Tero Klemola

FLEXIBLE HALLUX VALGUS
RESULTS OF A NEW SURGICAL TECHNIQUE
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Results of a new surgical technique

Academic Dissertation to be presented with the assent of the Doctoral Training Committee of Health and Biosciences of the University of Oulu for public defence in Auditorium 1 of Oulu University Hospital (Kajaanintie 50), on 18 May 2018, at 12 noon

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**Abstract**

Hallux valgus (HV) decreases the forces under the first ray during the propulsive phases of gait and transfers loading to the lesser metatarsals. Biomechanical factors contribute to the development of HV through various mechanisms; however, the flexibility of HV has not been considered to be a major determinant when planning surgery for HV.

The aims of this thesis were to develop a clinical test and a new surgical technique for flexible HV, to report the mid-term follow-up results of this new correction method, and to compare the metatarsal load distribution after the new technique to that achieved with distal chevron osteotomy in a matched-pair analysis.

The new surgical technique, first tarsometatarsal joint derotational arthrodesis (FTJDA), includes rotational correction of the first metatarsal without surgery to the first metatarsophalangeal joint (MTPJ). It is indicated for patients who are able to reduce HV with peroneus longus (PL) function (PL activation test). Between 2003 and 2009, a total of 88 flexible HV underwent FTJDA operations. Seventy-six operated feet were re-examined after an average of 5.1 (range 3.0 to 8.3) years of follow-up. Outcome measures included the American Orthopaedic Foot and Ankle Society (AOFAS) score and pre- and postoperative radiological analysis. Gait analysis was used to compare the metatarsal load distribution after the FTJDA with a distal chevron cohort in 30 pairs matched by HV angle and follow-up time.

The mean HV and intermetatarsal correction angles between preoperative and six-week follow-up radiographs were 19.8 degrees and 8.9 degrees, respectively. HV and intermetatarsal angle (IMA 1-2) correction were satisfactorily maintained (13.4 degrees [95% CI 11.6 to 15.1] and 4.5 degrees [95% CI 3.7 to 5.2], respectively) at mid-term follow-up. AOFAS score was excellent or good in 72% of the operated feet. In gait analysis, the FTJDA group had 8% higher relative impulses under the first metatarsal head (MTH), whereas chevron group had central loading pattern.

In conclusion, FTJDA corrects flexible HV effectively without intervention to the MTPJ. The correction is satisfactorily maintained at the late follow-up and the clinical results are good. In the gait analysis, the FTJDA produces better postoperative dynamic loading capacity of the first ray in comparison to distal chevron osteotomy.

**Keywords:** closed operative technique, flexible HV, gait, mid-term follow-up results, peroneus longus activation test.
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**Tiivistelmä**

Vaivaisenluu heikentää voimantuottoa ensimmäisen säteen alla kävelyn ponnistusvaiheiden
aikana ja kuormitus siirtyy ulommille jalkapöytäluiille. Biomekaanisilla tekijöillä arvellaan ole-
van osuutta vaivaisenluun kehittymiseen. Vaivaisenluun joustavuutta ei ole pidetty ratkaisevana
tekijänä kirurgisen hoidon suunnittelussa.

Tämän tutkimuksen tavoitteina oli kehittää kliininen testi ja uusi kirurginen korjausmenetel-
mä joustavalle vaivaisenluuvirheasennolle, raportoida uuden korjausmenetelmän keskipikkan
seuranta-ajan tulokset ja verrata jalkapöytäluiden kuormitusjakaumaa uuden korjausmenetel-
män jälkeen distaaliselle chevron -osteotomiaan kaltaistettujen parien analyysillä.

