Subtalar joint kinematics and arthroscopy: insight in the subtalar joint range of motion and aspects of subtalar joint arthroscopy

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CHAPTER 1

General introduction
Anatomic description of the subtalar joint
The foot and ankle joints work in an intricate way in the complex action of propulsion of the human body. The talocalcaneal joint, or subtalar joint, plays a significant role in the transmission of loads between the leg and the foot and the adaptation of the foot to the slope of the ground. The subtalar joint consists of multiple articulations between the talus, the calcaneus and the navicular bone. [Fig. 1] There are two independent synovial subtalar joint cavities, the anterior and posterior chambers, separated by the tarsal canal. The anterior talocalcaneal chamber is also part of the talocalcaneonavicular joint. The talocalcaneonavicular ligament, also known as the spring ligament, supports the floor of the anterior chamber. The dorsal surface of the spring ligament presents a fibrocartilaginous facet, on which the head of the talus partially rests. The posterior talocalcaneal facet is convex and the corresponding talar facet is concave. The reverse is true for the articular surfaces of the anterior chamber where the navicular and calcaneal facets are concave and provide a socket into which the convex articular facets of the talar neck and head fit. Anatomical variations of the number, the shape and orientation of the articular facets of the subtalar joint have been documented for both the talus and the calcaneus.1-4 The talus is interposed between the mortise of the ankle and the underlying tarsal bones. No muscle tendons originate from or insert to the talus. The calf muscles insert through the Achilles tendon on the dorsal aspect of the calcaneal bone. On the medial side of the calcaneal tuberosity the plantaris tendon inserts. The muscles that originate from the calcaneus are the extensor and flexor digitorum brevis, the abductor hallucis and the abductor digiti minimi muscles. The complex geometry of the subtalar joint articulations provides substantial intrinsic stability for the joint. Extrinsic stability results from the joint capsule and the numerous ligaments that surround the subtalar joint. The lateral ligamentous support of the subtalar joint consists of a superficial, intermediate and deep layer.9,10 The superficial layer comprises the lateral talocalcaneal ligament, the lateral root of the inferior extensor retinaculum and the calcaneofibular ligament. The intermediate layer is formed by the intermediate root of the inferior extensor retinaculum and the cervical ligament. Finally, the deep layer consists of the medial root of the inferior extensor retinaculum and the interosseous ligament in the tarsal canal. [Fig. 2] On the medial side of the subtalar joint, the deep and superficial layer of the medial collateral ligament (including the medial talocalcaneal ligament) provide secondary stability to the subtalar joint. [Fig. 3] In addition, stability of the subtalar joint is provided by forces from the muscles that span the subtalar joint.

Subtalar joint motion
The main function of the subtalar joint is to adapt the foot to the slope of the ground and to facilitate internal and external rotation of the lower leg during the stance phase of gait.12-14 To achieve this, the subtalar joint allows for supination and pronation of the foot to occur. Subtalar joint supination is defined as the combined triplanar motion of hindfoot inversion, adduction of the foot and ankle joint plantarflexion. The combined triplanar motion of subtalar joint pronation includes hindfoot eversion, foot abduction and ankle joint dorsiflexion. [Fig. 4] Many attempts have been made to determine the position and orientation of the subtalar joint axis for motions between the talus and calcaneus. Early in-vitro studies used cadaveric ankle and foot specimens for assessment of the anatomical location and angulation of the subtalar joint axis relative to the anatomic planes.13,15-18 Authors agreed on the average resultant subtalar joint axis to run in an oblique infero-postero-lateral to supero-antero-medial direction.15,16,18,21-25 This resultant subtalar joint axis deviated from the sagittal plane by a mean of 23 degrees (medial angulation) and from the transverse plane by a mean inclination of 42 degrees (upward tilt).15,16,24,25 However, considerable variation was found for the position and direction of the subtalar joint axis between the subjects in these studies. Detailed analysis of the movements of the talus and calcaneus during weight-bearing supination and pronation of the foot using roentgen stereophotogrammetric analysis (RSA) in cadaveric specimens and healthy volunteers confirmed that subtalar motion takes place around an axis of which the position and orientation change during joint motion.14,22,26 Van Langelaan studied 10 cadaveric specimens using RSA and his results appear to suggest a medially and superiorly directed change in axis position as the subtalar joint supinates from a pronated position.26 The main explanation for the variable subtalar joint axis position and orientation is that changes in the curvature of an articular surface produce a variety of centres of rotation during joint motion.23 Joint motion involving rotation combined with translation occurs around a so-called helical or screw axis. Manter was one of the first authors to recognize that the subtalar joint had a helical axis and calculated that for 10 degrees of rotation around the axis, the talus translated 1.5 mm along the subtalar joint axis.15 Other authors found no evidence of translation along the rotation axis of the subtalar joint.16,21,27
The assessment of the amount of motion of the foot and ankle joints during walking or standing or with the ankle and foot unconstrained has challenged numerous investigators.\textsuperscript{28-40} In clinical practice, the range of subtalar joint motion is usually assessed by measuring the range of supination and pronation separately. The subtalar neutral position is used as a reference position from which the ranges in the two motion directions can be measured. However, there is little consensus on the subtalar joint neutral position. In addition, as the position of the talus cannot be exactly determined visually or by palpation, the accuracy of these measurements is also questionable. Studies on calcaneal inversion and eversion measurements showed low to moderate interrater reliability.\textsuperscript{41-43} The subtalar joint range of motion should be calculated as the total amount of rotation around the subtalar joint axis. As the subtalar joint axis is not parallel to any of the anatomical planes, measuring heel inversion and eversion relative to the lower leg in the frontal plane is only indicative of the range of subtalar joint motion.\textsuperscript{43-47} With the introduction of computed tomography (CT) and magnetic resonance imaging (MRI) new imaging tools have become available to study ankle and hindfoot joint motion in-vivo in a less invasive fashion.\textsuperscript{46-49} In general, these studies were able to confirm the results of the early cadaveric studies on ankle and subtalar joint motion and also confirmed the concept of the moving subtalar joint axis. However, the outcomes of most reports are difficult to compare as the type of motion that was studied varied and different coordinate systems were used. More specific, most reports investigated stepwise input motion of the subtalar joint and the total range of subtalar joint motion was not assessed. Insight in subtalar joint motion is relevant for the understanding, the diagnosis and the classification of subtalar joint pathology and surgical procedures. Secondly, it is important for the development of biomechanical models of the ankle and foot, the design of subtalar joint implants and the design of footwear and orthotic devices. Therefore, the total range of subtalar joint motion needs further investigation.

**Subtalar joint injuries**

Subtalar joint injuries can lead to a stiff and painful joint resulting in limited mobility. However, the true incidence of subtalar joint injuries seen in the emergency department is not known. Physical examination of the subtalar joint in the acute phase of injury is generally painful and difficult. Furthermore, no specific diagnostic tests exist for acute subtalar joint injury. Subtalar joint injuries range from mild sprains of the lateral ligaments to intra-articular subtalar fracture dislocations with comminution. The mechanism of injury in subtalar sprains is described as an inversion force applied to the foot while the ankle is in dorsiflexion. In this position, the lateral ligaments that mainly stabilize the subtalar joint (i.e. the talocalcaneal interosseous ligament, lateral talocalcaneal ligament, calcaneofibular ligament, cervical ligament) are stressed causing disruption and subsequent subtalar joint instability.\textsuperscript{50,54} In the acute phase of a lateral ankle or subtalar joint sprain, there is seldom an indication for surgical intervention.\textsuperscript{55-57} The conservative treatment of these injuries generally includes rest, ice, compression and elevation (RICE) in combination with physical therapy for strengthening of the peroneal muscles and improving proprioception of the ankle and hindfoot. Subtalar joint injuries have been associated with other injuries of the lower extremity. The subtalar joint instability is thought to occur in 10 – 25% of the patients suffering from lateral ankle instability.\textsuperscript{56-64} Subtalar joint instability has received increasing attention in the literature as a cause for chronic functional ankle and hindfoot instability.\textsuperscript{65-67} Symptomatic chronic subtalar joint instability can be treated either with a tendon transfer or tenodesis procedure, or with an anatomic ligament reconstruction depending on the extent of damage to the ligaments.\textsuperscript{55,56,60} Because subtalar ligamentous injury is often associated with ankle ligamentous injury, most of the surgical procedures for subtalar instability are aimed at resolving both. Several diagnostic techniques have been proposed in the assessment of chronic subtalar joint instability including arthrography, stress radiography and computed tomography.\textsuperscript{68-76} However, most techniques are cumbersome to use and the lack of standardized values make the results difficult to interpret. Therefore, the range of subtalar joint motion has to be quantified to create a database of standardized values for assessment of subtalar joint motion in healthy and symptomatic individuals.

Adult acquired flatfoot deformity is a problem frequently seen in adults and may lead to a painful foot. The normal vault structure of the foot is considered to be built up essentially by two longitudinal arch systems; a short and lower lateral arch and a long and higher medial arch.\textsuperscript{77} A variety of foot problems can lead to adult acquired flatfoot deformity, a condition that results in a fallen medial arch with the foot pointed outward. The most common cause for the adult acquired flatfoot is incompetence of the posterior tibial tendon (PTT) and the supporting medial ligaments.\textsuperscript{78} The treatment of the adult acquired flatfoot depends on the symptoms and the stage of the flatfoot deformity. Surgical treatment for painful flexible adult acquired flatfoot deformity resulting from PTT insufficiency usually includes a flexor digitorum longus (FDL) tendon transfer in combination with a bony procedure. The rationale for the lateral column lengthening procedure is to restore the medial longitudinal arch by realigning the foot around the talus, thereby correcting the hindfoot valgus and neutralizing...
the forefoot abduction.\textsuperscript{78,79} Evans described an anterolateral open wedge calcaneal distraction osteotomy (ACDO) just proximal to the calcaneocuboid joint for lateral column lengthening.\textsuperscript{80} Another surgical option for lateral column lengthening is a calcaneocuboid joint distraction arthrodesis (CCDA). Both techniques showed significant improvement in terms of the postoperative radiographic parameters of the foot and the American Orthopaedic Foot and Ankle Society (AOFAS) clinical scores.\textsuperscript{81-89} Following CCDA for flexible flatfoot deformity, one might expect a decreased tarsal and thus a decreased subtalar joint range of motion. This results from an essential structural and functional feature of the tarsal joints, the interdependence of tarsal joint motion which means that the immobilization of one joint in the hindfoot limits the mobility of other joints.\textsuperscript{77} This loss of subtalar joint motion could possibly lead to a symptomatic hindfoot. On the other hand, there also might be an effect on the subtalar joint range of motion with the ACDO procedure if the anteroposterior length of the calcaneus is increased. To our knowledge, the effect of the two different LCL procedures on the talocrural and subtalar joint ranges of motion in-vivo was not previously described. This matter should be analysed further in detail to gain insight in the surgical treatment of adult acquired flatfoot deformity.

Degeneration, inflammation, fractures and subtalar joint dislocations can eventually lead to osteoarthritic changes of the articular surfaces. Patients with degenerative, inflammatory and post-traumatic osteoarthritis of the subtalar joint have a stiff and painful joint and report difficulties with walking on uneven terrain. The diagnosis of subtalar joint osteoarthritis is usually based on the history, physical examination and plain radiographic images of the hindfoot. A chronic symptomatic osteoarthritic subtalar joint, which is unresponsive to conservative treatment may be treated with a subtalar arthrodesis in which the bones of the subtalar joint are surgically fused. The subtalar arthrodesis is commonly carried out through an open procedure. Although open subtalar joint arthrodesis is considered a routine surgical procedure in orthopaedic practice, authors have described several issues such as wound healing problems and non-union of the subtalar arthrodesis.\textsuperscript{90-92} A detailed analysis of the open subtalar arthrodesis procedure may help to clarify these issues.

In recent years, arthroscopy for the treatment of hindfoot pathology has received increasing attention in the literature. The advantages of minimally invasive hindfoot surgery include a decrease in tissue trauma during surgery, yielding less postoperative pain, fewer wound problems such as infection or skin break down and a quicker recovery for the patient. However, the complex anatomy of the subtalar joint makes the arthroscopic evaluation challenging. The development of small diameter arthroscopes along with precise surgical techniques has allowed arthroscopy of the subtalar joint to expand. In 1986, Parisien was the first to report preliminary clinical results of diagnostic and therapeutic arthroscopy of the posterior subtalar joint for adhesiolysis, manipulation of the subtalar joint or removal of loose chondral bodies in three cases with good results.\textsuperscript{93} From then on an increasing number of reports were published on subtalar joint arthroscopy yielding good results.\textsuperscript{94-96} In 1998, Jerosch reported excellent results in 3 patients with osteoarthritis of the subtalar joint treated with an arthroscopic subtalar arthrodesis using lateral portals with the patient in the supine position.\textsuperscript{97} In 2000, a 2-portal posterior portal approach for hindfoot arthroscopy with the patient in the prone position was introduced.\textsuperscript{98} The posterior approach using separate posterolateral and posteromedial portals has clear advantages. It gives very good access to the posterior ankle compartment, the subtalar joint, and the extra-articular structures such as the os trigonum.\textsuperscript{99} Furthermore, it seems more accurate to assess hindfoot alignment with the patient in the prone position in case of an arthroscopic subtalar arthrodesis. The introduction of talocalcaneal lag screws is also convenient with the patient in the prone position. The posterior approach was successfully used for arthroscopic subtalar arthrodesis in a series of patients with post-traumatic osteoarthritis.\textsuperscript{99} A painful talocalcaneal coalition is another recognized indication for talocalcaneal arthrodesis in skeletally mature patients.\textsuperscript{100,101} The presence of a talocalcaneal coalition presents a technical challenge since the talocalcaneal bar only allows limited opening up of the subtalar joint during surgery. As standard arthroscopic techniques for subtalar arthrodesis do not provide means of opening up the joint, they are difficult to use in patients with limited subtalar joint space. The development of an arthroscopic technique for subtalar joint arthrodesis could therefore be beneficial for patients with a talocalcaneal coalition.

**Aim of thesis**

The aim of this thesis is firstly to obtain insight in the normal subtalar joint range of motion. Secondly, to provide knowledge of the subtalar joint range of motion following two different surgical procedures for flexible adult acquired flatfoot deformity. And finally, to enhance endoscopic treatment options for subtalar joint pathology. More specific, the purpose of this thesis is: (1) to investigate the accuracy of a computed tomography based bone contour segmentation and registration method (CT-BCM) to measure bone to bone motion in the hindfoot and compare CT-BCM to the current gold standard roentgen stereophotogrammetric...
analysis (RSA), (2) to analyse the normal ranges of motion of the subtalar joint in healthy individuals using the CT-BCM technique, (3) to describe the difference between two surgical techniques for lateral column lengthening in patients with adult flatfoot deformity with regard to postoperative ankle and subtalar joint ranges of motion, (4) to investigate the problems with the surgical techniques of subtalar joint arthrodesis by reviewing the literature that is available and provide possible solutions, (5) to provide an overview of the aspects of the surgical technique for subtalar joint arthroscopy, and (6) to report on the technique and results of the arthroscopic subtalar arthrodesis technique in patients with a symptomatic talocalcaneal coalition using the 2-portal posterior approach with an accessory sinus tarsi portal.

Outline of the chapters

As stated earlier, there is no accurate technique for in-vivo assessment of the normal subtalar joint range of motion. Our group has developed a bone contour segmentation and registration technique using CT images (CT-BCM), to measure relative bone to bone motion in-vivo under non-weightbearing circumstances. The purpose of this CT-based technique is to acquire data of the position and the orientation of the ankle and hindfoot bones in the CT images in an accurate and time efficient way. Therefore, the CT-BCM technique has to be compared to the current gold standard technique, the roentgen stereophotogrammetric analysis (RSA).

Validation of the CT-BCM technique by assessment of its accuracy is reported in Chapter 2. The hypothesis was that CT-BCM was at least as accurate as the RSA method. There are no studies available that have measured the range of motion of the subtalar joint with an accurate technique in-vivo. In Chapter 3, the normal ranges of motion of the subtalar joint are studied in 20 healthy individuals using the CT-BCM technique.

Two frequently used surgical techniques for stage two adult acquired flatfoot deformity not responding to conservative treatment combine the augmentation of the posterior tibial tendon with a realignment osteotomy. The aim of these procedures is to help restore the normal architecture of the foot. Both the calcaneocuboid distraction arthrodesis (CCDA) and the anterior calcaneal open wedge osteotomy (ACDO) procedure result in lengthening of the lateral bony column of the foot. The ACDO procedure was compared to the CCDA for lateral column lengthening in patients with adult acquired flatfoot deformity in terms of postoperative ranges of motion of the ankle and subtalar joint in Chapter 4. Our hypothesis was that the ACDO is the preferred procedure in these patients as the CCDA has the possible disadvantage of restricting hindfoot motion as the calcaneocuboid joint is fused. The CT-BCM method that was validated in Chapter 2 was used.

The subtalar joint arthrodesis is the treatment of choice for severe symptomatic osteoarthritis of the subtalar joint unresponsive to conservative treatment. Although subtalar joint arthrodesis is considered a routine orthopaedic surgical procedure, a number of authors have described serious peri-operative problems with this procedure. In Chapter 5 the aspects of the different subtalar arthrodesis procedures are reviewed based on a literature study. The goal of this chapter was to present surgical pitfalls and possible solutions for problems with the subtalar arthrodesis techniques.

In recent years, there has been an increasing interest in arthroscopically assisted surgery of the subtalar joint. An overview of the indications, contraindications and different approaches for subtalar joint arthroscopy is provided in Chapter 6. Furthermore, the literature on arthroscopic treatment and results of sinus tarsi syndrome, os trigonum syndrome and subtalar arthrodesis is presented.

A painful talocalcaneal coalition is a recognized indication for a subtalar arthrodesis procedure in skeletally mature patients. However, because of the talocalcaneal coalition the workspace in the hindfoot is reduced. The hypothesis of Chapter 7 is that the posterior 2-portal approach to the subtalar joint could be used for arthroscopic subtalar arthrodesis in the patients with a symptomatic talocalcaneal coalition. An accessory portal at the level of the sinus tarsi is created to introduce a blunt trocar for opening up of the joint and providing more workspace for an arthroscopic subtalar arthrodesis. The results of this 3-portal technique used in three patients are also presented in Chapter 7.
REFERENCES

GENERAL INTRODUCTION


**FIGURES**

Figure 1 The talocalcaneal-navicular, or subtalar joint, consists of the multiple articular surfaces between the talus, the calcaneus and the navicular bone. In this figure on the left side the upper surface of a right calcaneus is shown and the dorsal aspect of the navicular bone. On the right side a drawing of the under surface of a left talus is shown with its three corresponding calcaneal articulating surfaces of the subtalar joint.

*From Gray’s Anatomy of the Human Body, 1918.*
Figure 2 Anatomic dissection of the lateral region of the foot and ankle. 1 Fibula and tip of the fibula; 2 tibia (anterior tubercle with arrows); 3 anterior tibiofibular ligament; 4 distal fascicle of the tibiofibular ligament; 5 interosseous membrane; 6 foramen for the perforating branch of the peroneal artery; 7 talus; 8 anterior talofibular ligament; 9 calcaneofibular ligament; 10 talocalcaneal interosseous ligament; 11 inferior extensor retinaculum (cut); 12 talonavicular ligament; 13 bifurcate ligament; 14 peroneal tubercle (arrows showing the peroneal tendons sulcus); 15 peroneus longus tendon; 16 peroneus brevis tendon; 17 calcaneal tendon.


Figure 3 Medial view of the foot and ankle following anatomic dissection. 1 Tibionavicular ligament; 2 tibiospring ligament; 3 tibiocalcaneal ligament; 4 deep posterior tibiotalar ligament; 5 spring ligament complex (superomedial calcaneonavicular ligament); 6 medial talar process; 7 sustentaculum tali; 8 medial talocalcaneal ligament; 9 tibialis posterior tendon.

Figure 4 A) Right foot supination as seen from a posterior view. Supination is the combined triplanar motion of hindfoot inversion, adduction of the foot and ankle joint plantarflexion. B) The right foot is in pronation; the combined triplanar motion of hindfoot eversion, foot abduction and ankle joint dorsiflexion.

CHAPTER 2

Accuracy of a CT-based bone contour registration method to measure relative bone motions in the hindfoot


ABSTRACT

Background For measuring the in-vivo range of motion of the hindfoot, a CT-based bone contour registration method (CT-BCM) was developed to determine the three-dimensional position and orientation of bones. To validate this technique, we hypothesized that the range of motion in the hindfoot is equally, accurately measured by roentgen stereophotogrammetric analysis (RSA) as by the CT-BCM technique.

Methods Tantalum bone markers were placed in the distal tibia, talus and calcaneus of one cadaver specimen. With a fixed lower leg, the cadaveric foot was held in neutral and subsequently loaded in eight extreme positions. Immediately after acquiring a CT-scan with the foot in a position, RSA radiographs were made. Bone contour registration and RSA was performed. Helical axis parameters were calculated for talocrural and subtalar joint motion from neutral to extreme positions and between opposite extreme positions. Differences between CT-BCM and RSA were calculated.

Results Compared with RSA, the CT-BCM data registered an overall root mean square difference (RMSd) of 0.21° for rotation about the helical axis, and 0.20 mm translation along the helical axis for the talocrural and subtalar joint and for all motions combined. The RMSd of the position and direction of the helical axes was 3.3 mm and 2.4°, respectively. The latter errors were larger with smaller helical rotations. The differences are similar to those reported for validated RSA and thus are not clinically relevant.

Conclusion CT-BCM is an accurate and accessible alternative for studying joint motion in-vivo, as it does not have the risk of infection and overlapping bone markers.

INTRODUCTION

Studying ankle and hindfoot kinematics is important for differentiation between normal and pathologic joint motion, gait analysis and diagnosis of ligamentous abnormalities. A number of radiographic stress tests can be performed for diagnosis, e.g. the talar tilt test for ankle instability. These tests can give unsatisfactory results, partly due to the fact that radiographs are two-dimensional (2D) projections, wherein bones can overlap. As out-of-plane motions cannot be detected unambiguously, the exact bone-to-bone movement cannot be determined. Recently, a new diagnostic method was developed that enables accurate in-vivo measurement of the extreme range of motion of the joints in the ankle and hindfoot. This is done by placing the unconstrained foot in different loaded positions relative to the lower leg and by using three-dimensional CT-imaging (3D CT stress-test). The technique is based on a bone contour registration method to find the three-dimensional position and orientation of ankle and hindfoot bones in the CT data sets (CT-based bone contour registration method (CT-BCM)). The first results show consistency of the measured range of motion in the subtalar joint in a healthy subject population. The CT-BCM has clear advantages in being accurate, discriminating kinematics at joint level and being reasonably time efficient. For further development of the CT-BCM technique, the accuracy of measuring joint rotations and translations with this technique has to be demonstrated by a comparison with a well-established and accepted technique. We chose the widely used roentgen stereophotogrammetric analysis (RSA) method for comparison, as it has been validated as a reliable and accurate technique for joint motion analysis in-vivo. The purpose of this study was to compare the CT-BCM technique with conventional RSA in measuring the talocrural and subtalar joint range of motion. The choice was made to mimic the in-vivo clinical setting as closely as possible. Thereto, a cadaveric specimen was loaded in an identical fashion, as the subjects during in-vivo tests in our previous study. The hypothesis was that the CT-BCM technique for measuring the range of motion of the ankle and hindfoot joints is equally accurate as RSA.

METHODS

Experimental set-up
A fresh cadaveric right lower leg from a male (70 years old) was positioned and fixated in a 3D CT stress footplate (Fig. 1). The length of the longitudinal axis of the cadaveric calcaneus was 84.5 mm, which was close to the mean length of the calcanei of the twenty volunteers...
used in our clinical study (84.7±5.7 mm). The first CT data set was acquired with the foot unloaded and in neutral position. Following the initial CT-scan, tantalum bone markers (beads with a radius of 0.8 mm) were placed for RSA image acquisition. The bone markers were inserted into the bones using a device containing a hollow needle with a spring-loaded piston. Six markers were placed in the tibia, five in the talus and seven in the calcaneus (Fig. 1). Unintentionally, one bone marker was placed into the navicular bone and another one into the talocrural joint space. These markers were discarded for analysis and did not limit talocrural joint motion. Subsequently, eight CT-scans were made with a loaded foot, starting from extreme dorsiflexion (DF) and continuing in a clockwise order: extreme combined eversion–dorsiflexion (EVDF), extreme eversion (EV), extreme combined eversion–plantarflexion (EVPF), extreme plantarflexion (PF), extreme combined inversion–plantarflexion (INPF), extreme inversion (IN) and extreme combined inversion–dorsiflexion (INDF). The foot was forced in an extreme position by applying a proximally directed load of 100 N on the footplate through a system of cables and pulley blocks (Fig. 1).

