition. We have found that a simulated articular surface mismatch, created by graded plantar displacement of the centre of rotation, was incompatible with normal conditions of loading. It could be postulated that incongruency of the articular surface is a consequence of abnormal kinetics resulting in a chevron-like articular surface because of a long-term repetitive erosion due to a tight medial band of the plantar fascia.

Osteotomies of the proximal phalanx and distal metatarsal have been described including the Kessel-Bonney procedure,\textsuperscript{32} the Moberg Osteotomy,\textsuperscript{3} the procedure of Vanore et al,\textsuperscript{33} the Watermann operation,\textsuperscript{34} the Green-Watermann modification,\textsuperscript{35} the Youngswick procedure\textsuperscript{36} and distal oblique osteotomy. Kilmartin\textsuperscript{37} is the only author to describe the long-term results of the Kessel-Bonney procedure. This operation which dorsiflexes the proximal phalanx, indirectly reduces the potential pull of the plantar fascia because the osteotomy is performed distal to its insertion. The author found a reduced range of movement and a reduction in the joint space as seen on radiographs two years after operation. He noted the presence of osteoarthritic changes in the interphalangeal joints because of the altered tilt of the proximal phalanx. All distal metatarsal osteotomies have been shown to give reasonable outcomes, but the studies have been on small numbers of patients and most results were anecdotal. Avascular necrosis of the head of the metatarsal may occur if the osteotomy has been performed too distally, interrupting the vascularity of the head.

Soft-tissue releases have gained little support because of the technical difficulties involved. Congenital or acquired tightening of the plantar fascia or FHB have been suggested as potential causes of restriction of dorsiflexion of the first MTPJ, resulting in the development of hallux rigidus. Release of the medial plantar fascia gives a significant increase in movement of the joint.\textsuperscript{38} Durrant and Siepert\textsuperscript{39} implicated tight plantar structures as the iatrogenic cause of hallux rigidus. The cause of the tight medial band of the plantar fascia is unknown. Tightening of the medial band could be congenital, as in the case of hallux limitus, acquired because of inflammation and subsequent contracture, or secondary in association with tightness of the hamstrings or gastrocnemius. In our model, tightness of the medial band affected stresses both in dorsiflexion and at the sesamoid-metatarsal joint, which are seen in the older patients with hallux rigidus. Dupuytren’s disease has been described in association with other soft-tissue restricting conditions such as adhesive capsulitis of the shoulder.\textsuperscript{40,41} It could be postulated that the medial band of the plantar fascia shows similar changes but there has been no histopathological study of this structure in hallux rigidus.

The limitations of finite-element analysis are in converting anatomical and physiological data into a mathematical model with boundary conditions. Assumptions must be made to match the model to normal physiological conditions. In our
study we fixed both the proximal end of the metatarsal and the sesamoids in order to ensure that the metatarsal rotated on the proximal phalanx on the stationary sesamoids. We initially treated the sesamoid-metatarsal joint as a normal synovial joint and then assumed a frictionless joint to ensure the minimal effect on the arc of movement. Both environments produced equal results, thus allowing us to use the sesamoids under fixed boundary conditions. Ideally, we would have preferred to use the entire first ray in the model, but because of the complexity of the mathematical analysis across many joints we could only accurately analyse the first MTPJ in isolation. However, although the aetiology of hallux rigidus is unknown, patients presenting in the early stages have joints with predominantly normal anatomy. We considered that the various theories should be tested on a normal mathematical joint, since static incongruity would result in the acceleration of abnormal stresses.

A common theme in the analysis of all the surgical procedures is either disregard of the biomechanical imbalances in the first MTPJ, as in cheilectomy, or the emphasis on one aspect of imbalance, as in osteotomies. At present neither excisional nor total joint arthroplasty has gained in popularity because of the poor results and failure to understand the kinematics and kinetics of the first MTPJ. Arthrodesis still remains the surgical treatment of choice for end-stage disease since it gives a stable, pain-free joint.

Our study concentrated on the early stages of hallux rigidus when there is still considerable debate as to the possible treatment. We consider that the aetiology is related to imbalance of the soft tissues rather than a congenital incongruency of the joint, therefore, we favour lengthening of these structures if possible. A dorsal cheilectomy or a Moberg procedure indirectly addresses this biomechanical imbalance, thus negating the need to perform release of the plantar fascia which may induce instability.42-45

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No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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