Uusi kirurginen toimenpide, ensimmäisen tarsometatarsaalinivelen derotaatioartrodeesi (FTJ-
DA), sisältää metatarsaalin rotaatiokorjauksen avoimalla ensimmäisen varpan tyviniveltä.
Menetelmä on tarkoitus potilaille, joilla vaivaisenluuvirheasento kiihtyy peroneus longu-
ksen toiminnallana (PL-aktivaatiotesti). Vuosina 2003–2009 operoittiin yhteensä 88 joustavaa vai-
vaisenluuvirheasentoa ensimmäisen tarsometatarsaalinvilven derotaatioartrodeesillä (FTJDA).
76 leikattua jalkaa tutkittiin uudelleen 5,1 vuoden (vaihteluväli 3,0 – 8,3) keskiseuranta-ajan jäl-
keen. Tulosten arvioinnissa käytettiin AOFAS-pisteytystä ja pre- ja postoperatiivisia radiologi-
sia mitaustakin. Kävelyanalyysillä verrattiin jalkapöytäluiden kuormitusta FTJDA- ja distaalisen
chevron -osteotomiaryhmän välillä 30 parilla, jotka kaltaistettiin vaivaisenluukulman ja seuran-
ta-ajan suhteen.

Keskimääräinen vaivaisenluu- ja intermetatarsaalikulmien korjautuminen oli preoperatiivis-
en ja kuiden viikon kontrollikuvin välillä 19,8 ja 8,9 astetta. Korjautumistulokset vaivaisen-
luu- ja intermetatarsaalikulmien osalta säilyivät hyvänä,13,4 astetta (95% luottamusväli 11,6-
15,1) ja 4,5 astetta (95% luottamusväli 3,7-5,2), keskipikkanajan seurannassa. AOFAS pisteytys
antoi erinomaisen tai hyvän tuloksen 72%:lle leikatuista jaloista. Kävelyanalyysissä FTJDA-
ryhmän relativinen impulssi oli 8% korkeampi ensimmäisen jalkapöytäluun pään alla, kun taas
chevron-ryhmällä todettiin päättä keskiösalen kohonnut kuormitusjakauma.

Yhteenvetona voidaan todeta, että FTJDA korjaa joustavan vaivaisenluun tehokkaasti ilman
l-vartenä tyvinivelen toimenpiteitä. Korjautumistulos säilyy pitkäaikaisseurannassa ja kliinisit
tulokset ovat hyviä. Kävelyanalyyssissä FTJDA tuottaa paremman postoperatiivisen, ensimmäi-
sen säteen dynaamisen kuormituskapasiteetin, distaaliselle chevron -osteotomiaan verrattuna.

**Asiassanat:** joustava vaivaisenluu, keskipitkä seuranta-aika, kävely, peroneus longus
aktivaatiotesti, sulkeinen leikkaustekniikka
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Oulu, March 2018

Tero Klemola
### Abbreviations

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<tr>
<td>AE</td>
<td>Ankle equinus</td>
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<tr>
<td>AOFAS</td>
<td>American Orthopaedic Foot and Ankle Society</td>
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<tr>
<td>HV</td>
<td>Hallux valgus</td>
</tr>
<tr>
<td>HVA</td>
<td>Hallux valgus angle</td>
</tr>
<tr>
<td>FHL</td>
<td>Flexor hallucis longus</td>
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<tr>
<td>FTJDA</td>
<td>First tarsometatarsal joint derotational arthrodesis</td>
</tr>
<tr>
<td>IMA 1-2</td>
<td>Intermetatarsal angle between the first and the second metatarsals</td>
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<tr>
<td>I MTPJ</td>
<td>First metatarsophalangeal joint</td>
</tr>
<tr>
<td>MTH</td>
<td>Metatarsal head</td>
</tr>
<tr>
<td>MTP-IP</td>
<td>Metatarsophalangeal-interphalangeal</td>
</tr>
<tr>
<td>PL</td>
<td>Peroneus longus</td>
</tr>
<tr>
<td>TA</td>
<td>Tibialis anterior</td>
</tr>
<tr>
<td>UAJ</td>
<td>Upper ankle joint</td>
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<tr>
<td>VAS</td>
<td>Visual analog scale</td>
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List of original publications