The following protocol was used for each of the eight positions. First, the foot was loaded until an extreme position was reached. We defined an extreme joint position as the position where the foot would not move any further by increased loading of the footplate. This was verified by manually checking the footplate. A complete CT data set was acquired in the concerning foot position. After image acquisition, the CT table with the cadaveric specimen and 3D CT stress footplate was transported through the CT scanner out of the gantry, where the RSA set-up was positioned. RSA radiographs were acquired with the cadaveric specimen in an unchanged position. Subsequently, the foot was placed in another extreme position and the protocol was repeated.

Computer tomography-based bone contour registration method
A Philips MX-8000 multidetector CT scanner (Philips Medical Systems, The Netherlands) was used to acquire the CT-images. The scan protocol was the same as used for the previous in-vivo study: gantry tilt was 0, field of view was 154 mm, slice thickness was 0.6 mm, increment was 0.3 mm, image matrix was 512×512, pitch was 0.875, rotation time was 0.75 s, resolution was ultra high and reconstruction filter was C. The key principle of the CT-based bone contour registration method is the detection of the position of the bones in the CT-data sets by registration of the surface contour of these bones. Thereafter, automated bone segmentation is performed by a region growing algorithm in the neutral position CT-data set.

Subsequently, the positions of the bones in other CT-data sets are calculated by matching the boundary voxels of each bone in the initial CT data set, with the corresponding boundary voxels of the bones in the other CT-scans. Even in noisy images, this registration method in itself has an accuracy better than 0.019° for rotation and better than 0.025 mm for translation. For optimal registration of the bony contours of the cadaveric distal tibia, talus and calcaneus, one CT-scan was made without bone markers with the foot in the neutral position using a regular-dose CT-scan (150 mAs/slice). This position is favoured, since the unloaded foot causes the joint to be loose with bones making no or little contact with each other. To minimize the influence of the extra scattering caused by the tantalum bone markers, the regular-dose CT-scans were used for the other foot positions as well. This gave a radiation dose of 1.2 mSv for the entire series of nine CT-scans.

Roentgen stereophotogrammetric analysis
Roentgen stereophotogrammetric analysis was developed for measuring the kinematics of rigid bodies, and was first introduced by Selvik in 1974. In this study, the stereophotogrammetric radiographs were acquired using two Siemens MobiHeel Plus mobile X-ray units (Siemens Medical Solutions, Den Haag, The Netherlands) in combination with standard roentgengraphic plates (AGFA, CR MD 4.0 General Imaging Plates). The positions of the two roentgen foci were assessed using a commercially available carbon type calibration box (MEDIS Medical Imaging Systems, Leiden, The Netherlands). The tantalum markers that were inserted in the cadaveric bones served as artificial landmarks. Detection, identification and matching of the bone and calibration markers on the RSA radiographs, as well as the subsequent RSA calculations were performed, as described by Vrooman et al. and Valstar.

Data processing and kinematic description
For comparison, all bone positions measured with CT-BCM and RSA were represented in one coordinate system. Therefore, the XYZ-coordinate system was chosen that coincided with the geometric principal axes of the talus in neutral fixed position (Fig. 2). The origin is located in the centroid of the talus. The major principal axis of the talus defined the X-axis (directed anteriorly) and the second principal axis defined the Y-axis (directed medially). The Z-axis is perpendicular to the XY-plane (directed proximally).
The CT data set with the foot in neutral position was acquired without bone markers. To express the RSA bone markers in the chosen XYZ-coordinate system, the spatial coordinates of the CT talus bone markers in the extreme positions were transformed to reconstruct the mean location of the talus bone markers in neutral position. Subsequently, the RSA talus bone markers for each extreme position were fitted to the mean CT talus bone markers in neutral position, using the Veldpaus algorithm.\(^{17}\) Subsequently, the RSA bone markers of the tibia and calcaneus for each extreme position were transformed with the talar bone transformation matrices derived from the Veldpaus fitting procedures (Matlab, version 7.2.0.232, R2006a, The Mathworks, Natick, USA). Not all bone markers could be identified with RSA, due to overlap of bone markers with the cortical bone projections. The Veldpaus algorithm requires at least four markers. For the tibia in extreme position EV, only three bone markers were identified. The required fourth bone marker was added as the geometric centre of the three other bone markers. In position INDF, only two bone markers could be identified for the talus. Considerable bony overlap gave too low contrast for accurate detection on the radiograph. Therefore, this position was excluded for further analysis. Following the in-vivo protocol, the clinically relevant talocrural and subtalar joint range of motions were calculated between the remaining three pairs of extreme opposite foot positions: from DF to PF, from IN to EV and from EVDF to INPF.\(^ {1}\) Supplementary, the motion from the neutral position to each of the remaining seven extreme positions was calculated for both joints accordingly. The calculation of the relative bone-to-bone motion was performed with the same Veldpaus fitting procedures. The motion of the tibia and calcaneus, relative to the fixed talus was expressed in a helical axis with direction \(n\), a rotation about this helical axis (\(\theta\)), and a translation along this axis (\(t\)).\(^ {19}\) By using helical axes and the derived attitude vector for the rotation components in anatomical directions, an easy interpretation of results by clinicians seems feasible.\(^ {20}\) The helical rotation and the components of the attitude vector along three coordinate axes always represent the true spatial rotation, as opposed to the three cardan angles in a cardinal representation. The orientation of the helical axis was expressed with the deviation angle (\(\eta\)) between two helical axis directions. Helical axis position was expressed by the shortest distance (\(s\)) from the helical axis to the origin of the XYZ-coordinate system.

**Statistics and validation**

To verify the rigidity of the experiment, absolute distances were calculated between pairs of bone markers for RSA and CT. To determine the presence of systematic differences, we calculated the mean and the standard deviations of differences in bone marker distances between both modalities (bias and variability). The bias and variability were also calculated for the helical axes parameters. Accuracy is defined as the closeness of measurements to the true value. Expressions for accuracy can be obtained when comparing actual measurements with a standard. For assessment of the accuracy of CT-BCM and RSA, the root mean square difference (RMSd) was calculated for the difference between both modalities. The RMSd is a measure of total difference and is defined as the square root of the sum of the variance and the square of the bias. The smaller the value of the RMSd, the more accurate the measurement technique is considered. The RMSd was calculated for the difference in \(\theta, t, \eta\) and \(s\) of the helical axis between the RSA analysis and the CT-BCM technique.

In Woltring et al. and De Lange et al., it was concluded that for the reconstruction of helical axis data from position measurements of a set of markers, the rotation angle and translation are relatively well determined, while the direction and position of the helical axis are sensitive to landmark measurement errors, in the cases of small rotations.\(^ {5,19}\) Small values of \(\theta\) were present for the DF–PF motion in subtalar joint.\(^ {1}\) If our data show a relationship close to the theoretical, it would explain part of eventual differences between the two techniques.\(^ {19}\) Therefore, we determined the relationship between the differences of the CT technique and RSA technique in helical axis position (\(\Delta s\)) and helical axis orientation (\(\eta\)) as function of the rotation (\(\theta\)). Data of the motions between opposite extreme positions and between neutral and the extreme positions for both the talocrural and subtalar joints were pooled.

**RESULTS**

The mean standard deviations of the absolute distances between pairs of markers per bone in each extreme position were 0.071 and 0.068 mm, for CT-BCM and RSA, respectively (Table 1). The bias of all bone markers distances was −0.058 mm and the variability was 0.119 mm (Table 1). For the talocrural joint, the direction of the helical joint axis is running from postero-lateral to antero-medial direction with a major planar–dorsiflexion component (Fig. 2, Table 2). The subtalar helical axes are running from postero-lateral-inferior to antero-medial-superior direction with a considerable inversion and eversion component (Fig. 2). The largest rotation for the talocrural joint motion occurred from DF to PF: CT-BCM 55.78° vs. RSA 55.39° (Table 2). For subtalar joint motion, the largest rotation was found from IN to EV: CT-BCM 28.53° vs. RSA 28.81° (Table 2). The bias values of the ankle joint motion are marginally larger than the variability values except for the translation (Table 3). The variability values for the subtalar joint motion are larger than the bias values, except for the
deviation angle (Table 3). The RMSd of the rotation $\theta$ varies from 0.18° to 0.27° and of the translation $t$ between 0.12 and 0.27 mm (Table 3). The RMS of the deviation angle $\eta$ is largest for the subtalar joint (3.75°), as well as the RSMe of the helical axis position $\Delta s$ (5.46 mm) (Table 3). Both the differences in helical axis position ($\Delta s$) and the helical axis orientation ($\eta$) approximate the theoretical dependency on rotation $\theta$ (Fig. 3).

**DISCUSSION**

The relative accuracy of the new CT-BCM method compared to the conventional RSA was measured for talocrural and subtalar joint motion in one cadaveric specimen. The specific purpose of this 3D CT stress-test is the determination of the range of motion of the hindfoot joints, as changes in the range of motion typically can indicate ligament damage. We preferred to simulate the clinical in-vivo setting of the 3D CT stress-test as close as possible. Therefore, no phantom was used, but a cadaveric specimen. This implies that CT-BCM and RSA could both have systemic differences in this study, and differences between the techniques cannot be attributed to CT-BCM inaccuracies solely. However, it is not expected that the relative accuracy, found in this study, would substantially be improved when using a phantom. The same holds for the fact that only one specimen was used. This is confirmed by the rigidity of the experiment and the absence of systematic differences. This is demonstrated by the bias values of the bone marker distances and the helical parameters, which are all within 95% of the measured values indicating that no significant difference can be detected between both modalities (Table 3). The seven foot positions measured with RSA and eight with CT-BCM gave a sufficient data set of ten clinically relevant motions. The results show small differences between both modalities for the rotation $\theta$ (RMSd less than 0.27°) and the translation $t$ (RMSd less than 0.27 mm). Orientation $\eta$ and position $s$ show dependency on the $\theta$, where a smaller rotation causes a higher difference (Fig. 3). Both are accurately determined for rotations larger than 5°. This is in agreement with the expected sensitivity of these two finite helical axis parameters, as described by Woltring et al. From our experience, the segmentation and bone contour matching of living human bone is easier to perform than for cadaveric bone. Cadaveric specimens are usually from elderly people, who have poorer bone quality, as was the case in this study. Therefore, the accuracy for CT-BCM might have been higher when in-vivo bones from young living subjects were analysed. Accuracy of the RSA technique depends on the type and quality of the calibration equipment, image quality, film flatness, the precision of the measuring software and the number and configuration of the tantalum bone markers. In our study, not all RSA bone markers could be detected in one joint position, due to the poor contrast level of the RSA radiographs and the overlap of bone markers with the dense cortices of bones. One position was excluded from further analyses. Finally, the time delay between the acquisition of the CT-scans and RSA radiographs could have attributed to differences. We believe that this effect was minimized, since we waited a couple of minutes before we started the CT-scan to let the cadaveric tissue settle and moved the CT-gantry at a slow speed to the RSA set-up. This was also confirmed by the small differences in marker reconstruction between CT and RSA.

RSA has been used for studying bone growth, prosthetic fixation, joint kinematics and stability, fracture stability and the healing course of spinal fusion and pelvic and tibial osteotomies. In a literature review by Kärrholm, the reported accuracy of RSA ranged between 0.010 and 0.250 mm for translations and between 0.03° and 0.6° for rotations. Few reports are available comparing the accuracy of new methods for studying joint kinematics with conventional RSA. Recently, Ioppolo et al. studied the relative position and orientation of skeletal segments using RSA and single-plane X-ray fluoroscopy in two in-vitro phantom knee and hip models. Measured translational accuracy was less than 0.1 mm parallel to the image plane and less than 0.7 mm in the direction orthogonal to the image plane. The measured rotational difference was less than 1°. Bey presented a model-based tracking technique for measuring three-dimensional in-vivo glenohumeral joint kinematics. Biplane radiographic images that tracks the position of bones based on their three-dimensional shape and texture were compared to RSA. Bone markers were implanted into the humerus and scapula of cadaveric specimens, and biplane radiographic images of the shoulder were recorded, while manually moving the specimen's arm. The position of the humerus and scapula was measured using the model-based tracking system and RSA. Overall dynamic accuracy indicated that RMSd in any one direction were less than 0.385 mm for the scapula and less than 0.374 mm for the humerus. These differences correspond to rotational inaccuracies of approximately 0.25° for the scapula and 0.47° for the humerus. The RMS differences found in this study are in the same order of magnitude, as the above referenced studies.

Considering the results, the limitations, and the overall accuracy of the RSA technique, it can be concluded that the level of accuracy achieved with the CT-BCM method is sufficient for evaluating joint motion in clinical practice. CT-BCM is a promising method for studying joint motion, by measuring bone position and orientation, as it is highly accurate and only requires...
a CT scanner available in most hospitals in contrast to the equipment that is required for the RSA method.

Acknowledgements

Ms. Suzanne Bringmann (Faculty of Medicine, University of Amsterdam, The Netherlands) is thanked for her assistance during the research project. Mr. M. Pouls and Ms. S. Kalaykhan–Sewraj (Department of Radiology, University Hospital AMC, Amsterdam, The Netherlands) are thanked for the assistance with acquiring CT and RSA images.

REFERENCES


### TABLES

**Table 1** Calculated standard deviations of distances between bone markers for the eight extreme foot positions of the tibia, talus and calcaneus.

<table>
<thead>
<tr>
<th></th>
<th>CT-BCM</th>
<th>RSA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean standard deviation of the distances per modality (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tibia</td>
<td>0.0347</td>
<td>0.0774</td>
</tr>
<tr>
<td>Talus</td>
<td>0.0826</td>
<td>0.0673</td>
</tr>
<tr>
<td>Calcaneus</td>
<td>0.0929</td>
<td>0.0602</td>
</tr>
<tr>
<td>Mean overall SD</td>
<td>0.071</td>
<td>0.068</td>
</tr>
<tr>
<td>Bias (mm)</td>
<td>−0.110</td>
<td>0.113</td>
</tr>
<tr>
<td>Variability (mm)</td>
<td>0.095</td>
<td>0.123</td>
</tr>
<tr>
<td>Mean overall</td>
<td>−0.058</td>
<td>0.119</td>
</tr>
</tbody>
</table>

Additionally, the bias was calculated as the mean of differences between CT-BCM and RSA marker distances (mm), and the variability as the standard deviation of differences between CT-BCM and RSA marker distances (mm).

**Table 2** The values of the helical parameters as determined for CT-BCM and RSA, for the three pairs of extreme opposite motions (n=3 per joint).

<table>
<thead>
<tr>
<th>Direction of movement</th>
<th>Talocrural joint</th>
<th></th>
<th></th>
<th>Direction vector n</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 (°)</td>
<td>t (mm)</td>
<td>nx</td>
<td>ny</td>
</tr>
<tr>
<td>Extreme dorsiflexion to extreme plantarflexion</td>
<td>CT-BCM 55.78</td>
<td>0.44</td>
<td>0.32</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>RSA 55.39</td>
<td>0.38</td>
<td>0.31</td>
<td>0.88</td>
</tr>
<tr>
<td>Extreme combined eversion–dorsiflexion to extreme combined inversion–plantarflexion</td>
<td>CT-BCM 53.93</td>
<td>1.24</td>
<td>0.37</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>RSA 53.79</td>
<td>1.15</td>
<td>0.36</td>
<td>0.85</td>
</tr>
<tr>
<td>Extreme eversion to extreme inversion</td>
<td>CT-BCM 23.71</td>
<td>1.51</td>
<td>0.53</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>RSA 23.49</td>
<td>1.67</td>
<td>0.52</td>
<td>0.85</td>
</tr>
<tr>
<td>Direction of movement Subtalar joint</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extreme dorsiflexion to extreme plantarflexion</td>
<td>CT-BCM 12.98</td>
<td>3.52</td>
<td>0.80</td>
<td>−0.20</td>
</tr>
<tr>
<td></td>
<td>RSA 12.97</td>
<td>3.59</td>
<td>0.80</td>
<td>−0.18</td>
</tr>
<tr>
<td>Extreme combined eversion–dorsiflexion to extreme combined inversion–plantarflexion</td>
<td>CT-BCM 19.58</td>
<td>0.13</td>
<td>−0.62</td>
<td>−0.15</td>
</tr>
<tr>
<td></td>
<td>RSA 19.35</td>
<td>0.43</td>
<td>−0.64</td>
<td>−0.13</td>
</tr>
<tr>
<td>Extreme eversion to extreme inversion</td>
<td>CT-BCM 28.53</td>
<td>1.57</td>
<td>−0.68</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>RSA 28.81</td>
<td>1.53</td>
<td>−0.69</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Table 3 The bias, variability and root mean square differences (RMSd) between differences of the CT-BCM and RSA helical parameters for the three pairs of extreme opposite motions (n=3 per joint) and for the motions of the neutral to extreme position (n=7 per joint).

<table>
<thead>
<tr>
<th>Joint</th>
<th>Movement</th>
<th>$\theta$ (°)</th>
<th>t (mm)</th>
<th>$\eta$ (°)</th>
<th>$\Delta s$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talocrural joint</td>
<td>Opposite extremes</td>
<td>0.25</td>
<td>0.00</td>
<td>0.57</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>Neutral to extreme</td>
<td>0.18</td>
<td>0.05</td>
<td>0.79</td>
<td>0.45</td>
</tr>
<tr>
<td>Subtalar joint</td>
<td>Opposite extremes</td>
<td>-0.01</td>
<td>-0.11</td>
<td>1.25</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Neutral to extreme</td>
<td>0.02</td>
<td>-0.15</td>
<td>2.33</td>
<td>3.06</td>
</tr>
</tbody>
</table>

Variability

<table>
<thead>
<tr>
<th>Joint</th>
<th>Movement</th>
<th>$\theta$ (°)</th>
<th>t (mm)</th>
<th>$\eta$ (°)</th>
<th>$\Delta s$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talocrural joint</td>
<td>Opposite extremes</td>
<td>0.13</td>
<td>0.14</td>
<td>0.28</td>
<td>0.11</td>
</tr>
<tr>
<td></td>
<td>Neutral to extreme</td>
<td>0.13</td>
<td>0.11</td>
<td>0.53</td>
<td>0.31</td>
</tr>
<tr>
<td>Subtalar joint</td>
<td>Opposite extremes</td>
<td>0.26</td>
<td>0.18</td>
<td>0.79</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>Neutral to extreme</td>
<td>0.19</td>
<td>0.24</td>
<td>3.17</td>
<td>4.89</td>
</tr>
</tbody>
</table>

RMSd

<table>
<thead>
<tr>
<th>Joint</th>
<th>Movement</th>
<th>$\theta$ (°)</th>
<th>t (mm)</th>
<th>$\eta$ (°)</th>
<th>$\Delta s$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Talocrural joint</td>
<td>Opposite extremes</td>
<td>0.27</td>
<td>0.12</td>
<td>0.61</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>Neutral to extreme</td>
<td>0.22</td>
<td>0.12</td>
<td>0.93</td>
<td>0.53</td>
</tr>
<tr>
<td>Subtalar joint</td>
<td>Opposite extremes</td>
<td>0.21</td>
<td>0.18</td>
<td>1.41</td>
<td>1.04</td>
</tr>
<tr>
<td></td>
<td>Neutral to extreme</td>
<td>0.18</td>
<td>0.27</td>
<td>3.75</td>
<td>5.46</td>
</tr>
</tbody>
</table>

$\Delta s$ is defined as the difference in helical axis position between CT-BCM-technique and RSA; $\eta$ is defined as the spatial angle between the axis as determined by the CT-BCM-technique and the axis as determined by RSA.

Figure 1 Experimental set-up. The cadaveric ankle was analysed with the CT-BCM method. Subsequently, the CT-table was pushed through the gantry with the cadaveric ankle still loaded in the same position. Stereophotogrammetric radiographs were acquired using two mobile X-ray units.
Figure 2 The helical axis positions for CT-BCM technique (grey lines) and RSA technique (black lines) for: (A) subtalar joint between two extreme positions (n=3) and (B) talocrural joint between two extreme positions (n=3). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figure 3 Difference between the CT-BCM technique and RSA technique for helical axis position ($\Delta s$) and helical axis orientation ($\eta$), as function of the helical axis rotation ($\theta$). All data are pooled, i.e. from the motion between two extreme positions (n=3 per joint) and motion between neutral and each extreme position of the talocrural joint (n=7 per joint) and of the subtalar joint.
CHAPTER 3

In-vivo range of motion of the subtalar joint using computed tomography

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CHAPTER 3

ABSTRACT

Background Understanding in-vivo subtalar joint kinematics is important for evaluation of subtalar joint instability, the design of a subtalar prosthesis and for analysing surgical procedures of the ankle and hindfoot. No accurate data are available on the normal range of subtalar joint motion. The purpose of this study was to introduce a method that enables the quantification of the extremes of the range of motion of the subtalar joint in a loaded state using multidetector computed tomography (CT) imaging.

Methods In 20 subjects, an external load was applied to a footplate and forced the otherwise unconstrained foot in eight extreme positions. These extreme positions were foot dorsiflexion, plantarflexion, eversion, inversion and four extreme positions in between the mentioned positions. CT images were acquired in a neutral foot position and each extreme position separately. After bone segmentation and contour matching of the CT data sets, the helical axes were determined for the motion of the calcaneus relative to the talus between four pairs of opposite extreme foot positions. The helical axis was represented in a coordinate system based on the geometric principal axes of the subjects’ talus.

Results The greatest relative motion between the calcaneus and the talus was calculated for foot motion from extreme eversion to extreme inversion (mean rotation about the helical axis of 37.3±5.9°, mean translation of 2.3±1.1 mm).

Conclusion A consistent pattern of range of subtalar joint motion was found for motion of the foot with a considerable eversion and inversion component.

INTRODUCTION

The subtalar joint has an important role in the complex hindfoot motion during gait.4,8,14 Subtalar joint instability has received increasing attention in the literature as a cause of hindfoot instability. No consensus exists regarding the diagnostic criteria for subtalar joint instability.3,24 One of the underlying causes is the lack of a standard method for accurately measuring subtalar joint motion. In addition, there are no clear reference values of normal subtalar joint motion. For the evaluation of subtalar joint instability accurate knowledge of the reference values of subtalar joint motion is necessary. Currently, for end-stage osteoarthritis of the subtalar joint unresponsive to conservative treatment the only operative option is a subtalar arthrodesis. Fournol reported a series of 100 implanted prostheses to replace subtalar arthrodesis for post-traumatic osteoarthritis.7 Over 50% of the patients had unsatisfactory results, mostly because of failure of the prosthesis. Better outcomes are expected with an improved design of the subtalar prosthesis. For this development, kinematic data of the subtalar joint are essential. In addition, an accurate quantitative data set of subtalar joint motion is required for the validation of biomechanical computer models of the ankle joint complex and for studying the kinematic effects of ankle and hindfoot surgery.

The lack of external landmarks of the talus in combination with the subtalar joint geometry has made the subtalar joint kinematics difficult to investigate in living subjects. In-vivo studies on subtalar kinematics used camera registration techniques of external surface markers attached to the skin during stance and walking. It is obvious that this technique cannot accurately measure rotations and translations of the bones of the subtalar joint.5,12,13,19,25 The invasive roentgen stereophotogrammetric analysis (RSA) has been considered an accurate technique for studying bone-to-bone motion in-vivo and was used by numerous authors to study ankle and foot kinematics.2,16,27 It is however a cumbersome method and also has the risk of infection and damaging the joint cartilage due to malpositioning of the bone markers. More recently, computed tomography (CT) and magnetic resonance imaging (MRI) techniques were used to study the ankle and subtalar joint motion in cadaveric specimens and living subjects.18,21-23,26 None of these studies reported on the extremes of the range of motion of the subtalar joint in-vivo. The purpose of this study was to introduce an accurate method that enables the quantification of the extremes of bone-to-bone motion in a loaded state using multidetector CT imaging. The method was applied to acquire a reference data set of the normal extremes of subtalar joint motion in a group of volunteers.
METHODS

The study was approved by the Medical Ethical Committee of our hospital. Twenty healthy volunteers (10 males, 10 females) signed informed consent prior to participation. The mean age in this group was 26.3 years, ranging from 22 to 35 years. None of the volunteers had any ankle/foot complaints, nor had a history of ankle/foot trauma or underwent surgery of the lower extremities. Physical examination of the ankle and hindfoot was performed to check for any abnormalities. Each subject was positioned on the scanner table in a supine position with the right lower leg fixed to the supporting platform using velcro straps (Fig. 1). The supporting platform was positioned 10 cm above the scanner table allowing for slight flexion of the knee, thereby relaxing the ankle/foot. The right foot sole was placed on a customized footplate that was made from radiolucent materials. The foot was fixed to the footplate with two velcro straps around the ankle and the forefoot. The footplate was fabricated by the Medical Technical Development Department of our hospital.