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1 Introduction

Hallux valgus (HV) is the most common deformity of the first toe (Fraissler, Konrads, Hoberg, Rudert, & Walcher, 2016). In this three-dimensional forefoot deformity, the first toe is deviated laterally and the first metatarsal medially. Typically, the first toe is also rotated into a pronated position along its longitudinal axis (Coughlin, 1996). The term “hallux valgus” was first mentioned in the literature by Carl Hueter in 1870 (Easley & Trnka, 2007a). HV is a progressive subluxation of the first metatarsophalangeal joint (1 MTPJ) (Coughlin, 1996). The wearing of high-heeled shoewear is usually thought to cause the development of HV, but insufficient evidence supports unaccommodative shoewear as the sole factor in the development of HV (Easley & Trnka, 2007a). Poor footwear, however, is important in accelerating the progression of HV. HV has been linked to functional disability, including pain, impaired gait patterns, poor balance, and falls in older adults (Nix, Smith, & Vincenzino, 2010).

HV leads to more than 200,000 surgeries every year among adults in the United States (Coughlin & Thomson, 1995). Consistently, the annual number of surgeries in Finland has been estimated at 78 operations per 100,000 persons (Torkki et al., 2001). Operative treatment has proven to be more efficient than conservative treatment with orthoses (Torkki et al., 2001), and over 130 operative techniques have been published for HV correction (Robinson & Limbers, 2005). All the generally known HV correction techniques include bunionectomy and/or distal soft-tissue procedures (Easley & Trnka, 2007b), but the rotational component of the deformity is commonly neglected. The eversion of the first metatarsal has been shown to increase sagittal stability of the first ray (Perez, Reber, & Christensen, 2008). Thus, the rotational component of the HV deformity should be addressed during correction.

HV has an impact on gait (Nix, Vincenzino, Collins, & Smith, 2013), as the HV deformity alters the kinematics of the first ray and reduces the plantar force generation of the first metatarsal and the hallux (Koller et al., 2014). Even a mild HV may disrupt the propulsion function of the foot (Cancelleri et al., 2008). Various loading patterns have been reported relating to HV (Nix et al., 2013), and the reduced dynamic stability of the first ray affects also the lower limb (Canseco et al., 2010). An internal rotation of the tibia compared to normal controls has been demonstrated in HV during the gait cycle (Canseco et al., 2010).

For these reasons, HV surgery should aim to restore the dynamic stability of the first ray (King & Toolan, 2014). None of the current HV techniques address the
flexibility of the deformity in patient selection or the eversion of the first metatarsal during correction. Potentially, the flexibility of the HV enables correction without surgery to the I MTPJ, if the development of the deformity is considered primarily a consequence of the first metatarsal malposition. Respectively, an eversion correction potentially increases the first ray dynamic loading capacity during propulsive phases of gait, as it mimics the PL function (Faber et al., 1999; Johnson & Christensen, 1999; Perez et al., 2008).

The purpose of this thesis is to increase the information concerning the treatment of HV. It describes the first HV correction technique in which the I MTPJ and surrounding soft tissue are left intact, in accordance with a three-dimensional correction of the first metatarsal that mimics the PL function. Additionally, a new patient selection method, based on the flexibility of the deformity, is presented. The mid-term follow-up results, the static radiological results, and the dynamic loading characteristics of the new operative technique are reported and compared to the widely used distal chevron osteotomy.
2 Review of the literature

2.1 Anatomy and normal biomechanics of the foot

The foot is a unique structure between the body and the ground, as it receives and transmits static and dynamic stresses that generate major compression and shearing forces during the bipodal gait (Biga, 2009; Valmassy, 1996). It has been estimated that an average person walks 10,000 steps per day, 1,000,000 steps per year, and over 185,000 kilometers during their lifetime. The foot has to withstand 3 to 4 times the body weight during running (Alazzawi, Sukeik, King, & Vemulapalli, 2017). The foot is protected from stress related injuries by its special architectural structure and function.

The average human foot has 28 bones (including two sesamoids) and 33 joints (Alazzawi et al., 2017; Ferner & Staubesand, 1982). The foot can be divided into three anatomical regions: hindfoot, midfoot, and forefoot. The hindfoot is composed of talus and calcaneus. The talonavicular and calcaneocuboidal joints form the Chopart joint line, which separates the midfoot and hindfoot. The forefoot consists of metatarsals and toes and is separated from the midfoot by the Lisfranc joint line, which is the line between the three cuneiforms and cuboidal bone and the bases of the five metatarsals (Fraissler et al., 2016; Hansen, 2000).

A major difference between the anatomy of the hand and the foot is the stability of the first ray (Hansen, 2000; Morton, 1924). The hand has a mobile first ray, which opposes the lesser rays to enable grasping, whereas the first ray in the foot is relatively stable and positioned parallel to the second metatarsal to better serve the requirements of bipodal gait (Hansen, 2000; Morton, 1924). In the forefoot region, five rays (consisting of metatarsals and cuneiform bones) can be divided into three functional columns: the medial (first ray), middle (second and third rays), and lateral (fourth and fifth rays) columns. The middle column is rigid due to strong bony and ligamentous attachments to the midfoot, with the second metatarsal base serving as the keystone. The lateral column is the most flexible. The medial column (first ray) has a dual nature as it is either flexible or stable depending on the different phases of the gait cycle (Hansen, 2000).

The foot has two main arches: the medial longitudinal and the transverse arch. These arches are not stationary, but their height is increased and decreased dynamically according to the different phases of the gait. The medial longitudinal arch is based on the stability of the hindfoot and the medial column (first ray). On
the lateral aspect of the foot, the arch is considerably lower (i.e., the mobile fifth metatarsal is almost entirely in contact with the ground). The medial longitudinal arch protects the neurovascular structures and tendons running medially in the foot. The base of the rigid second metatarsal is the keystone of the transverse arch, which is highest in the midfoot. The double-arched structure of the foot enables even loading distribution in the forefoot and provides a strong lever arm during the propulsive phase of the gait (Hansen, 2000).

The references for describing the direction of motion in the foot are the frontal, sagittal, and transverse planes. The sagittal plane divides the body into left and right halves, the frontal plane into front and rear halves, and the transverse plane into top and bottom halves (Valmassy, 1996). The motion at a joint around its imaginary axis is called an axis of the joint. An axis is a line located perpendicular to the direction of motion of a joint, or a joint complex, whereas the direction in which motion occurs is called the plane of motion. All the axes are not stationary, but may shift with motion, as in the knee or the I MTPJ (Ferner & Staubesand, 1982; Valmassy, 1996).

The motion in one joint affects the other joints in a kinetic chain. This dynamic interaction of the joints is based on the shape of the joint surfaces and the ligamentous attachments of the bones. The same muscle function may produce different kinds of interactions of the joints, depending on whether the foot is under loading. The motion produced in the foot or limb with non-weightbearing is called the open kinetic chain. When the foot or limb is loaded during motion, the interaction of the joints takes place in the closed kinetic chain (Valmassy, 1996).

The motion in the kinetic chain is initiated and guided by muscles and tendons, which, in the foot, are called intrinsic muscles. The plantar intrinsic muscles provide stability to the foot and allow flexion in the metatarsophalangeal joints (Hansen, 2000). The tendons that have muscle origin above the ankle joint are called extrinsic tendons. In the hindfoot, the axis of the talocrural joint and the axis of the talocalcaneonavicular and subtalar joint divide the foot according to provided motion into four quadrants (Ferner & Staubesand, 1982; Valmassy, 1996). These two motion axes can be used to classify the extrinsic tendons to plantarflexors or dorsiflexors (the talocrural joint axis located more perpendicularly relative to the foot) and supinators or pronators (the talocalcaneonavicular and subtalar joint axis located more longitudinally relative to the foot). The main plantarflexors of the foot are the gastrocnemius-soleus complex, tibialis posterior, flexor hallucis longus (FHL), flexor digitorum longus, and peroneus brevis and PL muscles. The main dorsiflexors of the foot are the tibialis anterior (TA), extensor hallucis longus,
extensor digitorum longus, and peroneus tertius muscles. The main supinators of
the normal foot are the gastrocnemius-soleus complex, tibialis posterior, FHL,
flexor digitorum longus muscles, and the TA muscle. The main pronators of the
foot are the peroneus brevis, extensor digitorum longus and peroneus tertius
muscles. The extensor hallucis longus is neutral or acts as a mild pronator in the
open kinetic chain, due to close routing next to the longitudinal axis of the foot.
The peroneus longus (PL) has a dual function: in the open kinetic chain, it works
as a pronator of the foot, but in the closed kinetic chain it acts like a supinator,
producing plantarflexion of the first metatarsal and increasing the medial
longitudinal arch. The plantarflexors and the supinators are initially stronger than
the dorsiflexors and the pronators (Perry & Burnfield, 2010; Root, Orien, & Weed,
1977).