For computer segmentation of the talus and calcaneus, the first series of CT images of the right ankle and hindfoot was acquired with the foot in a neutral position relative to the lower leg (i.e. the sole of the foot was placed in approximately 90° relative to the anterior rim of the tibia). This neutral position with no stress applied to the subtalar joint was necessary as computer segmentation of one particular bone is more difficult with the articular surfaces of the joint having contact. Bone segmentation is the process of making a three-dimensional computer segmentation of one particular bone based on the automatic detection of the outer osseous surface of the bone in a CT data set using a radiation dose of 150 mAs/slice. This step is necessary to be able to determine the exact location of the same bone in a different CT data set with a low radiation dose scanning technique. In this study the Philips MX8000 multidetector CT scanner was used (Philips Medical Systems, The Netherlands). The scanner settings are shown in Table 1. An external load (i.e. weighted sandbags) was applied to the footplate through a system of a wire and pulleys to force the foot in eight extreme positions. The footplate had eight fixed attachment points for the pulling wire located at the periphery of the footplate. In all instances, the pulling force of the external load to the footplate through the wire was directed cranially. The eight extreme foot positions resulting from the load applied to the footplate were the following: dorsiflexion, combined inversion-dorsiflexion, eversion, combined inversion-plantarflexion, plantarflexion, combined inversion-plantarflexion, inversion, and, combined inversion-dorsiflexion. CT scanning was performed in each of the eight extreme foot positions starting from dorsiflexion (assigned position 1) and continued in a clockwise order to end with position 8. Approximately 2 cm of the distal tibia, the complete talus, the calcaneus, the navicular and the cuboid bone were scanned. In each extreme foot position, a series of CT images was acquired with a low radiation dose technique (26 mAs/slice). The total external load that was applied in each of the extreme foot positions was the maximum load that was tolerated by the subject. The means of the external loads applied to the footplate to force the foot in the eight extreme positions ranged from 58 to 62 N. The relaxed status of the lower leg muscles was checked by asking the subjects and by palpation of the muscles.

A workstation (IBM RS 6000) was used for image processing and visualization. Software was developed in C and C++ to implement segmentation and registration algorithms. For reconstruction of the CT images data an image matrix of 512×512 pixels was used. The pixel size of 0.3 mm and the slice interval of 0.3 mm resulted in a volume of isotropic voxels (voxel size 0.3×0.3×0.3 mm3). First, bone segmentation of the talus and calcaneus was performed by a region growing algorithm using the regular dose CT scan images with the right foot in a neutral position. With this technique for each voxel a weighted grey value mean was calculated using a small sphere (radius of 0.5 mm). Whenever the spherical grey value mean was higher than a predefined grey value this voxel was classified as bone tissue and assigned to the bone region in the process of growing. The region growing algorithm was able to automatically find the outline of the bone structure in most cases but did not always comprise the inner bone structure. To close the boundaries of the bones and completing the registration of the inner and outer bone structure, an additional procedure based on binary operators was used. In the second step, the talus and calcaneus were matched in the low-dose CT data sets with the foot in the eight extreme positions. The boundary voxels of each bone in the regular dose CT scans were matched with the corresponding boundary voxels of the bones in the low-dose CT scans. To speed up computation, a randomly chosen subset of the boundary voxels of each bone was used for the first stage in the matching procedure. A cost function based on grey value correlation of the boundary voxels of each bone was minimized. The downhill simplex method by Nelder and Mead was used to minimize the cost function between the grey values of the regular dose and the low-dose scan. The matching procedure required a rough estimate of the rotation and translation parameters of the bones. This was done by visually overlying the centers of gravity of the corresponding bones in the low-dose CT data sets. Next, the matching software was able to find an optimal fit in a three-dimensional search window around each bone. In the second step both translation and rotation parameters for
each bone were optimized starting from the optimal position in the search window. In this final step, all boundary voxels of the bones were used to gain an accurate estimation of all rotation and translation parameters. In all instances, the centre of gravity of the segmented bone structure was defined as the origin of the embedded coordinate system.

For quantitative analysis of subtalar joint kinematics, the helical axis parameters for motion of the calcaneus relative to the talus between opposite extreme foot positions were computed. The helical transformation is expressed in terms of a rotation about a helical axis, and a translation along this axis. The helical axis was represented in a right-hand rule XYZ-coordinate system based on the geometric principal axes of the talus of the subject (Fig. 2). The origin of the talus-based coordinate system was placed in the centroid of the talus. To define the orientation of the helical axis in the XYZ-coordinate system, the inclination and deviation angle of the helical axis was calculated for each testing subject. The inclination angle is defined as the angle between the helical axis and the XY-plane. The deviation angle is defined as the angle between the projection of the helical axis on the XZ-plane and the X-axis. A positive value of the deviation angle of the helical axis indicates a medially oriented helical axis in an anterior direction. In addition, the absolute angle between the helical axis of one subject and the mean helical axis of the 20 subjects was calculated. The helical axis parameters were calculated with mathematical routines developed in Matlab software (Matlab Version 6.5, The MathWorks Inc., Natick, United States of America) using a Pentium 4 processor type computer (Hewlett-Packard, United States of America) running Microsoft Operating System Windows XP Professional (Microsoft Corporation, United States of America).

RESULTS

The position of the calcaneus relative to the fixed talus in the eight extreme foot positions for one subject is shown in Fig. 3(A, B). Two consistent extreme positions of the calcaneus relative to the talus were observed, i.e. extreme eversion and extreme inversion, irrespective of the combination with plantarflexion or dorsiflexion of the foot. The helical axes that represented the range of motion of the subtalar joint between two opposite extreme foot positions, were consistent in the group of 20 subjects, except for the motion between dorsiflexion and plantarflexion (Fig. 4; Table 2, Table 3, Table 4 and Table 5). The inclination angle of the helical axes of the motion between extreme eversion and inversion, with and without combined dorsiflexion and plantarflexion, showed a good consistency with a standard deviation ranging from 4.0° to 4.8° (Table 2, Table 3 and Table 4). Comparable results were found for the absolute angles between the helical axes of the subjects and the mean helical axis for foot motion with a considerable eversion and inversion component (Table 2, Table 3, Table 4 and Table 5).

The range of motion of the subtalar joint as expressed by the rotation about the helical axis was on average the highest for the motion between extreme eversion and extreme inversion (37.3±5.9°) (Table 2, Table 3 and Table 4). The translation values for this type of subtalar joint motion were ranging from 0.2 to 5.1 mm. No correlation between the external loads applied to the footplate and the range of subtalar joint motion was found. In addition, there was no significant difference in outcome between male and female range of subtalar joint motion. The subtalar joint motion for extreme dorsiflexion to extreme plantarflexion of the foot was highly variable among the subjects as is shown by a large variation of the direction of the helical axes. Rotation, translation values and absolute helical axis angles were also highly variable for this type of subtalar joint motion (Fig. 4D; Table 5).

To assess the reproducibility of the CT scanning technique, in one subject a repeated scan was acquired with the foot in the extreme eversion position (position 3) after completing the protocol. The subject was not removed from the device for the repeated scan. The orientation of the helical axis for motion between the neutral position to extreme eversion appeared to be reproducible. For the repeated scan the rotation difference was 1.0° (23.8° versus 24.8° for the initial scan) and the translation differed 0.2 mm (1.5 mm versus 1.7 mm for the initial scan).

DISCUSSION

The extremes of the range of motion of the calcaneus relative to the talus in a loaded state in healthy subjects using a multidetector CT scanner were studied. For extreme positions of the foot with a considerable eversion and inversion component, the helical axis parameters for the subtalar joint were consistent between the subjects in our series. We found the helical axis of the right-sided subtalar joint running from postero-lateral-inferior to antero-medial-superior. This finding is in agreement with the literature. In contrast to other studies, we found a relatively little variation in the inclination angle, and moderate variation in the deviation angle of the mean helical axis for extreme foot positions with an eversion and inversion component. This might result from the talus-based coordinate system that was defined for every testing subject individually. The subtalar joint motion from extreme dorsiflexion to extreme plantarflexion of the foot resulted in widely varying helical axes...
parameters in our series and it was apparent that the subtalar joint was not in stable end positions.

Our study was the first to measure subtalar joint motion between the opposite extreme foot positions in a loaded state in-vivo using CT images. The greatest relative motion between the calcaneus and the talus was found for extreme eversion to extreme inversion of the foot and the mean subtalar joint rotation about the helical axis measured 37.3±5.9° (range 26.6–50.4°). CT and MRI techniques have been used for quantifying ankle joint motion between predefined input foot positions in-vivo.21,22,26 Others studied the response of the ankle and subtalar joint in-vivo to an inversion load and an anterior drawer load using an MRI technique.21,23 Outcomes of these studies are difficult to compare with the variation of subtalar joint in-vivo to an inversion load and an anterior drawer load using an MRI predefined input foot positions in-vivo.18,22,26 Others studied the response of the ankle and subtalar joint motion between the opposite extreme foot positions.

In addition, in this study we used a low-dose technique for CT scanning of the eight extreme foot positions. Fewer scans may be required for assessment of subtalar joint function by studying a limited number of extreme foot positions, thereby reducing the radiation dose. Reproducibility of the technique presented was not fully assessed in this study. Cadaveric specimens proved not useful for reproducibility tests as bone segmentation and bone matching was more difficult than in living bone due to the inferior quality of the cadaveric bones. Re-testing of human volunteers was not performed, as this was not the subject of the current study. This study presents a technique for quantitative analysis of bone-to-bone motion in a loaded state with the otherwise unconstrained foot in healthy volunteers. With the present study we aimed at providing kinematic data on the subtalar joint that is useful for both clinicians and researchers. It is of value from a basic-science perspective as the subtalar joint function is a subject of increasing interest. Secondly, this study is important from a clinical point of view because many problems that arise in the hindfoot are thought to be associated with an alteration of subtalar joint motion.

Acknowledgements

Mr. M. Poulos and Ms. M.A. de Graaf (Department of Radiology, University Hospital AMC, Amsterdam, The Netherlands) are thanked for the assistance with acquiring CT images. Mr. P. Broekhuizen and colleagues (The Department for Medical Technical Development (M.T.O.), University Hospital AMC, Amsterdam, The Netherlands) are thanked for development of the footplate for CT scanning.

REFERENCES

21. Ringleb SI. A three-dimensional stress MRI technique to quantify the mechanical properties of the ankle and subtalar Joint—Application to the diagnosis of ligament injuries, Drexel University (2003).


### TABLES

Table 1 Settings of the Philips MX8000 multidetector CT scanner (Philips Medical Systems, The Netherlands) for scanning of the ankle and hindfoot in the neutral position and the eight extreme positions

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### Table 2 Helical axis parameters for the subtalar motion from extreme eversion to extreme inversion

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### Table 3 Helical axis parameters for the subtalar motion from extreme combined eversion-dorsiflexion to extreme combined inversion-plantarflexion

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Table 4 Helical axis parameters for the subtalar motion from extreme combined eversion-plantarflexion to extreme combined inversion-dorsiflexion

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Table 5 Helical axis parameters for the subtalar motion from extreme dorsiflexion to extreme plantarflexion

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(a) Means and standard deviations were not calculated as the helical axis values were highly variable for this range of subtalar joint motion.
Figure 1 The subject was positioned on the CT table with the right lower leg attached to the supporting platform and with the right foot attached to the footplate. An external load was applied to the footplate to force the otherwise unconstrained foot in the eight extreme positions. Following CT scanning with the foot in the neutral position, scanning was performed for each of the extreme positions separately.

Figure 2 For each subject, the helical axis for subtalar joint motion was represented in a XYZ-coordinate system based on the geometric principal axes of the talus of the subject. The major principal axis of the talus was defined the X-axis and the second principal axis was defined the Y-axis. The Z-axis was perpendicular to the XY-plane and coincided with the X- and Y-axis. The origin of the XYZ-coordinate system was located in the centroid of the talus. The positive X-axis was directed anteriorly, the positive Y-axis medially and the positive Z-axis proximally. The direction of the helical axis is represented by the normal vector $n$. Relative to the coordinate system the inclination angle of the helical axis is the angle between the XY-plane and the normal vector $n$. The deviation angle of the helical axis is the angle between the X-axis and the projection of the normal vector $n$ on the XY-plane. Shown is the graphic representation of the XYZ-coordinate system with the normal vector $n$ and talus of one subject.
Figure 3 Graphic representation of the position of the calcaneus relative to the talus for the eight extreme foot positions in one subject from an (A) anterior and (B) lateral view. The footplate is shown in the center as a reference to the extreme foot positions.

Figure 4 Graphic representation of the helical axes for subtalar motion from (A) extreme evasion to extreme inversion, (B) extreme evasion-dorsiflexion to extreme inversion-plantarflexion, (C) extreme evasion-plantarflexion to extreme inversion-dorsiflexion, and (D) extreme dorsiflexion to extreme plantarflexion of twenty normal feet. The helical axes are grouped by overlying the talus-based XYZ-coordinate system of the subjects. The helical axes have a constant length of 100 mm. In all graphs the right talus of one subject is shown in the center of the XYZ-coordinate system from an anteromedial view.
CHAPTER 4

Computed tomography-based measurements on the range of motion of the talocrural and subtalar joints in two lateral column lengthening procedures


Foot and Ankle International, In Press
ABSTRACT

Background Lateral column lengthening (LCL) has become an accepted procedure for the operative treatment of the flexible flatfoot deformity. Hindfoot arthrodesis via a calcaneocuboid distraction arthrodesis (CCDA) has been considered a less favourable surgical option than the anterior open wedge calcaneal distraction osteotomy (ACDO), as CCDA has been associated with reduced hindfoot joint motion postoperatively. The talocrural and subtalar joint ranges of motion were measured in patients who underwent an ACDO or CCDA procedure for flatfoot deformity.

Methods CT scanning was performed with the foot in extreme positions in five ACDO and five CCDA patients. A bone segmentation and registration technique for the tibia, talus and calcaneus was applied to the CT images. Finite helical axis (FHA) rotations representing the range of motion of the joints were calculated for the motion between opposite extreme foot positions of the tibia and the calcaneus relative to the talus.

Results The maximum mean FHA rotation of the talocrural joint (for extreme dorsiflexion to extreme plantarflexion) after ACDO was 52.2° ± 12.4° and after CCDA 49.0° ± 12.0°. Subtalar joint maximum mean FHA rotation (for extreme eversion to extreme inversion) following ACDO was 22.8° ± 8.6°, and following CCDA 24.4° ± 7.6°.

Conclusion An accurate CT-based technique was used to assess the range of motion of the talocrural and subtalar joints following two lateral column lengthening procedures for flatfoot deformity. Comparable results with a considerable amount of variance were found for the range of motion of the ACDO and CCDA procedures.

INTRODUCTION

Acquired degenerative flatfoot deformity is a problem frequently seen in adults and may lead to a painful foot with progressive planovalgus deformity. The most common cause for the unilateral adult acquired flatfoot is incompetence of the posterior tibial tendon (PTT) and the supporting medial ligaments. Intermediate (stage two) incompetence of the PTT is described as the loss of normal alignment of the foot but with the associated flatfoot deformity remaining flexible. Surgical treatment for the stage two PTT insufficiency usually includes a flexor digitorum longus (FDL) tendon transfer in combination with a bony procedure to realign and stabilize the hindfoot passively. Current bony procedures include the lateral column lengthening procedure, the medial displacement calcaneal osteotomy, or a double osteotomy technique. The rationale for the lateral column lengthening procedure is to restore the medial longitudinal arch by realigning the foot around the talus, thereby correcting the hindfoot valgus and neutralizing the forefoot abduction. Evans described an anterolateral open wedge calcaneal distraction osteotomy (ACDO) just proximal to the calcaneocuboid joint for lateral column lengthening. Another surgical option for lateral column lengthening is a calcaneocuboid joint distraction arthrodesis (CCDA). Both techniques showed significant improvement in the postoperative radiographic parameters of the foot and AOFAS clinical scores. Following CCDA for flexible flatfoot deformity, one might expect a decreased tarsal and thus decreased subtalar joint range of motion. This could possibly lead to a symptomatic hindfoot. Therefore, surgeons might prefer the ACDO over the CCDA, as the ACDO procedure preserves calcaneocuboid joint motion resulting, theoretically, in better hindfoot function. On the other hand, there might be an effect on the subtalar joint range of motion with the ACDO procedure as the anteroposterior length of the calcaneus is increased and thereby the length and/or the function at the calcaneal facets of the subtalar joint is disturbed. The effect of the two different LCL procedures on the talocrural and subtalar joint ranges of motion in-vivo was not previously described. The purpose of this study was to describe the range of motion of the talocrural and subtalar joints of patients who underwent the anterior calcaneal distraction osteotomy (ACDO) or the calcaneocuboid distraction arthrodesis (CCDA) for the operative treatment of flexible adult acquired flatfoot. An accurate computed tomography-based bone registration technique was used for this purpose.

METHODS

The study was approved by our Medical Ethical Committee. Patients with a flexible adult acquired flatfoot that had been treated surgically by a lateral column lengthening procedure
were selected at random from the hospital database (Table 1). These patients received a study information package by mail. Ten patients (nine female, one male) agreed to participate and signed informed consent prior to participation. The first group consisted of five patients that had been treated with a calcaneocuboid distraction arthrodesis (CCDA) for symptomatic flexible adult acquired flatfoot deformity. The second group consisted of five patients that had been treated with an anterior open wedge calcaneal distraction osteotomy (ACDO) for flatfoot deformity. The two groups were operated on serially in time, i.e. the CCDA group was operated in the early phase and the ACDO patients were operated on more recently. All surgery was performed by the same foot and ankle surgeon (JWKL). Pre-operatively, patients complained of pain in the medial and/or lateral hindfoot. The patients were able to walk approximately 15 to 30 minutes. On pre-operative physical examination, patients exhibited a subluxation of the forefoot in relation to the hindfoot (peritalar dorsolateral subluxation), resulting in increased hindfoot valgus. Typically, the patients were not able to perform the single heel rise test on the symptomatic foot due to insufficiency or pain of the PTT. In all cases, complete manual correction of the hindfoot valgus deformity and peritalar dorsolateral subluxation was easily possible, thus assuring that the patient had a flexible flatfoot deformity.

Surgical technique
In the anterior calcaneal open wedge distraction osteotomy (ACDO), a lateral skin incision was made to expose the lateral calcaneus and the anterior calcaneal process. Following identification of the calcaneocuboid joint, the calcaneocuboid joint was temporary fixated using a single K-wire. The calcaneal open wedge osteotomy was made at approximately 20 mm posterior from the calcaneocuboid joint line. The anterior calcaneal osteotomy cut was made perpendicular to the long calcaneal axis. Care should be taken to leave the medial cortex of the calcaneus intact to act as a semi-rigid hinge. Using a laminar spreader, the anterior calcaneal osteotomy was opened up. For distraction, an autogenous tricortical bone graft of approximately 10 mm originating from the os ilium was used. The osteostomy was usually fixated with an X-plate and screws bridging the graft (Figure 1A and 1B). The calcaneocuboid distraction arthrodesis (CCDA) was performed through an identical lateral skin incision proximal to distal as this is considered to be more safe with regard to damaging the medial plantar nerve. At the level of Henry’s knot, the FHL and the FDL were sutured together. Then the FDL tendon was released proximally. The talonavicular joint was identified together with the spring ligament. In three patients, repair of the medial capsule-ligamentous structures was performed at this stage. The PTT was excised in case of severe involvement and loss of function. A 6.0 mm drill hole was made through the navicular bone for passage of the FDL tendon. The FDL tendon was pulled through the drill hole from plantar to dorsal and was firmly sutured on to itself and the periosteum of the navicular bone on the dorsal side. An additional lengthening of the Achilles tendon is most often necessary (Table 1). In that case, a percutaneous technique was used for Achilles tendon lengthening. The postoperative treatment and rehabilitation protocol was the same for both LCL procedures. A non-weightbearing lower leg cast was provided for four weeks followed by a weightbearing lower leg cast for another four weeks. With radiographs showing signs of bony consolidation at eight weeks postoperatively, patients were allowed full weightbearing without a cast. Support at this stage was provided by use of a walker brace.

Measuring the range of motion
For accurate assessment of talocrural and subtalar joint ranges of motion in-vivo following the lateral column lengthening procedure, a validated CT-based bone contour registration technique was used. In summary, the patients were positioned supine on the CT scanner table with the lower leg fixed on to a supporting platform and the foot fixated to a radiolucent footplate. For computer segmentation of the tibia, talus and calcaneus, the first series of CT images with normal radiation dose (150 mAs) was made with the foot in the neutral position relative to the lower leg. Subsequently, low radiation dose CT scans (26 mAs) were acquired with the foot in eight extreme positions using a cranially directed force applied to the footplate at eight different points. The external load (i.e. sand bags) was applied to the footplate through a system of a single pulling wire and pulleys to force the foot in the extreme position (Figure 3). The maximum external load that was applied was the maximum load that was tolerated by the patient. The eight extreme foot positions resulting from the load applied
to the footplate were: dorsiflexion, combined eversion-dorsiflexion, eversion, combined eversion-plantarflexion, plantarflexion, combined inversion-plantarflexion, inversion, combined inversion-dorsiflexion. CT scanning was performed starting from dorsiflexion (assigned position one) and continued in a clockwise order to end with position eight for the right foot. In case of a left foot, CT scanning was performed in each of the eight extreme foot positions starting from dorsiflexion (assigned position one) and continued in a counterclockwise order (position eight, position seven, etc). Semi-automated computer bone segmentation and automatic registration of the distal tibia, talus and calcaneus in the CT image sets was performed.1

Description of joint kinematics
The range of motion in the talocrural and subtalar joints was defined as the motion between two extreme positions. For each subject, ranges of motion were calculated of the tibia and calcaneus relative to the fixed talus from extreme dorsiflexion (DF) to extreme plantarflexion (PF), from extreme eversion (EV) to extreme inversion (IN), and from extreme eversion-dorsiflexion (EVDF) to extreme inversion-plantarflexion (INPF). For quantitative analysis, the range of motion of the talocrural and subtalar joints were expressed by a finite helical axis (FHA) with a rotation about this helical axis (θ) and a translation along this axis (t). The FHA’s were represented in a right hand rule XYZ-coordinate system that coincided with the geometric principal axes of the talus.1 The origin of the coordinate system was the geometric centroid of the talus. Each FHA rotation was decomposed into three rotation components relative to the coordinate axes of the talus by using the attitude vector. The rotation components facilitate the clinical interpretation of the range of motion of the talocrural and subtalar joints.17 The three rotation components are plantarflexion-dorsiflexion, inversion-eversion, and internal rotation-external rotation. No statistical analyses were performed for comparison of the outcome between the two patient groups.

RESULTS
The mean age at surgery was 59 years in the ACDO patients and 54 years in the CCDA patients. Follow-up ranged from six months to more than nine years (mean four years and six months) (Table 1). In the ACDO group the mean follow-up was 29 months, in the CCDA group the mean follow-up was 79 months. All osteotomies and arthrodeses had fused and no early complications had occurred. The postoperative pain at the lateral fourth and fifth tarsometatarsal joints was noted as a late complication of these lengthening procedures. At time of follow-up, the mean AOFAS score for the ACDO patients was 85 points (SD 14) and 76 points (SD 23) for the CCDA patients. The patients rated their own overall result of operative treatment as Excellent in two cases, Good in seven cases and Poor in one case. In all patients, the ACDO or CCDA procedure was combined with augmentation of the PTT using the flexor digitorum longus (FDL) tendon (Table 1). In case of a fixed pes equinus deformity after the ACDO or CCDA procedure, an additional percutaneous Achilles tendon lengthening was performed in seven patients. In two ACDO patients an additional first tarsometatarsal joint arthrodesis was performed to stabilize and correct the flattened medial arch of the foot. In two other ACDO patients an additional proximal first metatarsal osteotomy combined with a distal soft tissue procedure was performed to correct hallux valgus deformity. In three patients (in one ACDO and two CCDA patients), a secondary resection arthroplasty of the fourth and fifth tarsometatarsal joints was performed for treatment of persistent pain at these two joints in a later stage.