2.1.1 Gait cycle

The anatomical properties, and thus the human gait, vary between individuals. The
complex, dynamic function of the foot can be evaluated with the help of the gait
cycle. This cycle consists of a pair of steps, also known as strides, starting when
the heel touches the ground and lasting until the next heel contact of the same limb.
The gait cycle can be divided into the stance phase (closed kinetic chain) and the
swing phase (open kinetic chain). The durations of the stance and swing phases are
normally 60% and 40% of the gait cycle, respectively. One gait cycle will last
approximately 1 second, so the stance phase will take 0.6 seconds (Perry &
Burnfield, 2010; Valmassy, 1996). The body weight is shifted to the opposite limb
during the double stance phase, when both feet are momentarily in contact with the
floor. According to the gait cycle progression, the tasks of the foot and limb are
weight acceptance, single limb support and swing limb advancement. The gait
cycle, or stride, includes eight functional phases, which all should be found in a
normal gait: initial contact, loading response, mid stance, terminal stance, pre-
swing, initial swing, mid swing, and terminal swing (Perry & Burnfield, 2010)
(Figure 1).
Fig. 1. Gait cycle, right foot: A initial contact, B loading response, C mid stance, D terminal stance, E pre-swing, F initial swing, G mid swing, H terminal swing.

Weight acceptance is the first task of stance and includes two functional phases: initial contact (duration 0 to 2%) and loading response (duration 2 to 12%). The body weight transfer from the opposite limb starts from initial contact. In the loading response, the objectives are shock absorption, weight-bearing stability during body weight transfer, and preservation of progression. During the loading response, the heel rocker function extends the ankle joint briefly and the extrinsic tendons of the anterior tibial compartment relax after slowing down foot plantarflexion. The knee flexes, and subtalar pronation enables the foot to land softly on the ground. The center of body mass is shifted medially in the forefoot with help of pronation. This period ends when the foot is flat and in contact with the floor, and the opposite limb is lifted for swing (Perry & Burnfield, 2010; Valmassy, 1996).

The second task of stance is single limb support, which includes two functional phases: mid stance (duration 12 to 31%) and terminal stance (duration 31 to 50%). The foot stays stationary when the limb advances over the foot by ankle dorsiflexion (ankle rocker). In addition to progression over the stationary foot, the limb and trunk stability should be maintained in the sagittal and frontal planes during single limb support. The subtalar pronation is shifted to supination with the help of knee extension and external rotation of the limb (Perry & Burnfield, 2010; Valmassy, 1996).
The swing limb advancement has four functional phases. The pre-swing (duration 50 to 62%) is the final phase of stance, where the second double stance interval takes place and the progression is accelerated. The knee flexes and the dorsiflexion of the toes completes the windlass mechanism tightening. The initial swing (duration 62 to 75%) is responsible for the foot clearance of the floor, which continues in the mid swing (duration 75 to 87%). In the terminal swing (duration 87 to 100%), the knee extension completes limb advancement. The foot is supinated by the tibialis anterior (TA) tendon and the foot is prepared for a new stance (Perry & Burnfield, 2010; Valmassy, 1996).

2.1.2 Upper ankle joint

The upper ankle joint (UAJ), also known as the talocrural joint, consists of the tibia, fibula, and talus. The tibia and fibula are stabilized at syndesmosis with the anterior and posterior tibiofibular ligaments and the interosseous ligament and membrane. On the lateral side, the talus is fixed to fibula with anterior and posterior talofibular ligaments. On the medial side, the deep, anterior, and posterior deltoid ligaments stabilize talus to tibia. The talus has no muscle or tendon attachments. The lack of muscle function and stable anatomic attachments to the tibio-fibular complex makes the talus functionally a leg bone, a hinge-like extension of the tibia and fibula with principle motion in the sagittal plane and some rotational motion in the transverse plane (Ferner & Staubeand, 1982; Valmassy, 1996).

The axis of UAJ is not stationary, but shifts during sagittal plane motion. The lateral trochlea of the talus has an arc of a true circle. However, the medial trochlear contour is complex: the anterior third (dorsiflexed position) has an arc of a smaller circle when compared to the posterior two thirds (the plantarflexed position), which has an arc of a large circle. An average UAJ axis is oblique from the transverse (8 degrees) and frontal planes (20 to 30 degrees out), an imaginary axis drawn via malleolar tips (Valmassy, 1996).

In the sagittal plane, plantarflexion of the talus is restricted by the anterior talofibular ligament and the posterior tubercle of the talus. Dorsiflexion is restricted by the posterior deltoid ligament and the gastrocnemius (or gastro-soleus complex) (Valmassy, 1996). In the UAJ, a plantarflexion of 30 degrees is possible and a dorsiflexion of 20 degrees (Ferner & Staubeand, 1982). In the gait, during the late mid stance, UAJ dorsiflexion over a neutral 90 degrees is needed for body advancement over the stationary foot on the ground (ankle rocker function) (Perry & Burnfield, 2010; Valmassy, 1996). If this requirement is not fulfilled,
compensatory motion of the adjacent joints, especially the subtalar joint pronation, will be used in a closed kinetic chain to enable body mass advancement over the planted foot (Valmassy, 1996). Compensatory subtalar pronation prevents the midfoot locking mechanism and shifts the body weight excessively to the first ray, which is functionally unstable due to prolonged subtalar pronation. This leads to compensatory forefoot varus in time (Valmassy, 1996). The current estimate is that approximately five degrees of passive UAJ dorsiflexion are needed for the asymptomatic foot when the knee is extended, as in mid stance (DiGiovanni et al., 2002).

### 2.1.3 Subtalar and Chopart joint

The joint between the talus and calcaneus is called the subtalar joint. In the closed kinetic chain, the subtalar joint enables rotational limb movements relative to the foot, while the UAJ is mostly responsible for producing sagittal plane motion and enabling body progression during ambulation. In locomotion, the average rotation of the lower leg is 19 degrees (range of 13 to 26 degrees). These rotational movements, transmitted by the subtalar joint, respond to closed kinetic chain foot positions (i.e., pronation and supination). The subtalar joint axis varies according to the individual’s anatomy. On average, the axis is oblique from the transverse plane at 42 degrees and from the sagittal plane at 16 degrees medially. Due to the position of the axis, the subtalar joint transmits an almost equal amount of rotation in the transverse and frontal planes. In the closed kinetic chain, the amount of limb rotation is equally transmitted to the mid- and forefoot, and vice versa. In the open kinetic chain, the average subtalar inversion from the neutral position is approximately 20 degrees and eversion is 10 degrees (Valmassy, 1996).