Helical axis range of motion
The mean finite helical axis (FHA) rotation θ was 52.5° (SD 12.4°) for the talocrural range of motion from extreme dorsiflexion to extreme plantarflexion in the ACDO patients, the mean FHA rotation θ was 49.0° (SD 12.0°) for talocrural range of motion in the CCDA patients (Table 2). If dorsiflexion and plantarflexion was combined with inversion or eversion of the foot, the FHA range of motion was smaller. For the subtalar joint, in both groups the mean FHA rotation θ was calculated for extreme eversion to extreme inversion of the foot. The maximum mean FHA rotation θ for the subtalar joint was 22.8° (SD 8.6°) in ACDO patients, and 24.4° (SD 7.6°) in CCDA patients respectively (Table 2). If eversion and inversion was combined with dorsiflexion or plantarflexion of the foot, then the FHA range of motion was smaller. FHA translations were small and variable for talocrural and subtalar range of motions with means ranging from 0.0 to 2.2 mm in the two groups (Table 2).

Rotation components of the range of motion
For extreme dorsiflexion to extreme plantarflexion of the foot, the motion in the talocrural joint is a combination of plantar flexion, inversion and some internal rotation if dissolved about the principal axes of the talus (Figure 4A). These talocrural joint motions can be considered as coupled motions. For foot dorsiflexion to plantar flexion, there is very little
motion in the subtalar joint. For joint motion from extreme eversion to extreme inversion, there is a comparable amount of inversion and internal rotation of the subtalar joint for the ACDO and CCDA patients (Figure 4B). For joint motion from extreme eversion-plantarflexion to extreme inversion-dorsiflexion and for extreme eversion-dorsiflexion to extreme inversion-plantarflexion, the three rotation components for the talocalcaneal and subtalar joints were also comparable between the two groups (Figure 4C and 4D). Notice that with considerable inversion-eversion in the subtalar joint, there is also a substantial amount of internal-external rotation within the joint (Figure 4B, 4C and 4D).

DISCUSSION
An accurate CT-based technique was used to evaluate the in-vivo range of motion of the talocrural and subtalar joints in patients who were treated with a lateral column lengthening procedure and PTT augmentation for flexible adult acquired flatfoot deformity. In this study, comparable results were found in the ACDO and CCDA patient groups for the talocrural and subtalar joint range of motion. It must be emphasized that there was considerable variation in outcome between the patients within each group. In addition, the patient groups only consisted of 5 eligible patients each as these are low volume procedures. Furthermore, as the ACDO procedure is more commonly carried out nowadays, the CCDA group would hardly increase in size over time and the difference in follow-up periods would also increase. Therefore, with the small number of patients in both groups for the above mentioned reasons no statistical analyses were performed and no statistically supported conclusions could be drawn from this study. All patients in the current study were operated by the same surgeon. The reason that the two surgical techniques were used by the one surgeon is explained as follows. In the past, patients with acquired flatfoot deformity that did not respond to conservative treatment were advised correction through a calcaneocuboid distraction arthrodesis with percutaneous lengthening of the Achilles tendon and medial soft tissue augmentation. The results of this technique reported in 2006 by Krans et al. were discussed as having a less favourable outcome than after a lengthening procedure through a distraction osteotomy of the anterior calcaneus as reported by Hintermann et al. earlier.5,7 Based on these reports, from then onwards patients were operated with lengthening of the lateral column using an anterior calcaneal distraction osteotomy (ACDO). This was combined with the same medial soft tissue procedures and if necessary, other additional procedures. There are some limitations to this study. Using the two surgical techniques in different time periods also implies that the follow-up times are different. For the CCDA patients the mean follow-up time was larger than for the ACDO patients; 79 and 29 months respectively. Although there was a 50 month difference in follow up between the two groups, the early CCDA patients did not do worse compared to the ACDO patients in terms of talocrural and subtalar joint range of motion. Moreover, as clinical results might deteriorate over time for several reasons, there was also no difference in AOFAS scores between the two groups. Therefore, it can not be stated that the difference in follow up time between the two groups automatically resulted in worse results for the group of patients that were operated first (i.e. the CCDA patients). Another limitation is that preoperative measurements of the talocrural and subtalar joint range of motion were not available for comparison.

The talocrural and subtalar joint range of motion were reported earlier for a group of 20 non-matched normal subjects (mean age 26.3 years, range 22 to 35 years) using the same CT scanning technique and research protocol.1 The talocrural joint range of motion (extreme dorsiflexion to extreme plantarflexion) following the CCDA procedure in the five patients (49.0 ± 12.0 degrees) was smaller compared to the normal subjects (63.3 ± 11.0 degrees). Subtalar joint range of motion (extreme eversion to extreme inversion) was smaller following both LCL procedures (ACDO 22.8 ± 8.6 degrees; CCDA 24.4 ± 7.6 degrees) as compared to the normal subjects (37.3 ± 5.9 degrees). It should however be kept in mind that extreme foot positions that result in end positions of the joint (extreme dorsiflexion, extreme plantarflexion, extreme eversion, etc) may not be required for normal function in activities of daily living. In addition to that, ankle and hindfoot surgery might reduce the range of motion of the joints. However, this reduction might not be of importance for a normal function of the ankle and foot of the individual subject that has been operated on. Lundgren et al. studied hind-, mid- and forefoot joint motion in volunteers during walking on a flat surface using invasive bone markers.8 From the data of the in-vivo measurements during walking in the five volunteers by Lundgren et al., helical axis rotations could be calculated by conversion of the sagittal, frontal and transverse plane rotations. For the talocrural joint during walking, the mean helical axis rotation was 18.7 degrees (± 3.5 degrees). The mean helical axis rotation for the subtalar joint was 13.9 degrees (± 2.0 degrees). In the present study, the postoperative individual helical axis rotations for the talocrural and subtalar joint range of motion were larger than the results for normal walking from the study by Lundgren et al.8 Measuring the total range of subtalar joint motion (rotations about the helical axis for subtalar joint motion from maximum eversion to maximum inversion) in ten cadaveric specimens, DeLand et al. found an average of 30% loss of subtalar joint range of motion following isolated calcaneocuboid arthrodesis.
with a 10 mm lengthening fusion. In our patients, the mean subtalar range of joint motion was 61% (22.8/37.3 degrees) for the ACDO patients, and 65% (24.4/37.3 degrees) for the CCDA patients of the mean range of subtalar joint motion as measured in the group of 20 normal subjects. Although DeLand et al. used cadaveric specimens, the results from the present in-vivo study seem to resemble their results.

In summary, an accurate CT-based technique was used to assess the range of motion in the talocrural and subtalar joints in patients who underwent a calcaneocuboid distraction arthrodesis (CCDA) or an anterior open wedge calcaneal osteotomy (ACDO) procedure for flexible adult flatfoot deformity. Although a substantial variance was noted in both patient groups, the procedures yielded comparable outcomes with regard to the range of motion of the talocrural and subtalar joint. Further in-vivo studies should be conducted to assess the actual reduction of the talocrural and subtalar joint ranges of motion following specific surgical procedures.

REFERENCES
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Patient demographics.

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<td>FDL Tendon</td>
<td>Proximal MT-1 Osteotomy</td>
<td>DISTP</td>
<td></td>
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<tr>
<td>10</td>
<td>Male</td>
<td>Left</td>
<td>65</td>
<td>ACDO</td>
<td>Yes (No)</td>
<td>FDL Tendon</td>
<td>Triceps Tenotomy</td>
<td></td>
<td></td>
</tr>
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CCDA=Calcaneoabdom Distraction Arthrodesis, ACDO=Anterior Calcaneal Distraction Osteotomy, FDL=Flexor Digitorum Longus, DISTP=Distal Soft Tissue Procedure, MT=Metatarsal, TMT=Tarsometatarsal.

Table 2

Foot helical axis (FHA) rotation and translation values for the talocrural and subtalar joints of motion between the extreme foot positions for the anterior calcaneal distraction osteotomy (ACDO) and the calcaneoabdom distraction arthrodesis (CCDA) patients.

<table>
<thead>
<tr>
<th>Direction of joint movement</th>
<th>FHA rotation θ (°)</th>
<th>FHA translation t (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ACDO Mean</td>
<td>S.D.</td>
</tr>
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<td>Extreme dorsiflexion to extreme plantarflexion</td>
<td>Talocrural joint</td>
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<td>Subtalar joint</td>
<td>8.6</td>
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<td>Extreme eversion-dorsiflexion to extreme inversion-plantarflexion</td>
<td>Talocrural joint</td>
<td>47.3</td>
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<tr>
<td>Extreme eversion to extreme inversion</td>
<td>Talocrural joint</td>
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<td>23.8</td>
</tr>
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<td>Extreme eversion-plantarflexion to extreme inversion-dorsiflexion</td>
<td>Talocrural joint</td>
<td>44.4</td>
</tr>
<tr>
<td></td>
<td>Subtalar joint</td>
<td>17.2</td>
</tr>
</tbody>
</table>

S.D. = standard deviation
CHAPTER 4

FIGURES

Figure 1 A Preoperative lateral weightbearing radiograph of the foot showing the pes planus deformity in a patient with flexible acquired flatfoot deformity.

Figure 1 B Postoperative lateral weightbearing radiograph showing correction of the flatfoot deformity through an anterior calcaneal osteotomy using a screw for fixation. In addition, a first tarsometatarsal joint arthrodesis was performed. The medial arch of the foot is restored postoperatively as shown by the increased navicular to ground distance.

Figure 2 A Preoperative lateral weightbearing radiograph of the foot showing the pes planus deformity in a patient with flexible acquired flatfoot deformity.

Figure 2 B Postoperative lateral weightbearing radiograph showing correction of the flatfoot deformity through a calcaneocuboid distraction arthrodesis with the use of an X-plate and screws for fixation of the arthrodesis. The medial arch of the foot is restored postoperatively as shown by the increased navicular to ground distance.
Figure 3 Patient laying on the CT scanner table with the lower leg fixed on to a supporting platform and the foot fixated to a radiolucent footplate. CT scans were acquired with the foot in eight extreme positions using a cranially directed force applied to the footplate at eight different points. Here the foot was forced in extreme dorsiflexion using an external load (i.e. sand bags) applied to the footplate through a system of a single pulling wire and pulleys.

Figure 4 A - D The three rotation components for the talocrural and subtalar joint ranges of motion for the ACDO and CCDA patients. Figure 4 A shows the rotation components for ankle and subtalar joint range of motion from extreme dorsiflexion to extreme plantarflexion of the foot, figure 4 B from extreme eversion to extreme inversion.
Figure 4 C shows the rotation components for ankle and subtalar joint range of motion from extreme combined eversion-plantarflexion to extreme combined inversion-dorsiflexion and figure 4 D from extreme combined eversion-dorsiflexion to extreme combined inversion-plantarflexion.

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ABSTRACT

Background Subtalar arthrodesis (SA) is the preferred treatment for painful isolated subtalar joint disease. Although results are generally favourable, analysis of current operative techniques will help optimizing this treatment. The aim was to give an overview of SA-techniques and their pitfalls. Possible solutions were identified.

Materials and methods A literature search was performed for papers that presented SA operative techniques. The general technique was divided into phases: surgical approach, cartilage removal, bone graft selection, hindfoot deformity correction and fixation.

Results The published series were invariably retrospective reviews of small heterogenous groups of different hindfoot pathologies. The weighted outcome rate for SA was 85% (68–100%) performed in 766 feet and for SA requiring correction of malalignment 65% (36–96%) in 1001 feet. Non-union (weighted percentage 12%), malalignment (18%), and screw removal (17%) were the prevailing late complications.

Pitfalls The following pitfalls were identified: 1) early complications related to the incisions made in open approaches, 2) insufficient cartilage removal, improper bone graft selection and fixation techniques, all possibly leading to non-union, 3) morbidity caused by bone graft harvesting and secondary screw removal, 4) under- or overcorrection of the hindfoot possibly due to improper intraoperative verification of hindfoot alignment and 5) inadequate assessment of bony fusion.

Solutions The review provides solutions to possibly overcome some pitfalls: 1) if applicable use an arthroscopic approach in combination with distraction devices, 2) if possible use local bone graft or allografts, 3) use two screws for fixation to prevent rotational micromotion, and 4) improve assessment of operative outcome by application of detailed measurement protocols and validated outcome criteria.

Conclusion The literature review provides practical suggestions to optimize subtalar joint arthrodesis techniques.

INTRODUCTION

The subtalar joint is a complex joint, which plays a major role in inversion and eversion of the foot. The joint articulates between the talus superiorly and the calcaneus inferiorly (Fig. 1). Subtalar arthrodesis is an accepted surgical procedure for isolated subtalar disease unresponsive to conservative treatment. Indications include hindfoot disorders caused by posttraumatic, degenerative or rheumatoid arthritis, neuromuscular disorders, talocalcanealcoalitions, and hindfoot deformities. The primary goals of a subtalar arthrodesis are pain relief, and restoration of hindfoot alignment, which should ultimately lead to increased mobility (Fig. 2). Pain relief is achieved by bony fusion which will prevent shear forces in the joint, and restoration of malalignment will diminish intra-articular peak forces.

Although the subtalar arthrodesis technique can be considered a routine procedure in orthopaedic practice, it has been frequently indicated as technically demanding. Additionally, many authors have reported on significant postoperative problems such as non-union and malunion of the arthrodesis. The purpose of this study is to give an overview of existing subtalar arthrodesis techniques, indicate the pitfalls, and extract solutions.

METHODS

A literature search was performed in PubMed and Web of Science (up to May 2009), and a hand search using cross-references. Search terms were combined in various sets: subtalar joint, talocalcaneal joint, arthrodesis, technique, arthroscopy, fusion, hindfoot deformity, arthritis and biomechanics. All languages other than English, German, and Dutch were excluded. Selection was based on an abstract search where papers were included that presented a new subtalar arthrodesis technique, modifications of existing techniques, cross-references that occurred frequently, reviews, and studies with large population groups (more than 40 patients). This gave a database of ninety-one relevant papers of which sixty describe clinical results, and sixty-seven the operative technique (partly) in detail. Generally, the surgical procedure consists of removing the cartilage layers and subchondral bone from the joint. Subsequently, the bleeding bone surfaces of the talus and the calcaneus are realigned if required and fixated. Eventually, the surfaces will fuse thereby invalidating the subtalar joint. Following this general protocol, a structured analysis was performed by dividing the subtalar arthrodesis procedure into five separate phases (Fig. 2: grey area). For each phase, the various options as described in literature are summarized, followed by their pitfalls and potential solutions as presented in literature.
CHAPTER 5

Statistical analyses were not possible as little objective evidence was available. Therefore, to support the identification of pitfalls and limitations, a weighted success rate and a complication rate were calculated. Studies reporting results of less than 10 patients with a short follow up were excluded to minimize bias (10 papers). The patient populations with hindfoot deformity requiring anatomic restoration were clustered into one group.9,12,16-21,26-29,36 The papers with other indications were clustered in a second group.8,11,13,15,22-25,27,28,37-64 The clinical outcome of these 50 studies, a weighted success rate was calculated for each group. This consisted of the summation of a weight factor multiplied by the percentage of good and excellent clinical results that were explicitly described in a study. The weight factor of each concerning study was defined as the number of operated subtalar joints of that study divided by the total number of operated subtalar joints of all other studies describing the clinical outcome in a similar fashion. This way the studies presenting results of larger patient populations have a higher share in the weighted rate than papers reporting on smaller patient groups. A similar calculation was performed for the weighted complication rate. The complication rates for wound infection, damage to neurovascular structures and delayed wound healing were not split into separate groups. All references that were used to calculate a weighted clinical outcome or complication rate are indicated as well as the total number of feet that was used for the calculation.

RESULTS

Surgical approach

The surgical approach was divided into patient positioning and access (Fig. 3). For common open procedures, patients are placed in the lateral decubitus position lying on the unaffected side.11,12,22,24,27,28,33,48-50,63,64 or in supine position with an elevated hip.55,47,54,55,57,61,65,66 The subarticular joint is routinely (68% of the 63 papers) accessed with a lateral approach, where either an oblique incision is made over the sinus tarsi, an incision from the tip of the fibula to the base of the 4th metatarsal, or a longitudinal L-shape incision is made (Fig. 1).8-10,12,15,17,19-23,25-29,31-35,37,39,44,46,50,55-58,60,61,63,65,67-69 The surgical approach was divided into patient positioning and access (Fig. 3). For common open procedures, patients are placed in the lateral decubitus position lying on the unaffected side.9,12,16-21,26-29,36 The subarticular joint is routinely (68% of the 63 papers) accessed with a lateral approach, where either an oblique incision is made over the sinus tarsi, an incision from the tip of the fibula to the base of the 4th metatarsal, or a longitudinal L-shape incision is made (Fig. 1).8-10,12,15,17,19-23,25-29,31-35,37,39,44,46,50,55-58,60,61,63,65,67-69 The subarticular joint is routinely (68% of the 63 papers) accessed with a lateral approach, where either an oblique incision is made over the sinus tarsi, an incision from the tip of the fibula to the base of the 4th metatarsal, or a longitudinal L-shape incision is made (Fig. 1).8-10,12,15,17,19-23,25-29,31-35,37,39,44,46,50,55-58,60,61,63,65,67-69

Kalamchi and Evans introduced a posterior approach using an incision on the lateral side parallel to the Achilles tendon while the patient is lying in prone position (Fig. 1).34 Other authors have adopted this position with11,13,62,70-72 or without combination of an arthroscopic technique.30,36,39,50,59,64,73 For the arthroscopic techniques, various combinations of access portals are suggested (Fig. 1).24,47,51-54,62,70,71

Compared to the size of the foot, relatively large incisions are used in the open techniques that carry the risk of wound infection (weighted rate 5% of 1089 feet, range 1–45%)8,11,13,15,21,23,26-28,31,35,39,40,42,48,50,58,59,74, neurovascular damage (weighted rate 10% of 426 feet, range 3–33%)8,22,27,39,40,45,50,57,59,61,64, and delayed wound healing (weighted rate 2.5% of 262 feet, range 1–5%)20,33,39,46,61,74. To prevent these early complications, an arthroscopic approach can be performed, as efforts are taken to develop safe access portals.75-77, and clinical studies show absence of infections or neurovascular damage.24,47,52,53,62,71. However, contraindications for arthroscopy are gross malalignment of the hindfoot, and significant bone loss of the talus or calcaneus.24,47,52,53,74,77

Additionally, arthroscopic techniques are indicated as more demanding in terms of surgical skills.24,52,54 As most studies presenting arthroscopic approaches for subtalar arthrodesis reported results of less than 10 patients with a short follow up, they were excluded from calculation of weighted success or complication rates.

Cartilage removal

The creation of bleeding contact surfaces of the subtalar joint is a key step in obtaining solid fusion. All cartilage should be removed and a layer of around 2 mm of the subchondral bone, while maintaining congruent surfaces. Removal of all facets is performed with a chisel and an osteotome in the case of open techniques.8 Removal of the posterior facet is performed with a shaver, curettes and burrs in the case of arthroscopic techniques (Fig. 4).51,71

A pitfall of this operative step is insufficient removal of cartilage and subchondral bone. Hintermann et al. have measured the contact area in the subtalar joint with a single screw fixation (mean contact area 119–197 mm2).78 These values are on average only about 30% of the size of the entire posterior facet (582 ± 103 mm2).79 Insufficient tissue removal was probably the cause of non-unions as Gross80 and Fellmann and Zollinger80 argued for their clinical studies. Articular cartilage removal can be quite difficult and time consuming13 due to the limited exposure of the complex subtalar joint shape. To facilitate complete removal, extra workspace can be created by soft tissue removal12,17,20,21,24,26,41,42,50,51,53,61,68, lamina spreaders55,27,33,35,36,41,45,46,49,50,57,59-61,64,65,68,74, distraction devices13,22,27,54,59,64 or blunt trocars53,62,71. Nowadays, non-invasive distractors are available to increase the intraoperative joint space.81 Complete tissue removal is facilitated as well by the improved joint visualization when using an arthroscopic approach.51,54 Other solutions are the performance of initial distraction with the fixation screw82 and the development of a compliant shaver83.
Bone graft

Bone grafts can be applied in case of bone defects or in patients where correction of alignment is needed. Although insertion of bone grafts is not always required, they appear to enhance fusion. Three types of grafts have been used: cortical, cancellous, and combined corticocancellous grafts (Fig. 5). Cancellous bone grafts are mainly used to fill wedges thereby increasing bone-on-bone contact surface. Cortical grafts provide a strong and stiff strut which is suitable for correction of hindfoot deformity. A disadvantage could be a prolonged time till fusion and a slightly more likelihood of non-union when compared to the results with cancellous bone grafts. Therefore, corticocancellous bone grafts are a good alternative and are advocated by many authors.

Cortical grafts provide a strong and stiff strut which is suitable for correction of hindfoot deformity. A disadvantage could be a prolonged time till fusion and a slightly more likelihood of non-union when compared to the results with cancellous bone grafts. Therefore, corticocancellous bone grafts are a good alternative and are advocated by many authors.

Hindfoot deformity correction

Manual realignment of the foot in an anatomical position during surgery has been described as well as removal of excessive bone on either medial or lateral side at the subtalar joint level, and bone graft placement in an open wedge. A popular technique to perform hindfoot correction is the bone-block distraction technique to correct hindfoot valgus by placing a bone block on the lateral side of the subtalar joint (Fig. 6). For functional outcome, precise correction is important. Several tools are applied to achieve this: uni- or bilateral assessment of hindfoot alignment on preoperative and postoperative lateral weightbearing radiographs of the ankle, and assessment of pre- and postoperative hindfoot alignment with goniometers (Fig. 6).

Alternatively, some authors have measured the resulting open wedge when the talus and the calcaneus are repositioned, and cut the bone graft to fit in the open wedge. Recently, fluoroscopy has been introduced for measurement of the amount of correction intraoperatively. The clinical results for patients requiring correction of hindfoot deformity are generally less favourable (weighted rate 65% of 1001 feet, range 36–96% for other indications (weighted rate 85% of 766 feet, range 68–100%) compared to a weighted rate of 5% of 421 feet for the studies with other indications (range 3–9%) compared to a weighted rate of 5% of 421 feet for the studies with other indications (range 3–9%) compared to a weighted rate of 5% of 421 feet for the studies with other indications (range 3–9%) compared to a weighted rate of 5% of 421 feet for the studies with other indications (range 3–9%). These numbers are merely indicative, because the methods for determining hindfoot alignment after arthrodesis vary widely. Issues should be addressed in achieving a good correction: relation between per-, intra- and postoperative assessment and accurate assessment of correction (Fig. 6). Both radiographs and goniometric measurements are taken in a standing weightbearing state, which differs from the non-weightbearing patient position in the operating room. As a result, many surgeons have used the experienced eye to position the hindfoot in relation to the lower leg. The prone and supine positions are favoured, especially the lateral decubitus position impedes the usage of anatomical reference axes. Goniometric measurement should be avoided, because they lack accuracy and reliability. If pre- and postoperative radiographic measurements are performed, a precise measurement protocol should be described. Additionally, it is recommended to use specific views for radiographic hindfoot evaluation as they visualize the subtalar joint and the calcaneus more clearly. Means to judge correct alignment intraoperatively are limited. Measurement of the open wedge to match the size of a bone graft is a subsequent step where alignment already has been performed by visual inspection. New technical developments that have potential are 3D radiographic imaging, a device for measuring hindfoot alignment both in weightbearing standing position and in non-weightbearing prone position, and a ramp cage to provide stable correction, where the size of the ramp determines the amount of correction. The use of fluoroscopy is currently the best option for intraoperative verification.

Fixation

Initial compression of the bony surfaces is important to obtain solid fusion of the arthrodesis. Three approaches are described for fixation: the anterior approach with the screw inserted
from the talocrural joint, the posterior approach with the screw inserted from the calcaneal tuberosity in the talus, 8,22,27,36,46,51,61-64,71,72, and the plantar approach 50,97 (Fig. 7). Generally, compression is achieved by means of one or two cannulated screws that are positioned through the center of the talus and calcaneal joint surfaces. An alternative is fixation with staples 11,23,35,68 (Fig. 7). Different techniques are used to verify the correct position of the screw: cruciate ligament drill guides 22,33,46,57,58,60,68, fluoroscopy 8,25,27,34,47,64,71, guide wires 44,55,65, and a combination of fluoroscopy and guidewires 13,15,24,32,36,45,47,50,53,54,61,66,70,74 (Fig. 7). With some arthroscopic techniques screw placement can be verified under direct arthroscopic view. 71

Problems that can occur are inadequate fixation leading to non-union: weighted rate 14% in 953 feet for the studies with solely hindfoot deformities (range 2–46%) 12,17-21,26,30-32,34-36 vs. weighted rate 10% in 864 feet for the studies with other indications (range 2–30%) 8,13,22,25,27,28,44,46,48,53,55,58-61,64,66,69; and symptomatic hardware requiring screw removal: weighted rate of 14% in 168 feet for the studies with solely hindfoot deformities (range 10–25%) 31,32,34,36 vs. weighted rate of 18% in 841 feet for the studies with other indications (range 1–64%) 8,13,15,23,24,27,42,45,47,48,50,53,54,56,57,59,62,64,71. Fixation with press-fit bone grafts only were reported to give significant rates of non-union and malalignment 9,12,16-21,26,28,67. Additionally, fixation with one screw might not always be sufficient as rotational movement of the joint surfaces cannot be controlled. Therefore, the use of two screws is advocated (Fig. 7). 8,25,27,45,98 For specific patient groups such as people with severe rheumatoid arthritis, specific screw fixation techniques are proposed. 99,100 Traditionally, assessment of consolidation has been performed with lateral weightbearing radiographs. Since that time, authors have expressed their doubts whether radiographic assessment of consolidation is reliable and accurate. 8,12,20,24,44,84,101 Recently, it has been confirmed by Coughlin et al. that assessment of union cannot be determined accurately from standard radiographs. 84 Assessment of bony fusion with CT-scans is significantly more reliable. Relative to the most appropriate means for assessing fusion are the criteria that define solid fusion. Only a few studies describe a more detailed evaluation protocol where solid fusion has been defined as osseous trabeculae crossing the arthrodesis site. 8,23,36,47,48,87 Coughlin et al. 84 and Davies et al. 15 have proposed that fusion areas of more than 50% of the subtalar joint surfaces should be marked as solid union. Screw removal is independent of the approach used for screw insertion 31, and apparently cannot be prevented by verification of correct screw position. No solution for this problem is available at this stage. Ultimately, the fixation device should adapt to the changing environment and decrease its stiffness in time. Screws fabricated of bioabsorbable might be candidates to achieve this. 102

**General**

Besides the operative techniques, the condition of the patient and postoperative care also influence functional outcome (Fig. 2). Obesitas, diabetes, rheumatoid arthritis and severe neuromuscular problems have a known negative effect on the outcome 8, as well as the severity of the hindfoot deformity and the necessity to perform tendon transfers 28,103. Especially, smoking has a significant negative influence on achieving solid fusion. 28,8,103 In general, a six weeks non-weightbearing cast, followed by a six weeks weightbearing cast is advocated (31 of 47 papers). In the past, early weightbearing (i.e. before six weeks) resulted in failures of the subtalar arthrodesis. 18,31,37,39 Recently, full weightbearing as tolerated at any time following surgery has been reintroduced with minor complications and high rates of union. 24,48-51,54,65,70

**DISCUSSION**

With this literature overview, we identified the options, pitfalls, and available solutions for each of the five operative phases of the subtalar arthrodesis techniques. Comparing existing literature was difficult due to the wide variety of indications, and the demography of patient populations. A meta analysis, including statistical analyses by data pooling was not possible, since the published series were invariably retrospective reviews of small heterogeneous groups of hindfoot pathologies. 15 An additional restriction was that only recently, operative techniques and evaluation protocols have been described in sufficient detail that allow for unambiguous interpretation and evaluation. 15,13,29,84 Notice that the calculated weighted outcomes in this study are merely indicative and no statistics can be performed.

Summarizing this overview, the following pitfalls were identified:

- Early complications related to large incisions,
- Insufficient cartilage removal, improper bone graft selection and fixation techniques, all possibly leading to non-union,
- Extra morbidity caused by bone graft harvesting and removal of painful screws,
- Under- or overcorrection of hindfoot malalignment
- Inadequate assessment of bony fusion.
Literature also provided solutions to overcome these pitfalls with the remark that some are still under development: if applicable use an arthroscopic approach in combination with new burrs and distraction devices, if possible use local bone graft or allografts, use two screws for fixation to prevent rotational micromotion, and improve assessment of operative outcome by application of appropriate diagnostics tools, detailed measurement protocols and validated outcome criteria. If doubt exists on solid bony fusion, a CT-scan is recommended and solid union is defined if more than 50% of the subtalar joint surfaces are fused. Further efforts can be taken to perform long-term follow-up studies to assess the effects of the many proposed adjustments to the subtalar arthrodesis operative techniques.

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Figure 1 Anatomy of the hindfoot focused on the subtalar joint. The three most frequently reported incisions are drawn for approaching the subtalar joint (obliquely over the sinus tarsi, tip fibula to fourth metatarsal and posterolateral approach) as well as the frequently reported arthroscopic portals.

Figure 2 Scheme indicating the primary functional outcomes of a subtalar arthrodesis: pain relief and increased mobility (1). This is achieved by bony fusion and if required restoration of hindfoot alignment. The categorization of operative phases is shown within the grey area (2). Factors that influence the surgical intervention complete the diagram (3).
Figure 3 Surgical approach: options, pitfalls and possible solutions. The numbers between square brackets indicate the number of papers describing this approach explicitly.

Figure 4 Cartilage removal: options, pitfalls and possible solutions. The numbers between square brackets indicate the number of papers describing this approach explicitly.
Figure 5 Bone graft: options, pitfalls and possible solutions. The numbers between square brackets indicate the number of papers describing this approach explicitly.

Figure 6 Correction hindfoot deformity: options, pitfalls and possible solutions. The numbers between square brackets indicate the number of papers describing this approach explicitly.
Figure 7 Fixation: options, pitfalls and possible solutions. The numbers between square brackets indicate the number of papers describing this approach explicitly.
ABSTRACT

The subtalar joint is a functionally important joint of the lower extremity. Due to the complex anatomy of the subtalar joint, radiographic and arthroscopic evaluation of the subtalar joint can be difficult. The development of small diameter arthroscopes with excellent optical capacity along with the precise techniques has allowed subtalar joint arthroscopy to expand. An overview of the indications, contraindications and different approaches for subtalar joint arthroscopy is provided. Furthermore, the literature on arthroscopic treatment and results of sinus tarsi syndrome, os trigonum syndrome and subtalar joint arthrodesis is presented.

INTRODUCTION

The subtalar joint is a complex and functionally important joint of the lower extremity that plays a major role in the movement of inversion and eversion of the foot. The complex anatomy of the subtalar joint makes arthroscopic and radiographic evaluation difficult. The development of arthroscopes with small diameters and excellent optical capacity along with precise techniques has allowed arthroscopy of the subtalar joint to expand. Anatomic portals and arthroscopic anatomy of the posterior subtalar joint in cadaveric specimens were first described by Parisien and Vangsness in 1985. One year later, Parisien published the first clinical report on subtalar arthroscopy, which evaluated three cases with good results. Since then, a number of reports on posterior subtalar arthroscopy and its clinical applications have become available. Lateral and posterior anatomic approaches have been used for performing posterior subtalar joint arthroscopy. Arthroscopic subtalar management has been credited with clear advantages for the patient, including faster postoperative recovery period, decreased postoperative pain, and fewer complications. Although posterior subtalar arthroscopy is still met with some skepticism, the technique has slowly evolved as an alternative to open subtalar surgery.

INDICATIONS AND CONTRAINDICATIONS

Subtalar arthroscopy may be applied as a diagnostic and therapeutic instrument. The diagnostic indications for subtalar arthroscopy include persistent pain, swelling, stiffness, locking, or catching of the subtalar area resistant to all conservative treatment. In addition, subtalar joint arthroscopy can be used for visual assessment of the subtalar articular surfaces when persistent pain is present after a chronic ankle sprain or a fracture of the os calcis. Therapeutic indications for subtalar joint arthroscopy include debridement of chondromalacia, subtalar impingement lesions, excision of osteophytes, lysis of adhesions with post-traumatic arthrofibrosis, synovectomy, and the removal of loose bodies. Other therapeutic indications are instability, debridement and drilling of osteochondritis dissecans, retrograde drilling of cystic lesions, removal of a symptomatic os trigonum, and calcaneal fracture assessment and reduction. Arthroscopic arthrodesis of the subtalar joint was introduced in 1994.

Absolute contraindications to subtalar arthroscopy include localized infection leading to a potential septic joint and advanced degenerative joint disease, particularly with deformity. Relative contraindications include severe edema, poor skin quality, and poor vascular status.
EQUIPMENT AND SETUP

Two different anatomic approaches are used for arthroscopy of the posterior subtalar joint. The arthroscope generally used for lateral subtalar joint arthroscopy is a 2.7-mm 30° short arthroscope (Box 1). Others prefer to use the 10° or 25° arthroscope of the same diameter for subtalar arthroscopy. In addition, a 70° arthroscope can be helpful to look around corners and to facilitate instrumentation. In subtalar joints that are too tight to allow a 2.7-mm arthroscope, a 1.9-mm 30° arthroscope is advised. A small joint shaver set with a 2.0- and 2.9-mm shaver blade and small abrader is also needed. For a two-portal posterior approach to the posterior subtalar joint, the instrumentation used is essentially the same as for knee joint arthroscopy (Box 2). With this technique, the subtalar joint capsule and the adjacent fatty tissue are partially resected. A sufficiently large working space adjacent to the joint is created, making it possible to use a 4.0-mm 30° arthroscope. The arthroscope is placed at the joint level and looks inside the joint without entering the joint space. The maximum size of the intra-articular instruments depends on the available joint space.

Box 1.
Equipment for subtalar joint arthroscopy

- 1.9-mm, 2.7-mm 30° and 70° video arthroscopes, cannulae
- 2.0-mm, 2.9-mm full-radius blades, whiskers, and burrs
- 18-gauge spinal needle
- K-wires
- Drill
- Ring curettes, pituitary
- Small joint probes and graspers
- Normal saline and gravity system
- Noninvasive distractor

Distraction of the subtalar joint can be accomplished with noninvasive and invasive methods. The type of distraction chosen depends on the tightness of the joint and the location of disease. Noninvasive distraction during arthroscopy can be done manually by an assistant or by a noninvasive distraction strap around the hindfoot. In most cases, joint distraction is obtained using normal saline and a gravity system. Regarding invasive joint distraction, using talocalcaneal distraction with pins inserted from laterally is a better choice than tibiocalcaneal distraction, especially with a tight posterior subtalar joint. The disadvantage of using an invasive distractor is the potential damage to soft tissues (ie, the lateral calcaneal branch of the sural nerve) and ligamentous structures, the risk of fracturing the talar neck or body, and infection.

Box 2.
Equipment for subtalar joint arthroscopy using the two-portal approach

- 4.0-mm 30° video arthroscope, cannulae
- 4.5-mm, 5.5-mm full-radius blades, whiskers, and burrs
- 21-gauge needle
- K-wires
- Drill
- Ring curettes, pituitary
- Small joint probes and graspers
- Normal saline and gravity system
- Noninvasive distractor

SUBTALAR JOINT ANATOMY

The subtalar joint can be divided, for arthroscopic purposes, into anterior (talocalcaneonavicular) and posterior (talocalcaneal) articulations (Fig. 1). The anterior and posterior articulations are separated by the tarsal canal; the lateral opening of this canal is called the sinus tarsi (a soft area approximately 2 cm anterior to the tip of the lateral malleolus). Within the tarsal canal, the medial root of the inferior extensor retinaculum, the cervical and talocalcaneal interosseous ligaments, fatty tissue, and blood vessels are found. The lateral ligamentous support of the subtalar joint consists of superficial, intermediate, and deep layers (Fig. 1). The superficial layer comprises the lateral talocalcaneal ligament, the posterior talocalcaneal ligament, the medial talocalcaneal ligament, the lateral root of the inferior extensor retinaculum, and the calcaneo Tibial ligament. The intermediate layer is formed by the intermediate root of the inferior extensor retinaculum and the cervical ligament. The deep layer comprises the medial root of the inferior extensor retinaculum and the interosseous ligament. The talocalcaneonavicular, or anterior subtalar joint, is composed of the talus, the posterior surface of the tarsal navicular, the anterior surface of the calcaneus, and the plantar calcaneo navicular, or spring ligament. The posterior talocalcaneal, or posterior
subtalar joint, is a synovium-lined articulation formed by the posterior convex calcaneal facet of the talus and the posterior concave talar facet of the calcaneus. The joint capsule is reinforced laterally by the lateral talocalcaneal ligament and the calcaneofibular ligament. This joint also has a posterior capsular pouch with small lateral, medial, and anterior recesses. Arthroscopic visualization of the subtalar joint is limited to its posterior facet. The anterior portion of the subtalar joint is generally thought to be inaccessible to arthroscopic examination because of the thick ligaments that fill the sinus tarsi.

PORTAL PLACEMENT AND SAFETY

Lateral approach
Access to the posterior subtalar joint can be achieved through a lateral approach and a posterior approach. Three portals are recommended for visualization and instrumentation of the subtalar joint using the lateral approach. The anatomic landmarks for lateral portal placement include the lateral malleolus, the sinus tarsi, and the Achilles tendon. The lateral malleolus is routinely palpable. The sinus tarsi is also usually palpable, although it can be filled with large amounts of adipose tissue.6 Inversion and eversion of the foot may be helpful in palpating the sinus tarsi. The anterolateral portal is established approximately 1 cm distal to the fibular tip and 2 cm anterior to it (Fig. 2). Anatomic structures at risk with placement of the anterolateral portal include the dorsal intermediate cutaneous branch of the superficial peroneal nerve, the dorsal lateral cutaneous branch of the sural nerve, the peroneus tertius tendon, and a small branch of the lesser saphenous vein. The dorsal intermediate cutaneous branch of the superficial peroneal nerve is located an average of 8 mm inferior to the lateral malleolus.6 The accessory posterolateral portal was located 4 mm posterior to the sural nerve in most cases.17 Literature has also described accessory portals for posterior subtalar arthroscopy.6,18 The accessory anterolateral portal was located 4 mm posterior to the sural nerve in most cases.17 Literature has also described accessory portals for posterior subtalar arthroscopy.6,18 The accessory posterolateral portal is made behind the peroneal tendons, lateral to the posterolateral portal.

Posterior approach
Posterior subtalar arthroscopy can be performed using a posterolateral and posteromedial portal.19 This two-portal endoscopic approach to the hindfoot with the patient in the prone position has been credited to offer better access to the medial and anterolateral aspects of the posterior subtalar joint.12,20 The medial aspect of the posterior subtalar joint is tighter than on the lateral side, possibly increasing the risk of iatrogenic cartilage damage and necessitating the use of an invasive distractor.18 The tibial nerve, the posterior tibial artery, and the medial calcaneal nerve can be at risk when the posteromedial portal is used.6,21 Investigators studied the relative safety of the posterior portals for hindfoot endoscopy in cadaveric specimens. (Table 1).12,21-23 Mekhail and colleagues measured an average distance between the point of entry of the posteromedial arthroscope and the posterior tibial neurovascular bundle of 1.0 cm (the closest distance was 8 mm).12 Sitler and colleagues evaluated the safety of posterior ankle arthroscopy with the use of posterior portals with the limb in the prone position in 13 cadaveric specimens.22 The average distance between the posteromedial cannula and the tibial nerve was 6.4 mm (range, 0–16.2 mm). In addition, the distance between the posterior tibial artery and the cannula averaged 9.6 mm (range, 2.4–20.1 mm) and the average distance between the cannula and the medial calcaneal nerve was 17.1 mm (range, 19–31 mm). The height of the posteromedial portal in relation to the tip of the lateral malleolus is an important determinant regarding the proximity of the relevant anatomic structures to the edge of the cannula. It is unfortunate that not all investigators specified this measure. Other factors that could explain the variety in outcome are the use of joint distraction and the size of the arthroscope. Compared with the conventional posterolateral portal, the posteromedial portal is essentially equidistant to the neurovascular structures. It appears that the posteromedial portal in hindfoot endoscopy is relatively safe and reproducible and can be used for the treatment of intra- and extra-articular hindfoot pathology. The main difference between the two techniques is that the 2.7-mm lateral approach for posterior subtalar arthroscopy is a true arthroscopy technique in which the arthroscope and the instruments are placed within the joint, whereas the two-portal posterior technique (using a posterolateral and posteromedial portal) starts as an extra-articular approach. With the two-portal posterior technique, a working space is first created adjacent to the posterior subtalar joint by removing the fatty tissue overlying the joint capsule and the posterior part of the ankle joint. The joint capsule is then partially removed to
be able to inspect the joint from outside-in, with the arthroscope positioned at the edge of the joint without entering the joint space. As mentioned earlier, the maximum size of the intraarticular instruments depends on the available joint space.

**SURGICAL TECHNIQUE**

Subtalar joint arthroscopy is performed with the patient under general or regional anesthesia. A tourniquet is applied to the proximal thigh and is inflated only when required for visualization. Using the lateral approach, the patient is placed in the lateral decubitus position with the operative extremity draped free. Padding is placed between the lower extremities and under the contralateral extremity to protect the peroneal nerve. The contralateral extremity is bent to 90° at the knee. The best portal combination for access to the posterior joint includes placement of the arthroscope through the anterior portal and the instrumentation through the posterior portal. This portal combination allows direct visualization and access of practically the entire surface of the posterior facet, the posterior aspect of the ligaments, the lateral capsule and its small recess, the os trigonum, and the posterior pouch of the posterior joint with its synovial lining. Instrumentation through the anterior portal provides access to the lateral aspect of the posterior facet. The medial, anterior, and posterior aspects cannot be reached well through the anterior portal. In addition, significant risk of iatrogenic damage to underlying subchondral bone exists. Access to the anterior and lateral portions of the posterior facet and structures located in the extra-articular sinus tarsi can also be obtained by placing the arthroscope through the anterior portal and instrumentation through the middle portal. In addition, excellent visualization of the medial and posterior aspects of the posterior facet is possible, even though they cannot be reached by instrumentation through the middle portal. This portal combination is recommended for visualization and instrumentation of the sinus tarsi and anterior aspects of the posterior subtalar joint.

The anterior portal is first identified with an 18-gauge spinal needle, and the joint is inflated with a 20-mL syringe. The needle is removed and a small skin incision made. The subcutaneous tissue is gently spread using a straight mosquito clamp. Using the same path, an interchangeable cannula with a semiblunt trocar is placed, followed by a 2.7-mm 30° oblique arthroscope. The middle portal is now placed under direct visualization using an 18-gauge spinal needle and outside-in technique. When visualized, the needle is removed and replaced with an interchangeable cannula. The posterior portal can be placed at this time using the same outside-in technique. It is easy to become disoriented while arthroscoping the posterior subtalar joint. The arthroscope may be placed inadvertently in the ankle joint or may penetrate the capsule of the ankle and enter the lateral ankle gutter. For this reason, fluoroscopic confirmation of the position of the arthroscope can be useful.

The technique of the two-portal endoscopic approach to the hindfoot using the posterolateral and posteromedial portals adjacent to the Achilles tendon should be performed as described here (Fig. 3). The posterolateral portal is made at the level or slightly above the tip of the lateral malleolus, just lateral to the Achilles tendon. After making a vertical stab incision, the subcutaneous layer is gently split by a mosquito clamp. The mosquito clamp is directed anteriorly, pointing in the direction of the interdigital webspace between the first and second toe. When the tip of the clamp touches bone, it is exchanged for a 4.0-mm arthroscope shaft with blunt trocar pointing in the same direction. By palpating the bone in the sagittal plane, the level of the posterior subtalar joint can most often be distinguished by palpating the prominent posterior talar process. The posteromedial portal is made just medial to the Achilles tendon. In the horizontal plane, it is located at the same level as the posterolateral portal. After making the skin incision, a mosquito clamp is introduced and directed toward the arthroscope shaft. When the mosquito clamp touches the shaft of the arthroscope, the shaft is used as a guide to travel anteriorly in the direction of the posterior subtalar joint. All the way, the mosquito clamp must touch the arthroscope shaft until the mosquito clamp touches bone. The blunt trocar is exchanged for a 4.0-mm 30° arthroscope. The direction of view is to the lateral side to prevent damage to the lens system. The arthroscope is pulled slightly backward until the tip of the mosquito clamp comes into view. The clamp is used to spread the extraarticular soft tissue just in front of the tip of the arthroscope. The mosquito clamp can now be exchanged for a 4.5-mm full-radius resector to remove the subtalar joint capsule posterolaterally to visualize the joint (Fig. 3). The next step is to remove the posterior talocalcaneal ligament to visualize the posterior and posteromedial part of the subtalar joint. In most cases, it is not possible to introduce the 4.0-mm arthroscope into the posterior subtalar joint; however, the posterior subtalar joint can be adequately visualized from its margins without entering the joint with the 4.0-mm arthroscope. At this time, intra-articular joint pathology can be treated under direct view looking from outside-in using small-sized instruments. After completing the arthroscopic procedure, the portals are closed with sutures. When there is extravasation of fluid into the subcutaneous tissue, the portals are sometimes left open so that the irrigation solution can escape. A compression dressing is applied from the toes to the midcalf. This dressing is removed the following day; ice is applied, with the leg...
CHAPTER 6

Arthroscopic evaluation of the posterior subtalar joint

When performing diagnostic subtalar arthroscopy, it is imperative to have a reproducible and systematic method of anatomic review to consistently examine the entire joint. A standard 13-point arthroscopic evaluation of the posterior subtalar joint has been advocated by Ferkel and Williams and Ferkel. Diagnostic subtalar arthroscopy examination begins with the arthroscope viewing from the anterolateral portal (Fig. 4). From the anterolateral portal, the interosseous talocalcaneal ligament is readily visualized. Medially, the deep interosseous ligament (evaluation area 1) is observed and, as the arthroscope is slowly withdrawn, the superficial interosseous ligament (evaluation area 2) is seen. From the anterior portal, an assessment of the floor of the sinus tarsi may be made. When the arthroscopic lens is rotated more anteriorly, the anterior process of the calcaneus can be evaluated. As the arthroscopic lens is rotated laterally, the anterior aspect of the posterior talocalcaneal articulation (evaluation area 3) is observed. Next, the anterolateral corner (evaluation area 4) is examined, and reflections of the lateral talocalcaneal ligament (evaluation area 5) and the calcaneofibular ligament (evaluation area 6) are observed. The lateral talocalcaneal ligament is noted anterior to the calcaneofibular ligament. The arthroscopic lens may then be rotated medially, and the central articulation (evaluation area 7) is observed between the talus and the calcaneus. Finally, the posterolateral gutter (evaluation area 8) may be seen from the anterolateral portal. The arthroscope is then switched to the posterolateral portal and the inflow cannula is switched to the anterolateral portal. From this view, the interosseous ligament may be seen anteriorly in the joint (Fig. 4). As the arthroscopic lens is rotated laterally, the lateral talocalcaneal ligament (evaluation area 5) and calcaneofibular ligament (evaluation area 6) reflections may again be observed and their relationship noted. From this posterior view, the central talocalcaneal joint (evaluation area 7) may be examined and the posterolateral gutter (evaluation area 8) carefully assessed for synovitis and loose bodies. The posterolateral recess (evaluation area 9) and the posterior gutter (evaluation area 10) are then carefully evaluated in the normal bare area where the articulation ends and the posterior corner of the talus is assessed. The posteromedial recess (evaluation area 11) is carefully observed, and the posteromedial corner (evaluation area 12) of the talocalcaneal joint and, finally, the most posterior aspect of the talocalcaneal joint is seen (evaluation area 13). By rotating the arthroscope upward while keeping it in area 13, the os trigonum can be visualized on the talus (if present).

RESULTS

Posterior subtalar arthroscopy has been shown to be beneficial over the past several years. Williams and Ferkel collected information on 50 patients who had hindfoot pain who underwent simultaneous ankle and subtalar arthroscopy. Twenty-nine patients had subtalar pathology consisting of degenerative joint disease, subtalar dysfunction, chondromalacia, symptomatic os trigonum, arthrofibrosis, loose bodies, or osteochondritis of the talus that was treated arthroscopically. The anterolateral and posterolateral portals were used to visualize the posterior subtalar joint; distraction (invasive and noninvasive) was used in all cases. At an average follow-up of 32 months, these investigators reported good to excellent results in 86% of the patients. Overall, less favorable results were noted with associated ankle pathology, degenerative joint disease, age, and activity level of the patient. No operative complications were reported. Goldberger and Conti retrospectively reviewed 12 patients who underwent subtalar arthroscopy for symptomatic subtalar pathology with nonspecific radiographic findings. The preoperative diagnoses were subtalar chondrosis in 9 patients and subtalar synovitis in 3 patients. The anterolateral and posterolateral portals were used to visualize the posterior subtalar joint. A femoral distractor was applied in patients when visualization was difficult. The follow-up averaged 17.5 months. The average preoperative American Orthopaedic Foot and Ankle Society (AOFAS) Hindfoot Score was 66 (range, 54–79); the average postoperative score was 71 (range, 51–85). In the 7 patients who improved after subtalar arthroscopy, the average improvement was 10 points on the AOFAS Hindfoot Score. Four patients' symptoms progressively worsened after surgery; all 4 were diagnosed as having grade 4 chondromalacia of the subtalar joint at the time of arthroscopy. Three of these patients progressed to subtalar arthrodesis at an average of 18 months following the arthroscopy. It is of interest that all patients stated that they would have the surgery again. In addition, 2 patients were very satisfied with the surgery, 6 patients were satisfied, and 4 patients were satisfied with reservations; none were dissatisfied. No operative complications occurred in this series. The investigators concluded that subtalar arthroscopy is the most accurate method of diagnosing subtalar articular cartilage damage but has limited therapeutic benefit in the
treatment of early degenerative joint disease. The preoperative imaging studies tended to be less accurate predictors of subtalar cartilage damage than arthroscopy.

**Sinus tarsi syndrome**

Sinus tarsi syndrome was first described by O’Connor in 1958. It has historically been defined as persistent pain in the tarsal sinus secondary to trauma (80% of the cases reported). There are no specific objective findings in this condition. The exact etiology is not clearly defined, but scarring and degenerative changes to the soft-tissue structure of the sinus tarsi are thought to be the most common cause of pain in this region. Walking on uneven terrain can result in pain and a feeling of instability. Clinical examination reveals pain on the lateral aspect of the hindfoot aggravated by firm pressure over the lateral opening of the sinus tarsi. Relief of symptoms with injection of local anesthetic directly into the sinus tarsi confirms the diagnosis. Surgical removal of the contents of the lateral half of the sinus tarsi improves or eradicates symptoms in roughly 90% of cases. Kashuk and colleagues stated that the application of arthroscopic techniques for decompression of the sinus tarsi has proved useful, is technically easy, and allows for a rapid recovery. Oloff and colleagues presented 29 patients who underwent subtalar joint arthroscopy for sinus tarsi syndrome by way of an anterolateral approach. Subtalar joint synovectomy was the most common procedure performed; 12 patients had additional procedures. The mean postoperative AOFAS Hindfoot score was 85 (range, 59–100) and there were no complications. All 29 patients stated they were better after surgery and would undergo the procedure again without reservation. Earlier results and those of Oloff and colleagues suggest that arthroscopic synovectomy alone is associated with symptom resolution in patients who have sinus tarsi syndrome as opposed to the open methods that involve the removal of the entire lateral contents of the sinus tarsi. According to Frey and colleagues, sinus tarsi syndrome is an inaccurate term that should be replaced with a specific diagnosis because it can include many other pathologies such as interosseous ligament tears, arthrofibrosis, synovitis, arthrofibrosis, and joint degeneration.

**Os trigonum syndrome**

The os trigonum is an unfused accessory bone found in close association with the posterolateral tubercle of the talus. Impingement of the os trigonum, or os trigonum syndrome, is a common condition in ballet dancers and athletes and initiated by repetitive trauma. Symptomatology is caused by extreme plantar flexion, whereby the os trigonum is compressed between the posterior border of the tibia and the superior surface of the calcaneus. Clinically, pain can be elicited on palpation at the level of the posterior ankle joint and deep to the peroneal tendons. After failing appropriate nonoperative treatment, surgical excision of the bony impediment is recommended. Marumoto and Ferkel performed a series of these arthroscopic procedures and reported favorable results in 11 patients after a mean follow-up period of 35 months. Ferkel also reported successful use of the arthroscope in the management of symptomatic os trigonum.

**Arthroscopic subtalar arthrodesis**

Arthroscopic subtalar arthrodesis was intended to yield less morbidity, preserve the blood supply, and preserve proprioception and neurosensory input. The decision to proceed with this surgical technique grew out of the success with arthroscopic ankle arthrodesis. The main indications for arthroscopic subtalar arthrodesis include persistent and intractable subtalar pain secondary to degenerative osteoarthritis, rheumatoid arthritis, and post-traumatic arthritis. Other indications include neuropathic conditions, gross instability, paralytic conditions secondary to poliomyelitis, and posterior tibial tendon rupture. Factors that play a role in determining when arthroscopic subtalar arthrodesis is appropriate include the severity of the deformity and the amount of bone loss. As with open subtalar arthrodesis, patients must have failed conservative treatment to qualify for arthroscopic subtalar fusion. The contraindications to this specific procedure are previously failed subtalar fusions, gross malalignment requiring correction, and significant bone loss.

In general, the procedure is performed as described here. The anterolateral and posterolateral portals are used in an alternating fashion during the procedure for viewing and for instrumentation. All debridement and decortication is performed posterior to the interosseous ligament. It is not as important to try to fuse the middle facet, although this can be done after resecting the contents of the sinus tarsi. The anterior facet of the subtalar joint is even more difficult to reach and is generally not fused. A primary synovectomy and debridement are necessary for visualization, as with other joints. Debridement and complete removal of the articular surface of the posterior facet of the subtalar joint down to subchondral bone is the next phase of the procedure. After the articular cartilage has been resected, approximately 1 to 2 mm of subchondral bone is removed to expose the highly vascular cancellous bone. Care must be taken not to remove excessive bone, which would lead to poor coaptation of the joint surfaces. After the subchondral plate is removed, small-spot-weld holes measuring approximately 2 mm in depth are created on the surfaces of the calcaneus and talus to create...
vascular channels. Careful assessment of the posteromedial corner must be made because residual bone and cartilage can be left there that can interfere with coaptation. The joint is then thoroughly irrigated of bone fragments and debris. In general, no autogenous bone graft or bone substitute is needed for this procedure. A joint defect and the sinus tarsi can be filled with small cancellous bone chips through an arthroscopic portal if desired. The foot is then put in the appropriate positions (about 0°–5° of hindfoot valgus) and the joint is compressed together. The fixation of the fusion is performed with a large cannulated self-drilling and self-tapping 6.5- or 7-mm lag screw. The guide pin is inserted from the dorsal anteromedial talus and angled posterior and inferior to the posterolateral calcaneus. It is important to place the guidewire under fluoroscopy with the ankle in maximum dorsiflexion to avoid any possible screw head impingement on the anterior lip of the tibia. Full weight bearing is allowed as tolerated at any time following surgery. In general, patients can tolerate full weight bearing without crutch support within 7 to 14 days after surgery. Tasto advocated the use of a small lamina spreader through the anterolateral portal during the procedure to improve visualization and facilitate the maneuvering of surgical instruments. This technique has been successfully performed in patients who have primary degenerative joint disease of the subtalar joint without gross deformity or bone loss (Table 2).

Subtalar arthroscopy and treatment of calcaneal fractures

The development of wound complications is a major concern in the open reduction and internal fixation of displaced intra-articular calcaneal fractures. Percutaneous, arthroscopically assisted screw osteosynthesis was developed to minimize the surgical approach without risking inadequate reduction of the subtalar joint. The method was applied in selected cases of displaced intra-articular calcaneal fractures with one fracture line crossing the posterior calcaneal facet (Sanders type II fractures). Percutaneous leverage is performed with a Schanz screw introduced into the tuberosity fragment under direct arthroscopic and fluoroscopic control. The subtalar joint space is evaluated with respect to intra-articular displacement and position of the fragments by way of the posterolateral portal. When small chips or avulsion fragments are present, they can be removed through a second, anterolateral portal with a small grasper or shaver. After anatomic reduction is achieved, the fragments are fixed with three to six cancellous screws introduced by way of stab incisions. Gavlik and colleagues treated 15 patients with this method and achieved good to excellent results in 10 patients, with a minimum of 1 year of follow-up.

Complications

The most likely complication to occur is an injury to any of the neurovascular structures in the proximity of the portals being used. Possible complications following subtalar joint arthroscopy include infection, instrument breakage, and damaging the articular cartilage. In addition, the use of invasive and noninvasive distraction devices can lead to various complications. Because of the limited number of reports on posterior subtalar arthroscopy, no detailed information on the incidence of complications associated with this technique is available. In a series of 49 subtalar arthroscopic procedures using the lateral three-portal technique for treating various types of subtalar pathologic conditions, only five minor complications were reported. There were three cases of neuritis involving branches of the superficial peroneal nerve. One patient had sinus tract formation and one had a superficial wound infection. Other studies report no complications with posterior subtalar arthroscopy; Ferkel evaluated 50 patients, with an average follow-up of 32 months (range, 16–51 months) and found no major complications following posterior subtalar arthroscopy. With arthroscopic arthrodiesis of the subtalar joint, in two instances hardware problems were encountered requiring removal of the lag screw. Jerosch reported algodystrophy in one patient who was treated with arthroscopically assisted subtalar arthrodesis.

SUMMARY

Diagnostic and therapeutic indications for posterior subtalar arthroscopy have increased. Subtalar arthroscopy can be performed using the lateral or the posterior two-portal technique, depending on the type and location of subtalar pathology. Arthroscopic subtalar surgery is technically difficult and should be performed only by arthroscopists experienced in advanced techniques. Arthroscopy of the subtalar joint and sinus tarsi is a valuable tool in the investigation of hindfoot pathology when conservative treatment fails and subtalar fusion is not indicated. There is a need for prospective clinical studies to provide data on the results and complications of subtalar arthroscopy.
REFERENCES

1. Inman VT. The subtalar joint The joints of the ankle, Williams & Wilkins Co., Baltimore (MD). 1976:35–44.
### TABLES

#### Table 1 Posteromedial portal safety for posterior subtalar and hindfoot arthroscopy determined with anatomic dissection studies

<table>
<thead>
<tr>
<th>Reference</th>
<th>No. of specimens</th>
<th>Achilles tendon</th>
<th>Flexor hallucis longus tendon</th>
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<th>Posterior tibial artery</th>
<th>Medial calcaneal nerve</th>
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</thead>
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<tr>
<td>Feiwell and Frey, 1993 [21]</td>
<td>18</td>
<td>—</td>
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<td>7.5 (0–13)</td>
<td>12.6 (3–20)</td>
<td>2.5 (0–6)</td>
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<td>Mekhail et al, 1995 [12]</td>
<td>6</td>
<td>—</td>
<td>—</td>
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<td>a</td>
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<td>Sitler et al, 2002 [22]</td>
<td>13</td>
<td>0.6 (0–5.5)</td>
<td>2.7 (0–11.2)</td>
<td>6.4 (0–16.2)</td>
<td>9.6 (2.4–20.1)</td>
<td>17.1 (19–31)</td>
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<td>10</td>
<td>—</td>
<td>—</td>
<td>13.3</td>
<td>17.3 (15–21)</td>
<td>14.7 (8–20)</td>
</tr>
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</table>

Values are average distances (and range) to relevant anatomic structures measured in millimeters. Abbreviation: —, not measured by authors.

- Tibial neurovascular bundle: 10 mm (at least 8 mm).

#### Table 2 Overview of arthroscopic subtalar arthrodesis

<table>
<thead>
<tr>
<th>Reference</th>
<th>No. of patients</th>
<th>Main indications</th>
<th>Follow-up</th>
<th>Technique</th>
<th>Results</th>
<th>Time until union</th>
<th>Complications</th>
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<tr>
<td>Jerosch, 1998 [41]</td>
<td>3</td>
<td>OA</td>
<td>3–5 mo</td>
<td>Supine, cancellous bone autograft</td>
<td>Excellent</td>
<td>3–5 mo</td>
<td>Algodystrophy (1)</td>
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<td>Scranton, 1999 [34]</td>
<td>5</td>
<td>OA or PTA</td>
<td>4 (6–25)</td>
<td>Supine, talocalcaneal distraction</td>
<td>Excellent</td>
<td>6 mo</td>
<td>Screw removal (1)</td>
</tr>
<tr>
<td>Tasto, 2003 [37]</td>
<td>25</td>
<td>OA (8), PTA (10)</td>
<td>22 mo (6–92)</td>
<td>Lateral, 2-portal</td>
<td>Excellent</td>
<td>8.9 wk (6–16)</td>
<td>Screw removal (1)</td>
</tr>
<tr>
<td>Asou et al, 2003 [36]</td>
<td>6</td>
<td>PTA and ankle sprains</td>
<td>10 wk</td>
<td>Lateral, 2 cannulated screws</td>
<td>Excellent</td>
<td>10 wk</td>
<td>None</td>
</tr>
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</table>

Postoperative regimens were different, possibly having an effect on the outcome. Abbreviations: OA, osteoarthritis; PTA, post-traumatic arthritis.

- Parameters required for a successful arthrodesis were generally defined as evidence of bone consolidation across the subtalar joint, no motion or radiolucency at the screw tract, the clinical absence of pain with weight bearing, and pain-free forced inversion and eversion.
FIGURES

Figure 1 (A) Anatomy of the subtalar joint. The talus is shown from under its surface and the calcaneus from above (superiorly). (B) Anatomy of the lateral subtalar joint with a view from posterior to anterior.

Figure 2 Anatomy of the lateral portal sites with the structures at risk.
Figure 3 (A) Cross-section of the ankle joint at the level of the arthroscope. 1, arthroscope placed through the posterolateral portal, pointing in the direction of the webspace between first and second toe; 2, full-radius resector introduced through the posteromedial portal until it touches the arthroscope shaft; 3, resector glides in an anterior direction until it touches bone; 4, crural fascia; 5, anterior superficial band of the deltoid ligament; 6, medial malleolus; 7, deep portion of the deltoid ligament; 8, posterior tibial tendon; 9, flexor digitorum tendon; 10, flexor hallucis longus tendon; 11, neurovascular bundle; 12, anterior talofibular ligament; 13, fibula; 14, posterior talofibular ligament; 15, peroneal tendons. (B) The arthroscope shaft is pulled backward until the shaver comes into view. The fatty tissue overlying the capsule of the talocrural joint and subtalar joint is removed. The flexor hallucis longus is used as a landmark; it is the medial border of the posterior working area. (C) The arthroscope and instruments are positioned in the area between the tarsal tunnel structures and the ankle joint. A posteromedial capsulectomy can be performed, and calcifications in this area or ossicles located posterior from the medial malleolus can be removed. The instruments can be brought into the posterior part of the ankle joint or subtalar joint when desired.

Figure 4 (A) The 13-point arthroscopic evaluation of the posterior subtalar joint starts with a 6-point examination, viewed from the anterolateral portal. The posterior subtalar joint is examined starting at the most medial portion of the talocalcaneal joint, progressing laterally and then posteriorly. (B) Seven-point examination, viewed from the posterolateral portal. The posterior examination starts by visualizing along the lateral gutter, going posterolaterally, then posteriorly and medially, and ending centrally. (Adapted from Ferkel RD. Subtalar arthroscopy. Arthroscopic surgery: the foot and ankle. Philadelphia: Lippincott-Raven; 1996. With permission.)
CHAPTER 7

A 3-portal approach for arthroscopic subtalar arthrodesis

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ABSTRACT

We present a 3-portal approach for arthroscopic subtalar arthrodesis with the patient in the prone position. The prone position allows the use of the two standard posterior portals and it allows for accurate control of hindfoot alignment during surgery. Furthermore, the introduction of talocalcaneal lag screws is easy with the patient in this position. In addition to the standard posterior portals, an accessory third portal is created at the level of the sinus tarsi for introduction of a large diameter blunt trocar to open up the subtalar joint. Due to the curved geometry of the posterior subtalar joint, removal of the anterior articular cartilage is impossible by means of the posterior portals only. An advantage of the 3-portal approach is that ring curettes can be introduced through the accessory sinus tarsi portal to remove the articular cartilage of the anterior part of the posterior talocalcaneal joint. Arthroscopic subtalar arthrodesis in patients with a talocalcaneal coalition presents a technical challenge as the subtalar joint space is limited. The 3-portal technique was successfully used in three subsequent patients with a symptomatic talocalcaneal coalition; bony union of the subtalar arthrodesis occurred at 6 weeks following surgery. With the 3-portal technique, a safe and time-efficient arthroscopic subtalar arthrodesis can be performed even in cases with limited subtalar joint space such as in symptomatic talocalcaneal coalition.

INTRODUCTION

In 2000, a 2-portal posterior approach for hindfoot arthroscopy with the patient in the prone position was introduced. This approach was successfully used for arthroscopic subtalar arthrodesis in a series of patients with post-traumatic osteoarthritis. A painful talocalcaneal coalition is a recognized indication for talocalcaneal arthrodesis in skeletally mature patients. The presence of a talocalcaneal coalition presents a technical challenge since the bar only allows limited opening up of the joint during surgery. As standard arthroscopic techniques for subtalar arthrodesis do not provide means of opening up the joint, they are difficult to use in patients with limited subtalar joint space. An accessory posterolateral portal for introduction of a blunt trocar for subtalar joint distraction in arthroscopic subtalar joint arthrodesis was described. However, the working space in the hindfoot is significantly reduced by using three posterior portals in the hindfoot. We present a technique for arthroscopic subtalar arthrodesis based on the 2-portal posterior approach with the patient in the prone position. Via an accessory third working portal at the level of the sinus tarsi, a large diameter blunt trocar is introduced in order to provide subtalar joint opening. The sinus tarsi portal is also used for introduction of ring curettes in order to remove the cartilage of the anterior part of the posterior talocalcaneal joint. We describe the technique and the results of three subsequent patients with a symptomatic talocalcaneal coalition who successfully underwent arthroscopic posterior subtalar arthrodesis using this 3-portal approach.

Operative technique

The patient is placed in the prone position. A tourniquet is inflated around the thigh. A triangular-shaped pad is placed under the lower leg to provide unconstrained motion of the ankle joint during surgery (Fig. 1). A lateral support is placed against the ipsilateral hip and the operating table is tilted towards the ipsilateral side. Following prepping and draping, the Achilles tendon and the lateral and medial malleolus are identified. The two standard posterior portals for hindfoot endoscopy are created using the technique as described before. First the posterolateral portal is made at the level or slightly above the tip of the lateral malleolus, just lateral to the Achilles tendon with the foot in the neutral position (Fig. 1). After making a longitudinal skin incision, the subcutaneous layer is split using a mosquito clamp. The mosquito clamp is pointed anteriorly, in the direction of the interdigital webspace between the first and second toe. When the tip of the clamp touches bone, it is exchanged for a 4.5 mm arthroscope shaft with the blunt trocar pointing in the same direction. By palpating the bone in the sagittal plane, the level of the ankle joint and subtalar joint most often can be
made at the level of the sinus tarsi (Fig. 2). A spinal needle is introduced via the sinus tarsi portal and is directed towards the arthroscope shaft. When the mosquito clamp touches the shaft, it is used as a guide to move the mosquito clamp over the shaft towards the ankle joint. All the way down to the ankle joint, the tip of the mosquito clamp has to touch the arthroscope shaft until the tip touches the bone. The blunt trocar is then exchanged for a 30° 4.0 mm arthroscope. The arthroscope is slightly pulled back until the tip of the mosquito clamp comes into view. The clamp is used to spread the extra-articular soft tissues in front of the tip of the arthroscope. In case of scar tissue or adhesives, the mosquito clamp is exchanged for a 5.0 mm full-radius shaver. The fatty tissue overlying the capsule of the subtalar joint is removed. After removal of the joint capsule of the subtalar joint, the posterior compartment of the subtalar joint is visualized. The posterior talar process can be freed from scar tissue and the flexor hallucis longus (FHL) tendon is identified medially. The FHL tendon is an important anatomic landmark in hindfoot endoscopy, as the posteromedial neurovascular bundle is located medially from the FHL tendon. Release of the flexor retinaculum from the posterior talar process is performed to have better access to the subtalar joint. Via the posterior portals the cartilage of the posterior facet of the subtalar joint is now removed using ring curettes. In case of a talocalcaneal coalition, the working area in the posterior subtalar joint is restricted due to the bar between the talus and calcaneus. A talocalcaneal coalition is a congenital osteofibrous, cartilaginous, or osseous union of the talus and calcaneus. A talocalcaneal coalition ossifies either completely or incompletely between 12 and 16 years of age. To open up the posterior subtalar joint, an accessory sinus tarsi portal is created for introduction of a large diameter blunt trocar. A small skin incision is made at the level of the sinus tarsi (Fig. 2). A spinal needle is introduced via the sinus tarsi portal and is directed towards the tip of the lateral malleolus. At the level of the subtalar joint the spinal needle is pointing posteriorly. The arthroscope is used to check the position of the needle. Following removal of the spinal needle, the large diameter blunt trocar (4.0 mm) is inserted through the sinus tarsi portal and is manoeuvred towards the posterior subtalar joint. For the purpose of opening up the joint, the blunt trocar is now forced into the subtalar joint. Since the direction of the blunt trocar is almost parallel to the subtalar joint space it can be forced in a sideward direction into the joint from laterally. The sideward movement prevents the trocar of making a false route into the subchondral bone (Fig. 3a). In case of a talocalcaneal coalition, the talus and calcaneus are connected by the talocalcaneal bar that is located at the medial side. A small size chisel (4.0 or 6.0 mm) is placed through the posteromedial or posterolateral portal into the area of the bar. An attempt can be made to remove the bar by using the small size chisel in order to further open up the joint (Fig. 3b). Removal of the articular cartilage of the posterior subtalar joint using ring curettes is performed by changing portals (Fig. 3c–e). After removal of the articular cartilage, the subchondral bone is entered to expose the highly vascular cancellous bone. Using the small size chisel, a number of approximately 2.0 mm deep longitudinal grooves are made in the subchondral cancellous bone of the talus and calcaneus (Fig. 3f). A vertical skin incision is made at the tip of the heel for introduction of two lag screws. Using fluoroscopy, the 6.5 mm lag screws are placed across the posterior subtalar joint. The estimated length and direction of the two screws can be preoperatively planned on the lateral weightbearing radiograph of the ankle. Before insertion of the two screws it is important to check the alignment of the hindfoot. Coaptation of the posterior subtalar joint surfaces can be checked arthroscopically when tightening the screws (Fig. 3g). The skin is closed using non-resorbable sutures. A non-weightbearing lower leg cast is provided for 4 weeks, followed by a walker boot for another 2 weeks. At 6 weeks following surgery, anteroposterior and lateral weightbearing ankle radiographs are made. With radiographic signs of union of the subtalar arthrodesis, the patient is allowed full weightbearing without further support. For patient comfort, the walker boot can be applied for another 2 weeks.

PATIENTS

From March 2006 to July 2006, three subsequent female patients with a painful talocalcaneal coalition (two left and one right foot) were operated on by the senior author using the technique as described. Computed tomography (CT) scanning of the hindfoot confirmed the presence of a medially located coalition between the talus and calcaneus. (Fig. 4). As conservative treatment eventually failed, the decision was made to perform an arthroscopic isolated subtalar arthrodesis using the 3-portal technique as described. Resection of the talocalcaneal coalition was not considered since the patients were skeletally mature and the coalition was of larger extent. In all patients joint opening and distraction using the large diameter blunt trocar introduced via the sinus tarsi portal, was sufficient to create enough working space to remove the articular cartilage from the posterior subtalar joint surfaces. The duration of surgery was on average 60 min (range, 52–65 min). Patients were discharged from the hospital the day after surgery. Postoperative radiographs 6 weeks following surgery,
showed bony union of the subtalar arthrodesis in all three patients (Fig. 5). At time of follow-up (range, 24–28 months), none of the patients had any complaints with ambulation and all were satisfied with the results. No complications had occurred.

DISCUSSION
Using the 3-portal hindfoot approach with the patient in the prone position, arthroscopically assisted arthrodesis of the posterior subtalar joint was successfully performed in three patients with a symptomatic talocalcaneal coalition. The talocalcaneal bar consists of osteofibrous tissue which allows for some micro-motion in the bar and the subtalar joint, thereby producing pain in the hindfoot on walking. Arthroscopic subtalar arthrodesis is technically challenging in patients with a talocalcaneal coalition since the bar is restricting access to the joint during surgery. The addition of an accessory portal at the level of the sinus tarsi provides safe access for introduction of a large diameter blunt trocar in order to open up the subtalar joint. This limited joint distraction is sufficient to allow introduction of ring curettes into the posterior subtalar joint. Due to the curvature of the posterior talocalcaneal joint it is not possible to remove the articular cartilage from the anterior part of the posterior talocalcaneal joint through the posterior portals. This will only be possible in case the talocalcaneal joint can be sufficiently opened. With a talocalcaneal bar the opening of the joint will always be limited. With the location of the sinus tarsi portal, the large blunt trocar is not interfering with the instruments and arthroscope that are in place via the posteromedial and posterolateral portals. A second posterolateral hindfoot portal was suggested for intra-articular placement of a large diameter blunt trocar for subtalar joint distraction. However, the accessory posterolateral portal is located close to the standard posterolateral portal, thereby reducing the working space in the hindfoot. Prone positioning of the patient allows for safe and easy placement of the two lag screws through the calcaneus and talus for fixation of the arthrodesis. In addition, the prone position facilitates accurate assessment of hindfoot alignment during surgery.

Lee et al. described a posterior arthroscopic approach with an accessory posterolateral portal for isolated subtalar arthrodesis with the patient in the prone position. All 10 feet that were operated for painful isolated osteoarthritis of the subtalar joint achieved fusion within 10 weeks. In his series of 25 patients, Tasto reported an average time until complete fusion of 8.9 weeks (range, 6–16 weeks) for arthroscopic subtalar arthrodesis. Perez Carro achieved radiographic union at a mean of 8 weeks (range, 6–11 weeks) in four patients. With this 3-portal arthroscopic technique in these patients with a talocalcaneal coalition, radiographic bony fusion was seen in all three patients 6 weeks following surgery. No bone grafting was used. The studies available on arthroscopic subtalar arthrodesis and the use of bone grafting (medial tibial plateau bone marrow, cancellous allograft, synthetic bone graft) have not shown better results for the time to fusion of the arthrodesis or the fusion rate in comparison to studies not using bone grafting. In our study, all debridement and removal of the cartilage of the posterior subtalar joint was done posterior to the interosseous ligament. This seems to become standard practice, as most studies showed that fusing solely the posterior facet in arthroscopic isolated subtalar arthrodesis is sufficient for bony fusion of the subtalar arthrodesis. With the 3-portal technique as described here, a safe and time-efficient arthroscopic subtalar arthrodesis can be performed even in cases with limited joint space such as in symptomatic talocalcaneal coalition.
REFERENCES

FIGURES

- **Figure 1 A** Patient positioning for arthroscopic subtalar arthrodesis. A triangular-shaped padding supports the lower leg for unconstrained ankle joint motion. A tourniquet is applied to the thigh. Note the lateral support for safe tilting of the patient to the ipsilateral side.
- **B** The posterolateral portal is made at the level or slightly above the tip of the lateral malleolus, just lateral to the Achilles tendon.
- **C** The posteromedial portal is made just medial to the Achilles tendon at the same height as the posterolateral portal.
Figure 2 The accessory portal for arthroscopic subtalar arthrodesis is located at the level of the sinus tarsi (arrow). The posterolateral portal is marked with a solid black arrow.

Figure 3 Intra-operative views of arthroscopic subtalar arthrodesis in a patient with talocalcaneal coalition. A) The blunt trocar is positioned laterally of the subtalar joint via the accessory sinus tarsi portal. B) The blunt trocar is sidwards forced into the subtalar joint. Using a small size chisel, an attempt is made to destruct the medially located talocalcaneal bar. C) and D) Ring curettes are used for removal of articular cartilage from the posterior subtalar joint. E) it is important to remove all cartilage from the posterior subtalar joint. A bone cutter shaver may also be used for this purpose. F) Longitudinal grooves are cut in the subchondral bone of the talus and calcaneus using the small size chisel. G) Under arthroscopic view, the screws are tightened and coaptation of the posterior subtalar joint surfaces is seen.

Figure 4 A) Coronal and B) sagittal CT images of the talocalcaneal coalition in one patient.

Figure 5 A) Preoperative lateral radiographs of a female patient with a symptomatic talocalcaneal coalition. Not the presence of the C-sign in the hindfoot [7]. B) Immediate postoperative radiograph. The gap of the posterior subtalar joint is closed. C) Six weeks following surgery, bony fusion of the posterior subtalar arthrodesis is seen.
CHAPTER 8

General discussion and conclusions
The subtalar joint range of motion

The subtalar joint is an important joint in the hindfoot for the transfer of the body weight in human propulsion and the adaptation of the foot to the ground. Subtalar joint injuries such as a subtalar sprain can lead to a painful hindfoot or subtalar instability.\(^1\)\(^-\)\(^6\) The clinical diagnosis of subtalar joint instability is difficult because there is no consensus on the diagnostic criteria for it.\(^6\)\(^-\)\(^9\) One of the underlying reasons for having no consensus on the diagnostic criteria is the lack of a definition of the normal subtalar joint range of motion. This results from the difficulties with studying the subtalar joint as it has a complex joint geometry and the subtalar joint motion takes place in all three anatomic planes. Furthermore, the exact position of the bones is difficult to determine in-vivo as there are no clear anatomic landmarks of the talus or calcaneus available. As stated by Huson, the tarsal bones are considered to be in a closed kinematic chain.\(^10\) The interdependency of motion of the tarsal bones makes assessment of isolated subtalar joint motion even more difficult. Accurate evaluation of in-vivo subtalar joint range of motion may aid the diagnosis of subtalar instability. In addition, it could be helpful for the evaluation of surgical interventions in the hindfoot and the design of a total subtalar joint prosthesis.

For the assessment of the range of motion in the subtalar joint in healthy individuals, a bone contour segmentation and matching technique was developed using computed tomography imaging (CT-BCM) for the precise registration of the position and orientation of the bones in the hindfoot. The CT-BCM technique was compared to roentgen stereophotogrammetric analysis (RSA). RSA is considered as the current gold standard for measurement of bone to bone motion in-vivo as it demonstrated high accuracy.\(^11\)\(^-\)\(^13\) According to our measurements, the accuracy of CT-BCM to measure bone to bone motion is comparable to the accuracy of RSA. The advantage of the CT-BCM technique is that the image acquisition is more time efficient and no extra special equipment is needed to acquire the CT images. In contrast to the CT-BCM technique, the accuracy of the RSA technique is more variable as it is dependent on many technique related factors (type and quality of the calibration equipment, image quality, film flatness, number of tantalum bone markers).\(^14\)\(^,\)\(^15\) Furthermore, the CT-BCM technique obviously does not have the risk of infection related to the placement of the bone markers or the risk of unintended intra-articular or otherwise faulty placement of bone markers. Although low dose CT settings are used, the disadvantage of CT-BCM is the radiation that is involved with image acquisition. Lowering the radiation dose for CT image acquisition is possible, however this could have a negative effect on the accuracy of the CT-BCM technique. Authors have also used the non-invasive magnetic resonance imaging (MRI) to study bone to bone motion in the hindfoot.\(^16\)\(^-\)\(^20\) However, for the semi-automatic bone segmentation and matching purposes the CT scan images are preferred over the MRI images as the CT is better able to depict the bony contours.

The range of motion of a joint is defined by the geometry of the articular surfaces, the ligaments, joint capsule, tendons and muscles that insert to the bones of the joint. For the assessment of the complete subtalar joint range of motion, the bones that constitute the joint have to be forced in extreme positions in different directions as far as allowed by the subtalar joint. An experimental device was designed in order to force the unconstrained foot in the extreme positions inside a CT-scanner. The eight extreme foot positions were defined in such a way that they describe the envelope of motion of the foot. The CT images of the foot in the extreme positions were used to reconstruct the geometry of the bones and to calculate the range of motion of the subtalar joint. To quantify the normal subtalar joint range of motion, the CT-BCM technique was used to study the subtalar joint range of motion in healthy volunteers. The helical axis parameters for the subtalar joint were consistent between the subjects in our series for extreme positions of the foot with a considerable eversion and inversion component. Furthermore, we found that the helical axis of the subtalar joint is running from postero-lateral-inferior to antero-medial-superior. This helical axis orientation is in agreement with the literature.\(^10\)\(^,\)\(^21\)\(^-\)\(^27\) Contrary to other studies, we found a relatively little variation in the inclination angle in the group of healthy individuals, and moderate variation in the deviation angle of the mean helical axis for the extreme foot positions with an eversion and inversion component.\(^25\)\(^,\)\(^28\) This could be the result from the talus-based coordinate system that was individually defined for every testing subject. The greatest relative motion between the calcaneus and the talus was found for the extreme eversion to the extreme inversion of the foot: a mean rotation about the helical axis of 37.3±5.9° and a mean translation along the helical axis of 2.3±1.1 mm. CT and MRI techniques have been used to quantify ankle joint motion between predefined input foot positions in-vivo.\(^16\)\(^,\)\(^19\)\(^,\)\(^20\) Other authors studied the response of the ankle and subtalar joint in-vivo to an inversion or anterior drawer load using an MRI technique.\(^30\)\(^,\)\(^31\) Outcomes of these studies are difficult to compare because of the variety of coordinate systems and joint motion definitions that were used in these studies. What minimum amount of subtalar motion should be required for a total subtalar joint prosthesis to function properly in the hindfoot of different groups of patients, is considered an interesting topic for future research.
An example of the application of in-vivo measurement of the hindfoot mobility after surgical intervention is the analysis of the effects of lateral column lengthening (LCL) in the treatment of adult acquired flatfoot deformity. The assessment of the postoperative talocrural and subtalar joint range of motion in-vivo could provide insight into the effects of the LCL procedures and this may help to guide clinical decision making in symptomatic flexible adult acquired flatfoot deformity. LCL has become an accepted procedure for the treatment of the symptomatic flexible adult acquired flatfoot deformity.32,33 One of the LCL techniques is the calcaneocuboid distraction arthrodesis (CCDA) in which the mobility and the function of the calcaneocuboid joint is lost. The other LCL technique is the anterior calcaneal distraction osteotomy (ACDO) in which the calcaneocuboid joint is preserved. The latter procedure appears to be a more favourable option as it may have a lesser effect on the ranges of motion in the hindfoot. On the other hand, due to the calcaneal distraction in the ACDO procedure, the joint pressures may increase in the calcaneocuboid joint possibly leading to early degenerative changes.34,35 Although comparative studies seem to favour the ACDO procedure over the CCDA procedure in terms of clinical outcome, the difference in subtalar joint and talocrural joint range of motion between the two procedures postoperatively was not previously described.36,37 In our study, we found comparable results in the ACDO and CCDA patient groups (5 patients per group) after surgery for the talocrural and subtalar joint range of motion means. It must be emphasized that there was considerable variation in outcome between the patients within each group. Comparing the preoperative ranges of motions with the postoperative measurements in these patient groups was not possible as preoperative measurements were not available. Compared to the results from the 20 non-matched normal subjects that were reported earlier, the subtalar joint range of motion (extreme eversion to extreme inversion) was smaller following both LCL procedures. It should be kept in mind that the reduction of joint motion might not be of importance for a normal function of the ankle and foot of the individual subject that is going to be operated on. Lundgren et al. measured hindfoot, midfoot and forefoot joint motion in volunteers during walking on a flat surface using invasive bone markers and a 3D optoelectronic tracking system.38 Lundgren measured less motion in the talocrural and subtalar joints in his healthy volunteers with normal walking than we did in our ACDO and CCDA patients since our postoperative measurements concerned the full range of motion. This finding illustrates that for normal walking the extremes of the full range of motion are not used. However, the extremes of the range of talocrural or subtalar joint motion might be required when walking on uneven surfaces or rough terrain with slopes.

Measuring the total range of subtalar joint motion (rotations about the helical axis for subtalar joint motion from extreme eversion to extreme inversion) in ten cadaveric specimens, DeLand et al. found an average of 30% loss of subtalar joint range of motion following isolated calcaneocuboid arthrodesis with a 10 mm lengthening fusion.39 In our patients, the mean subtalar range of joint motion was 61% for the ACDO patients, and 65% for the CCDA patients of the mean range of subtalar joint motion as measured in the group of 20 normal subjects.40 Although DeLand et al. used cadaveric specimens, the results from the present in-vivo study seem to support their results. Further prospective in-vivo studies should be conducted to assess the actual reduction of the talocrural and subtalar joint ranges of motion by measuring the range of motion before and after the specific surgical procedures. In addition, the CT-BCM technique can be used to study the differences in the ranges of ankle and subtalar joint motion in patients with hindfoot disease in comparison to their contralateral side. To reduce the radiation dose for the patient with uni- or bilateral CT image acquisition, a selection of the total number of extreme foot positions can be made, depending on the specific research question. With the introduction of the CT-BCM technique, an accurate and time-efficient technique has become available to study the bones in the hindfoot for the analysis of joint motion and the effects of surgical interventions on joint motion in detail.

Subtalar joint arthrodesis and arthroscopy
Subtalar joint arthrodesis (SA) is the treatment of choice for severe symptomatic osteoarthritis of the subtalar joint unresponsive to conservative treatment.41-43 The most frequent indications for SA include primary or posttraumatic osteoarthritis, congenital tarsal coalitions or joint inflammation. The reports on the open SA techniques are generally favourable with a high union rate.41,42,44 However, authors have reported complications such as hardware protrusion, lateral impingement, sural nerve injury, postoperative hindfoot malalignment, or infection.41,42,44,45 To improve the outcome of SA, an analysis of the current operative techniques for SA as described in the literature helps to identify possible pitfalls. Knowledge of such surgical pitfalls and providing possible solutions for these problems will improve the SA techniques. This has the potential of yielding better patient outcome after SA.

The aspects of the different subtalar arthrodesis procedures were analysed in a literature review on papers that presented subtalar arthrodesis techniques. A meta analysis, including statistical analyses by data pooling was not possible, since the published series were invariably retrospective reviews of small heterogeneous groups of hindfoot pathologies. An
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portals and arthroscopic anatomy of the posterior subtalar joint in cadaveric specimens were first described in sufficient detail to allow clear interpretation and evaluation. In summary, the following pitfalls were identified after reviewing the literature: complications related to the use of large incisions in open subtalar arthrodesis procedures, insufficient cartilage removal, improper bone graft selection and fixation techniques that could all possibly lead to a non-union of the arthrodesis. Other pitfalls included patient morbidity caused by bone graft harvesting, late hardware removal, postoperative varus or valgus hindfoot malalignment, and difficulties with the postoperative assessment of the state of bony fusion of the subtalar arthrodesis. The following solutions were suggested to overcome these potential pitfalls with the remark that some are still under development. If sufficiently trained and when applicable to the case of the patient, use of an arthroscopic approach to the subtalar joint is advised. If possible it is suggested to use local bone grafts (for example calcaneus) or allografts. Fixation of the subtalar arthrodesis should preferably be done by using two screws to prevent rotational micromotion that could lead to non-union of the arthrodesis. Furthermore, CT imaging of the subtalar joint arthrodesis is recommended for a detailed view of the state of the bony fusion. Further efforts should be taken to perform long-term follow-up studies to assess the effects of the many proposed adjustments of the subtalar arthrodesis.

An interesting alternative technique to the open approach to the subtalar joint is arthroscopic subtalar management as it has been credited with advantages for the patient. Anatomic portals and arthroscopic anatomy of the posterior subtalar joint in cadaveric specimens were first described by Parisien and Vangsness in 1985. One year later, Parisien published the first clinical report on subtalar arthroscopy, which evaluated three cases with good results. An overview of the aspects of the surgical technique for subtalar joint arthroscopy was provided based on a literature review and the experience of the authors with the 2-portal posterior approach. Subtalar joint arthroscopy was applied as a diagnostic and therapeutic instrument for various indications. Therapeutic indications include intra-articular subtalar joint pathology such as chondromalacia or loose bodies, and extra-articular pathology such as the os trigonum. It was concluded that the technique of subtalar joint arthroscopy has slowly evolved as an alternative to open subtalar surgery. However, arthroscopic subtalar surgery is technically difficult and should be performed only by arthroscopists experienced in advanced techniques. There is a need for prospective clinical studies to provide more data on the complications of subtalar arthroscopy for the different indications.

More recently, the indication for subtalar arthroscopy has expanded to include the arthroscopic subtalar arthrodesis for end stage osteoarthritis with good to excellent clinical results. Several different approaches and portal locations have been described for arthroscopic subtalar arthrodesis. A symptomatic talocalcaneal coalition not responding to conservative treatment, is another indication for a subtalar joint arthrodesis. Arthroscopic subtalar arthrodesis in patients with a talocalcaneal coalition presents a technical challenge as the subtalar joint space is limited and the workspace in the hindfoot is reduced. The subtalar joint space is necessary for the introduction of small-size instruments (for example curettes) to be able to remove all of the articular cartilage from the joint. When insufficient cartilage is removed from the articular surfaces, there is the risk of a non-union of the arthrodesis. Given the fact that standard arthroscopic techniques for subtalar arthrodesis do not provide means to open up the joint, such techniques are difficult to use in patients with limited subtalar joint space. An arthroscopic posterior hindfoot approach with an extra sinus tarsi portal for arthroscopically assisted hindfoot arthrodesis was used in patients with a talocalcaneal coalition. The prone position of the posterior hindfoot approach allows for control of hindfoot alignment during surgery. Furthermore, the introduction of talocalcaneal lag screws is convenient with the patient in the prone position. Besides the standard posterolateral and posteromedial portals, an accessory portal at the level of the sinus tarsi is created to introduce a large diameter blunt trocar to open up the subtalar joint and to provide more workspace for an arthroscopic subtalar joint arthrodesis. An advantage of the 3-portal approach is that ring curettes can be introduced through the accessory sinus tarsi portal to remove the articular cartilage of the anterior part of the posterior talocalcaneal joint. In all 3 patients in our study it was possible to carry out a successful arthroscopic subtalar arthrodesis using the 3-portal technique with the patient in the prone position. Recently, Albert reported the results of posterior arthroscopic subtalar arthrodesis in 2 patients with a tarsal synostosis. They used the 2-portal posterior hindfoot approach as described by Van Dijk. He confirmed rapid bony fusion in his patients with an average time of fusion of 7 weeks. However, in both patients the complication of postoperative lateral submalleolar impingement occurred related to a postoperative hindfoot valgus malalignment. One of these patients eventually required a surgical resection of the calcaneal external edge. They also reported difficulties to reach the most anteromedial aspect of the posterior facet of the subtalar joint. The sinus tarsi portal as described in our study, makes it possible to reach the anterior aspect of the posterior facet of the subtalar joint and the cartilage can be removed completely. Albert criticised the use of a sinus tarsi portal as it would endanger the vascular supply to the talus, thereby increasing the.
risk of a non-union of the subtalar arthrodesis. Non-unions were not encountered in our small series of subtalar arthrodesis in three patients. The posterior arthroscopic subtalar joint arthrodesis seems to offer a minimal invasive procedure with rapid bony fusion and fast recovery to address subtalar joint pathology. Long-term randomised clinical trials should be conducted to compare the outcome of the open and the arthroscopic subtalar arthrodesis technique using the 3-portal posterior approach.

Conclusions
1) The computed tomography based bone contour registration and segmentation method (CT-BCM) is an accurate technique for analysis of relative bone to bone motion in-vivo. The CT-BCM technique is equally as accurate as the current gold standard for bone to bone motion measurement, the roentgen stereophotogrammetric analysis (RSA).
2) The maximum range of motion of the talocrural and subtalar joint can be measured in-vivo using the CT-BCM technique.
3) The maximum range of subtalar joint motion measures a mean rotation about the helical axis of $37.3\pm5.9^\circ$ and a mean translation along the helical axis of $2.3\pm1.1$ mm for hindfoot motion from extreme eversion to extreme inversion as measured in a group of young healthy subjects.
4) The orientation and direction of the helical axes for hindfoot motion from extreme eversion to extreme inversion, or with a considerable eversion or inversion component, is consistently running from postero-lateral-inferior to antero-medial-superior.
5) There is substantial variance in terms of the postoperative ranges of motion of the talocrural and subtalar joint in patients surgically treated with a calcaneocuboid distraction arthrodesis (CCDA) or an anterior open wedge calcaneal osteotomy (ACDO) procedure for flexible adult flatfoot deformity.
6) The postoperative subtalar joint range of motion (from extreme eversion to extreme inversion) is smaller following two lateral column lengthening procedures (CCDA or ACDO) in flexible adult acquired flatfoot deformity as compared to a non-matched group of young healthy subjects.
7) Literature reviews are useful for identification of surgical pitfalls and provide possible solutions for the subtalar joint arthrodesis techniques.
8) The indications of subtalar joint arthroscopy have expanded and the technique of subtalar joint arthroscopy has slowly evolved as an alternative to open subtalar surgery for specific indications. However, arthroscopic subtalar surgery is technically challenging and should be performed by experienced arthroscopists.
9) A posterior arthroscopically assisted subtalar joint arthrodesis can successfully be performed in patients with a talocalcaneal coalition using the posterolateral and posteromedial portals in combination with an accessory sinus tarsi portal. Introduction of the blunt trocar through an accessory sinus tarsi portal can sufficiently open up the subtalar joint.
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CHAPTER 9

Introduction

The aim of this thesis was firstly to obtain insight in the normal subtalar joint range of motion. Secondly, to provide knowledge of the subtalar joint range of motion following two different surgical procedures for flexible adult acquired flatfoot deformity. And finally, to enhance endoscopic treatment options for subtalar joint pathology. Advancement in imaging techniques allows us to study joint motion in detail. Our group has developed a bone contour segmentation and registration technique using CT images (CT-BCM), to measure relative bone to bone motions in-vivo to gain insight in the normal subtalar joint range of motion. A study was performed to compare the accuracy of the CT-BCM method with the current gold standard technique, the RSA in Chapter 2. Tantalum bone markers were placed in the distal tibia, talus and calcaneus of one cadaver specimen. With a fixed lower leg, the cadaveric foot was held in a neutral position and subsequently loaded in eight extreme foot positions. Immediately after acquiring a CT-scan with the foot in a certain position, RSA radiographs were made. Following CT-BCM and RSA, helical axis parameters were calculated for talocrural and subtalar joint motion from neutral to extreme positions and between opposite extreme positions. Firstly, the overall root mean square differences between the CT-BCM and RSA for rotations around and translations along the helical axis for talocrural and subtalar joint motion were similar to those reported for the RSA method. Secondly, the root mean square differences between the CT-BCM and RSA of the position and direction of the helical axes were also similar to those reported for the RSA method. It was concluded that CT-BCM is an accurate and accessible alternative for studying bone to bone motion in-vivo.

Chapter 2

In comparison to the ankle joint or tibiotalar joint, detailed information on subtalar joint kinematics is relatively scarce. The lack of external landmarks of the talus in combination with the complex subtalar joint geometry has made the subtalar joint kinematics difficult to investigate in living subjects. The disadvantages of the roentgen stereophotogrammetric analysis (RSA) to study bone to bone motion are its invasiveness and the risk of infection, joint cartilage damage and malpositioning of the bone markers. Our group developed a bone contour segmentation and registration technique using CT images (CT-BCM) to measure relative bone to bone motions in-vivo. The purpose of this CT-based technique was to acquire data of the three-dimensional position and orientation of the ankle and hindfoot bones in the CT images in an accurate way. Therefore, the CT-based bone contour registration technique was compared to the current gold standard technique, the RSA in Chapter 2. Tantalum bone markers were placed in the distal tibia, talus and calcaneus of one cadaver specimen. With a fixed lower leg, the cadaveric foot was held in a neutral position and subsequently loaded in eight extreme foot positions. Immediately after acquiring a CT-scan with the foot in a certain position, RSA radiographs were made. Following CT-BCM and RSA, helical axis parameters were calculated for talocrural and subtalar joint motion from neutral to extreme positions and between opposite extreme positions. Firstly, the overall root mean square differences between the CT-BCM and RSA for rotations around and translations along the helical axis for talocrural and subtalar joint motion were similar to those reported for the RSA method. Secondly, the root mean square differences between the CT-BCM and RSA of the position and direction of the helical axes were also similar to those reported for the RSA method. It was concluded that CT-BCM is an accurate and accessible alternative for studying bone to bone motion in-vivo.
postero-lateral-inferior to antero-medial-superior. There was relatively little variation in the inclination angle, and moderate variation in the deviation angle of the mean helical axis for extreme foot positions with an eversion and inversion component. The CT-BCM technique can be used as a quantitative outcome measure for analysing changes in subtalar range of motion before and after operative interventions in the hindfoot.

Chapter 4
Lateral column lengthening (LCL) has become an accepted surgical procedure for the treatment of the symptomatic flexible adult acquired flatfoot deformity. Chapter 4 described the outcome of two commonly used LCL techniques for flatfoot deformity correction in terms of postoperative ankle and subtalar joint range of motion. The calcaneocuboid distraction arthrodesis (CCDA) or the anterior calcaneal open wedge osteotomy (ACDO) technique was used in two groups of five patients with flexible adult acquired flatfoot deformity. These bony procedures were combined with an augmentation of the posterior tibial tendon and other procedures. The hypothesis was that the ACDO procedure is preferred in these patients as the CCDA procedure has the possible disadvantage of restricting hindfoot motion with surgical fusion of the calcaneocuboid joint as there is a interdependency of motion of the tarsal bones (i.e. immobilization of one joint limits the mobility of others as the bones of the hindfoot are considered as a closed kinematic chain). The CT-BCM method that was validated in Chapter 2 was used. CT scanning was performed with the foot in eight extreme positions in five ACDO and five CCDA patients. With the small number of patients in both groups no statistical analyses were performed. The maximum mean finite helical axis (FHA) rotation of the talocrural joint (for extreme dorsiflexion to extreme plantarflexion) after ACDO was 52.2° ± 12.4° and after CCDA 49.0° ± 12.0°. Subtalar joint maximum mean FHA rotation (for extreme eversion to extreme inversion) following ACDO was 22.8° ± 8.6°, and following CCDA 24.4° ± 7.6°. It was concluded that our study yielded comparable results for the postoperative ranges of talocrural and subtalar joint motion in the ACDO and CCDA patients.

Chapter 5
Subtalar joint arthrodesis is the treatment of choice for severe symptomatic osteoarthritis of the subtalar joint unresponsive to conservative treatment. Although subtalar joint arthrodesis is considered a routine orthopaedic surgical procedure, authors have described peri-operative problems with this procedure. In Chapter 5 a literature review was performed of papers that presented subtalar arthrodesis techniques. The aspects of the different subtalar arthrodesis procedures were analysed. A meta analysis, including statistical analyses by data pooling was not possible, since the published series were invariably retrospective reviews of small heterogenous groups of hindfoot pathologies. An additional restriction was that only recently, operative techniques and evaluation protocols have been described in sufficient detail that allow for clear interpretation and evaluation. Five separate stages of the general technique of subtalar joint arthrodesis were identified; surgical approach, cartilage removal, bone graft use, hindfoot deformity correction, and, fixation. The following pitfalls were identified: complications related to the use of large incisions in open subtalar arthrodesis procedures, insufficient cartilage removal, improper bone graft selection and fixation techniques that could all possibly lead to a non-union of the arthrodesis. Furthermore; morbidity caused by bone graft harvesting and late screw removal, under- or overcorrection of the hindfoot malalignment, and difficulties with the postoperative assessment of the state of bony fusion of the arthrodesis. Literature also provided possible solutions to overcome these pitfalls with the remark that some are still under development: (1) if applicable use an arthroscopic approach in combination with burrs and distraction devices, (2) when possible use local bone graft or allografts, (3) fixation of the subtalar arthrodesis should be done by using two screws to prevent rotational micromotion, and (4) if doubt exists on solid bony fusion of the subtalar arthrodesis, a CT-scan of the subtalar joint is recommended. Further efforts should be taken to perform long-term follow-up studies to assess the effects of the many proposed adjustments to the subtalar arthrodesis operative techniques.

Chapter 6
Arthroscopic subtalar management has been credited with clear advantages for the patient, including a faster postoperative recovery period, decreased postoperative pain, and fewer complications. In Chapter 6 an overview of the aspects of the surgical technique for subtalar joint arthroscopy was provided. Subtalar joint arthroscopy may be applied as a diagnostic and therapeutic instrument. Therapeutic indications include intra-articular subtalar joint pathology such as chondromalacia or loose bodies, and extra-articular pathology such as an os trigonum. More recently, the indication for subtalar arthroscopy has expanded to include the arthroscopic subtalar arthrodesis. A noninvasive soft-tissue distractor was advised to open the subtalar joint during arthroscopic surgery. The lateral and posterior portals that are routinely used in subtalar joint arthroscopy are considered safe with regard to the important anatomical structures in the proximity of the portals. The safety of these portals has been assessed in cadaveric specimens. The literature on arthroscopic treatment and results of sinus tarsi
syndrome, os trigonum syndrome and subtalar arthrodesis demonstrated the use of subtalar joint arthroscopy. It was concluded that the technique of subtalar joint arthroscopy has slowly evolved as an alternative to open subtalar surgery. In addition, there is a need for prospective clinical studies to provide detailed information on the results and complications of subtalar joint arthroscopy.

Chapter 7
In Chapter 7 we reported on the technique and outcome of the arthroscopic subtalar arthrodesis in patients with a symptomatic talocalcaneal coalition using the posterior hindfoot approach and an accessory sinus tarsi portal. The prone position of the posterior hindfoot approach allows the use of the standard posterolateral and posteromedial portals. It also allows for accurate control of hindfoot alignment during surgery. Furthermore, the introduction of talocalcaneal lag screws is convenient with the patient in the prone position. Arthroscopic subtalar arthrodesis in patients with a talocalcaneal coalition presents a technical challenge as the subtalar joint space is limited and the workspace in the hindfoot is reduced. An accessory portal at the level of the sinus tarsi is created to introduce a large diameter blunt trocar to open up the subtalar joint and providing more workspace for an arthroscopic subtalar joint arthrodesis. Due to the curved geometry of the posterior subtalar joint, removal of the anterior articular cartilage is impossible by means of the posterior portals only. An advantage of the 3-portal approach is that ring curettes can be introduced through the accessory sinus tarsi portal to remove the articular cartilage of the anterior part of the posterior talocalcaneal joint. In all 3 patients with a symptomatic talocalcaneal coalition it was possible to carry out a successful arthroscopic subtalar arthrodesis using the 3-portal technique. Bony fusion of the subtalar arthrodesis was achieved and no complications occurred. It was concluded that with the 3-portal technique, a safe and time-efficient arthroscopic subtalar arthrodesis can be performed even in cases with limited subtalar joint space such as in symptomatic talocalcaneal coalition.
Introductie
Het doel van dit proefschrift was ten eerste om meer inzicht te krijgen in het normale totale bewegingsbereik van het subtalaire gewricht. Ten tweede, om kennis op te doen van het totale beweeglijkheid van het subtalaire gewricht. Geavanceerde beeldvormende technieken bieden de mogelijkheid om de beweeglijkheid van gewrichten gedetailleerd in-vivo te onderzoeken. Een nieuwe methode werd ontwikkeld waarbij de beweeglijkheid van de gewrichten in-vivo kon worden berekend op basis van segmentatie van de botten in computer tomografie (CT) data. Na botsegmentatie werden de contouren van de botten in de CT data geregistreerd. Met deze gegevens werden de bewegingsbereik van het subtalaire gewricht bemoeilijken. De nadelen van bewegingsstudies met de huidige gouden standaard, de röntgen stereofotogrammetrie analyse (RSA) zijn de invasiviteit van RSA, het risico van infectie, mogelijke beschadiging van gewrichtskraakbeen en onjuiste plaatsing van de bot markers. Een bot segmentatie en contour registratie techniek op basis van computer tomografie (CT) data (CT-BCM) werd ontwikkeld om relatieve bot-bot bewegingen in-vivo te analyseren. Het doel van de CT-BCM techniek was om gedetailleerde informatie te verkrijgen over de posities en de oriëntatie van de botten van het enkelgewricht en subtalaire gewricht in-vivo. In hoofdstuk 2 werd de nauwkeurigheid van CT-BCM vergeleken met de gouden standaard voor het meten van relatieve bot-bot bewegingen, de RSA. Tantalum bot markers werden geplaatst in de distale tibia, talus en calcaneus van een kadaver. Met een gefixeerd onderbeen werd de enkel in een neutrale stand gepositioneerd. Vervolgens werd de voet in acht verschillende richtingen belast waardoor de bewegingen in een maximale eindstand werden gedwongen. In iedere stand werd, direct na het maken van een CT-scan van de enkel, RSA fotografie verricht. Na CT-BCM en RSA werden de schroevingsassen berekend voor de totale beweeglijkheid van het enkelgewricht en subtalaire gewricht van de neutrale stand naar de eindstanden. Tevens werden de schroevingsassen van beide gewrichten berekend voor de bot-bot bewegingen van een bepaalde eindstand naar een tegengestelde eindstand (vier bewegingen). Deze studie toonde dat de gemeten onnauwkeurigheid van de CT-BCM methode nagenoeg gelijk was als die van de RSA. Hieruit kan worden geconcludeerd dat CT-BCM een nauwkeurige en toegankelijke methode voor het bestuderen van bot-bot bewegingen in-vivo is.

Hoofdstuk 2
In tegenstelling tot het enkelgewricht, is gedetailleerde kennis over de kinematica van het subtalaire gewricht relatief schaars. Het ontbreken van externe anatomische herkenningspunten van de talus in combinatie met de complexe geometrie van het subtalaire gewricht zijn factoren die gedetailleerde studie van de beweeglijkheid van het subtalaire gewricht bemoeilijken. De nadelen van bewegingsstudies met de huidige gouden standaard, de röntgen stereofotogrammetrie analyse (RSA) zijn de invasiviteit van RSA, het risico van infectie, mogelijke beschadiging van gewrichtskraakbeen en onjuiste plaatsing van de bot markers. Een bot segmentatie en contour registratie techniek op basis van computer tomografie (CT) data (CT-BCM) werd ontwikkeld om relatieve bot-bot bewegingen in-vivo te analyseren. Het doel van de CT-BCM techniek was om gedetailleerde informatie te verkrijgen over de bewegingsbereik van het subtalaire gewricht. De techniek van het operatief vastzetten van het subtalaire gewricht bij volwassenen. En tenslotte, om bij te dragen aan de wetenschap over de arthroscopische behandeling van aandoeningen van het subtalaire gewricht. Geavanceerde beeldvormende technieken bieden de mogelijkheid om de beweeglijkheid van gewrichten gedetailleerd in-vivo te onderzoeken. Met deze gegevens werden de bewegingsbereik van het subtalaire gewricht bemoeilijken. De nadelen van bewegingsstudies met de huidige gouden standaard, de röntgen stereofotogrammetrie analyse (RSA) zijn de invasiviteit van RSA, het risico van infectie, mogelijke beschadiging van gewrichtskraakbeen en onjuiste plaatsing van de bot markers. Een bot segmentatie en contour registratie techniek op basis van computer tomografie (CT) data (CT-BCM) werd ontwikkeld om relatieve bot-bot bewegingen in-vivo te analyseren. Het doel van de CT-BCM techniek was om gedetailleerde informatie te verkrijgen over de bewegingsbereik van het subtalaire gewricht. Ten tweede, om kennis op te doen van het totale beweeglijkheid van het subtalaire gewricht. Geavanceerde beeldvormende technieken bieden de mogelijkheid om de beweeglijkheid van gewrichten gedetailleerd in-vivo te onderzoeken. Een nieuwe methode werd ontwikkeld waarbij de beweeglijkheid van de gewrichten in-vivo kon worden berekend op basis van segmentatie van de botten in computer tomografie (CT) data. Na botsegmentatie werden de contouren van de botten in de CT data geregistreerd. Met deze gegevens werden de bewegingsbereik van het subtalaire gewricht bemoeilijken. De nadelen van bewegingsstudies met de huidige gouden standaard, de röntgen stereofotogrammetrie analyse (RSA) zijn de invasiviteit van RSA, het risico van infectie, mogelijke beschadiging van gewrichtskraakbeen en onjuiste plaatsing van de bot markers. Een bot segmentatie en contour registratie techniek op basis van computer tomografie (CT) data (CT-BCM) werd ontwikkeld om relatieve bot-bot bewegingen in-vivo te analyseren. Het doel van de CT-BCM techniek was om gedetailleerde informatie te verkrijgen over de posities en de oriëntatie van de botten van het enkelgewricht en subtalaire gewricht in-vivo. In hoofdstuk 2 werd de nauwkeurigheid van CT-BCM vergeleken met de gouden standaard voor het meten van relatieve bot-bot bewegingen, de RSA. Tantalum bot markers werden geplaatst in de distale tibia, talus en calcaneus van een kadaver. Met een gefixeerd onderbeen werd de enkel in een neutrale stand gepositioneerd. Vervolgens werd de voet in acht verschillende richtingen belast waardoor de bewegingen in een maximale eindstand werden gedwongen. In iedere stand werd, direct na het maken van een CT-scan van de enkel, RSA fotografie verricht. Na CT-BCM en RSA werden de schroevingsassen berekend voor de totale beweeglijkheid van het enkelgewricht en subtalaire gewricht van de neutrale stand naar de eindstanden. Tevens werden de schroevingsassen van beide gewrichten berekend voor de bot-bot bewegingen van een bepaalde eindstand naar een tegengestelde eindstand (vier bewegingen). Deze studie toonde dat de gemeten onnauwkeurigheid van de CT-BCM methode nagenoeg gelijk was als die van de RSA. Hieruit kan worden geconcludeerd dat CT-BCM een nauwkeurige en toegankelijke methode voor het bestuderen van bot-bot bewegingen in-vivo is.

Hoofdstuk 3
In dit hoofdstuk werd de normale totale beweeglijkheid van het subtalaire gewricht gemeten met behulp van CT-BCM. In 20 gezonde proefpersonen werd een externe belasting op de voetvoeler aangebracht om de voet in acht verschillende eindstanden te positioneren. CT scans werden gemaakt met de enkel en voet in een neutrale positie ten opzichte van de tibia en in elk van de acht verschillende eindstanden. Met behulp van CT-BCM werden de schroevingsassen berekend voor de relatieve bot-bot bewegingen van de calcaneus ten opzichte van de talus voor de vier verschillende bewegingen tussen twee tegengestelde eindstanden. De unieke schroevingsassen werden weergegeven in een coördinatenstelsel uitgaande van de geometrische hoofdassen van de talus van de betreffende proefpersoon. De grootste relatieve bot-bot beweging van de calcaneus ten opzichte van de talus werd gemeten.
voor de beweging van de voet tussen de eindstanden maximale eversie naar maximale inversie met een gemiddelde rotatie van $37,3 \pm 5,9^\circ$ en een gemiddelde translatie van $2,3 \pm 1,1$ mm. De schroevingsas voor de totale beweging van het subtalaire gewricht tussen twee tegengestelde eindstanden van de voet was consistent in de groep van 20 proefpersonen, behalve voor de beweging tussen de eindstanden dorsaalflexie en plantairflexie. De conclusie was dat voor eindstanden met een belangrijke eversie en inversie component, de schroevingsas parameters een hoge mate van consistentie lieten zien in de groep van 20 proefpersonen. De richting van de schroevingsas van het subtalaire gewricht was als volgt; van postero-lateraal-inferieur naar antero-mediaal-superieur. De gemeten inclinatiehoek van de gemiddelde schroevingsas toonde weinig variatie in de groep van 20 proefpersonen. Enige variatie werd gevonden voor de deviatiehoek van de gemiddelde schroevingsas. CT-BCM kan worden toegepast als een methode voor kwantificering van de totale beweeglijkheid van het subtalaire gewricht voor en na operaties van de enkel en/of achtervoet.

**Hoofdstuk 4**

Operatieve verlenging van de benige laterale kolom van de voet is een vaak gebruikte operatieve behandelingsoptie voor een flexibele pes planus deformiteit in volwassen patiënten. In hoofdstuk 4 werden de uitkomsten beschreven van een onderzoek naar het postoperatieve bewegingsbereik van het enkelgewricht en het subtalaire gewricht in twee groepen patiënten behandeld met een laterale kolom verlengingprocedure. De calcaneocuboid distractie-arthrodese (CCDA) en de anterieure calcaneus open wig distractie-osteotomie (ACDO) werden vergeleken in twee groepen van vijf patiënten met een symptomatische flexibele pes planus deformiteit. Augmentatie van de tibialis posterior pees werd in dezelfde operatieve sessie verricht bij alle patiënten als toevoeging op de CCDA of ACDO procedure. De hypothese van deze studie was dat de ACDO procedure voor de symptomatische flexibele pes planus deformiteit beter zou kunnen bijdragen aan de beweeglijkheid van de achtervoet vanwege het vastzetten van het calcaneocuboid gewricht. Deze hypothese is gebaseerd op het concept van de onderlinge afhankelijkheid van de beweeglijkheid van de gewrichten van de voet. Dit houdt in dat verstijving van een gewricht in de voetwoelt nadelige gevolgen heeft voor de beweeglijkheid van de overige omliggende gewrichten, omdat de gewrichten van de voetwoelt in een gesloten kinematische keten functioneren. De in hoofdstuk 2 beschreven en gevalideerde CT-BCM methode werd in deze studie gebruikt. De enkels van de vijf CCDA en de vijf ACDO patiënten werden gescand in de acht verschillende eindstanden van de voet volgens het standaard CT-BCM protocol. Gezien de kleine aantallen patiënten in beide groepen kon geen statistische analyse worden verricht. De grootste gemiddelde rotatie rond de schroevingsas voor de grootste bewegingsuitslag van het enkelgewricht (van de eindstanden maximale dorsaalflexie naar maximale plantairflexie van de enkel) na ACDO was $52,2^\circ \pm 12,4^\circ$ en in de CCDA patiënten $49,0^\circ \pm 12,0^\circ$. De grootste gemiddelde rotatie rond de schroevingsas voor de grootste bewegingsuitslag van het subtalaire gewricht (van de eindstanden maximale eversie naar maximale inversie) na ACDO procedure in de vijf patiënten was $22,8^\circ \pm 8,6^\circ$. Dit was $24,4^\circ \pm 7,6^\circ$ in de CCDA patiënten groep. Concluderend werd gesteld dat deze studie gelijke resultaten heeft aangetoond voor de totale postoperatieve beweeglijkheid van het enkelgewricht en het subtalaire gewricht na de ACDO en CCDA procedures in volwassen patiënten met een symptomatische flexibele pes planus deformiteit.

**Hoofdstuk 5**

Het operatief vastzetten van het subtalaire gewricht, de subtalaire arthrodese is de gewezen behandeling voor subtalaire arthrose in een eindstadium. Een subtalaire arthrodese wordt vaak gezien als een routine ingreep in de orthopedie. Echter, meerdere auteurs hebben moeilijkheden en complicaties van de subtalaire arthrodese beschreven. In hoofdstuk 5 werd een overzicht gegeven van de beschikbare literatuur over de chirurgische subtalaire arthrodese. De verschillende aspecten van de subtalaire arthrodese procedure werden geanalyseerd. Een meta analyse met inbegrip van een statistische analyse op basis van data pooling was niet mogelijk omdat de gepubliceerde studies retrospectief van opzet waren met kleine aantallen patiënten en heterogene groepen. Een bijkomende beperking was dat overwegend alleen recente publicaties de subtalaire arthrode techniek en protocollen in voldoende detail hebben beschreven. De subtalaire arthrode techniek werd ingedeeld in vijf verschillende stadia: de benadering, de verwijdering van het kraakbeen, de bot toevoeging, de correctie van de stand van de achtervoet en, de fixatie van de subtalaire arthrodese. De volgende potentiële problemen werden geïdentificeerd in de literatuur studie: wondd complicaties als gevolg van de huidincisie op de subtalaire arthrodese, kraakbeen restanten in het gewricht, problemen met de toevoeging van bot, en, problemen met voldoende fixatie van de arthrodese. Daarnaast werden de volgende problemen gezien; morbiditeit als gevolg van het oogsten van bot voor toevoeging aan de arthrodese, verwijdering van schroeven in een tweede operatieve sessie, over- of ondernodig correcetie van de stand van de achtervoet en moeilijkheden met de postoperatieve beoordeling van de mate van
consolidatie van de subtalaire arthrodese. Verschillende auteurs droegen oplossingen aan voor deze problemen van de subtalaire arthrodese techniek. Ten eerste kan er plaats zijn voor arthroscopische technieken voor de subtalaire arthrodese in combinatie met gespecialiseerde instrumenten en niet-invasieve distractie van het subtalaire gewricht. Ten tweede werd autoloog bot uit de directe omgeving van de operatiewond aangeraden indien bot toevoeging aan de subtalaire arthrodese nodig wordt geacht. Fixatie van de subtalaire arthrodese met tenminste twee schroeven zou ongewenste rotatiebewegingen van de subtalaire arthrodese moeten voorkomen. Tenslotte, bij twijfel postoperatief over de mate van consolidatie van de subtalaire arthrodese is een CT-scan van de achtervoet behulpzaam. Nieuwe studies zijn nodig om de lange termijn effecten van deze maatregelen op de uitkomsten van de subtalaire arthrodese techniek te evalueren.

**Hoofdstuk 6**

Arthroscopische behandeling van aandoeningen van het subtalaire gewricht heeft een aantal voordelen waaronder een kortere herstelperiode na de operatie, verminderde postoperatieve pijn en minder complicaties. In hoofdstuk 6 wordt een overzicht gegeven van de aspecten van arthroscopische chirurgie van het subtalaire gewricht. Subtalaire arthroscopie kan worden toegepast als een diagnostisch of als therapeutisch middel. Therapeutische indicaties voor de subtalaire arthroscopie zijn intra-articulaire subtalaire pathologie zoals chondromalacie of een corpus liberum of een extra-articulair os trigonum. Recentelijk is de arthroscopische subtalaire arthrodese beschreven in patienten met symptomatische talocalcaneale coalitie. Een niet-invasieve distractor werd geadviseerd om het subtalaire gewricht beter toegankelijk te maken tijdens intra-articulaire procedures of de arthroscopische subtalaire arthrodese. De laterale en posterieure portals die worden gebruikt bij subtalaire arthroscopie zijn op veilige afstand van de belangrijke anatomische structuren die zich in de onmiddellijke nabijheid van de portals bevinden. Dit is gebleken uit meerdere anatomische dissectie studies. De literatuur over arthroscopische behandeling en de resultaten van het sinus tarsi syndroom, het os trigonum syndroom en de subtalaire arthrodese werd besproken in hoofdstuk 6. Concluderend kan worden gesteld dat de subtalaire arthroscopie een geschikt alternatief vormt voor de open subtalaire chirurgie. Om meer kennis te verkrijgen over de uitkomsten van subtalaire arthroscopie op de lange termijn zijn prospectieve klinische studies nodig.

**Hoofdstuk 7**

In hoofdstuk 7 werden de operatieve techniek en de resultaten gepresenteerd van de arthroscopische subtalaire arthrodese bij patiënten met een symptomatische talocalcaneale coalitie. De standaard posteriore arthroscopische benadering van de achtervoet werd gebruikt in combinatie met een extra laterale portal ter hoogte van de sinus tarsi. De buikligging heeft als voordeel dat de stand van de achtervoet tijdens de operatie kan worden beoordeeld. Verder kunnen de schroeven voor de subtalaire arthrodese gemakkelijk via de hiel worden ingebracht met de patiënt in buikligging. In het geval van een talocalcaneale coalitie kan het lastig zijn om een arthroscopische subtalaire arthrodese uit te voeren vanwege de beperkte ruimte in de achtervoet en het starre subtalaire gewricht. Naast de standaard posterolaterale en posteromediale portal werd een extra portal gemaakt ter hoogte van de sinus tarsi. Een stompe trocar werd via de sinus tarsi portal ingebracht om het subtalaire gewricht open te kunnen wrikken en meer werkruimte te verkrijgen in de achtervoet voor de arthroscopische arthrodese. Verwijdering van al het kraakbeen van het voorste deel van het achterste facet van het subtalaire gewricht is niet mogelijk vanwege de kromming van het gewrichtoppervlak. Een voordeel van de 3-portal benadering is dat ring curettes via de extra sinus tarsi portal kunnen worden ingebracht om al het kraakbeen van het voorste deel van het achterste subtalaire facet te kunnen verwijderen. In drie patiënten met een symptomatische talocalcaneale coalitie werd een succesvolle arthroscopische subtalaire arthrodese uitgevoerd volgens de beschreven 3-portal benadering. Consolidatie van de subtalaire arthrodese slaagde in alle drie patiënten en er waren geen complicaties. De conclusie kan worden getrokken dat de 3-portal techniek met de patiënt in buikligging een veilige en efficiënte techniek is voor de arthroscopische subtalaire arthrodese bij patiënten met een beperkte werkruimte of starheid in de achtervoet zoals bij een talocalcaneale coalitie het geval is.
ADDENDUM

Dankwoord
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Prof.dr. C.N. van Dijk
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Biografie


In 2005 volgde toelating tot de opleiding orthopedie en werd de vooropleiding heelkunde gestart in het Zaans Medisch Centrum te Zaandam (opleider Dr. A.F. Engel). De opleiding orthopedie werd voortgezet in het AMC te Amsterdam (opleider Prof. Dr. C.N. van Dijk), TergooiZiekenhuizen Hilversum (opleider Dr. G.H.R. Albers) en het Slotervaart Ziekenhuis te Amsterdam (opleider Prof. Dr. R.G. Pöll). In juli 2011 volgde registratie als orthopedisch chirurg. Als jonge klare orthopeed werkte hij in het Reinier de Graaf ziekenhuis in Delft. Het gehele jaar 2012 werd gewijd aan een fellowship schouderchirurgie in het St. George Hospital in Sydney (Prof. Dr. G.A.C. Murrell).