Chopart’s joint, also known as the midtarsal joint, consists of the combined articulations of the talonavicular and calcaneocuboid joints. The ligamentous structures restrict the pronation and supination at the Chopart’s joint. The Chopart’s joint forms a single functional unit with two motion axes: the longitudinal and the oblique. The longitudinal axis of the Chopart’s joint enables the midfoot to respond to frontal plane variations in the rearfoot position. This mechanism is needed for the forefoot to maintain contact to the ground during the closed kinetic chain function. Opposing positions of the forefoot and rearfoot are possible due to this separate function of the longitudinal axis from the oblique axis of the Chopart’s joint (Valmassy, 1996).
The oblique axis produces principle motions of dorsiflexion coupled with abduction, and plantarflexion coupled with adduction. The position of the oblique axis varies in the frontal plane according to the subtalar pronation or supination. In subtalar pronation, the oblique axis shifts closer to the transverse plane (the floor), enabling more sagittal plane motion. This is why the oblique axis has been called the “secondary ankle joint.” Limitation in UAJ passive dorsiflexion is often compensated at the oblique axis of the Chopart’s joint. During supination of the subtalar joint, the oblique axis is more vertical, thereby resisting sagittal plane motion of the forefoot and contributing to the stability of the foot as a rigid lever arm at the late mid stance (Valmassy, 1996).

2.1.4 Windlass mechanism

The plantar aponeurosis, originating from the calcaneus, has a strong distal attachment through the plantar pads to the base of proximal phalanges of the toes. The intrinsic muscles, the abductor hallucis and flexor hallucis brevis, aid the supination of the oblique axis of the Chopart’s joint during propulsion. At the heel rise, dorsiflexion of the toes pulls the plantar aponeurosis and the pads forward around the metatarsal heads (MTHs), bringing the calcaneus closer to the MTHs, and thereby raising the longitudinal arch (Hicks, 1954). The windlass function of the plantar aponeurosis is created by forward momentum of the body advancement and does not need any direct muscle contraction (Hicks, 1954; Valmassy, 1996). The radius of the first MTH is greater than the radiiuses of lesser MTHs (Ferner & Staubesand, 1982). For this reason, the windlass mechanism has a stronger effect on the first ray and medial longitudinal arch. The higher tension of the plantar aponeurosis on the medial side helps the rearfoot to supinate during propulsion (Hicks, 1954; Valmassy, 1996).

When standing, the plantar aponeurosis works as a tie between the calcaneus and the toes, forming a supportive base for the longitudinal arch of the foot (Hicks, 1954). At the heel rise, the plantar aponeurosis becomes tensed. An externally rotated limb in a closed kinetic chain, with a supinated rearfoot and pronated forefoot, produces relaxation of the plantar aponeurosis and enables the toe dorsiflexion. Conversely, an internally rotated limb with a pronated rearfoot and supinated forefoot increases tension on the plantar aponeurosis and markedly limits the dorsiflexion of the toes (Hicks, 1954; Valmassy, 1996).
2.1.5 First ray

The first ray consists of the first metatarsal and the medial cuneiform, tightly bound together by ligaments. Functionally, these two bones are considered into a single unit. The first ray has an important role as it responds to varying positions of the hindfoot during the stance phase to maintain the forefoot contact plantigrade (Hicks, 1953; Valmassy, 1996). During early heel rise, the first ray carries 29% of the body weight in the normal foot (Jacob, 2001). The motion of the first ray is uniaxial and triplanar, without pronation and supination (Valmassy, 1996). The triplanar motion is due to the first ray axis, which deviates approximately 45 degrees from sagittal and frontal planes, with mild deviation from the transverse plane (Hicks, 1953). Dorsiflexion is coupled with inversion and adduction in pronation, and plantarflexion with eversion and abduction in supination, relative to the midline of the body (Hicks, 1953). The extrinsic tendons attached to the first ray are the TA and PL tendons, producing inversion, adduction, and dorsiflexion and eversion, abduction, and plantarflexion, respectively (Ferner & Staubesand, 1982; Valmassy, 1996).

Plantarflexion of the first ray of 10 degrees is required for sufficient I MTPJ dorsiflexion during mid stance and propulsion. The sufficient dorsiflexion of the metatarsophalangeal joint is needed for effective windlass mechanism during propulsion. Supination of the subtalar joint and a stable Chopart’s joint enable plantarflexion of the first ray. The hindfoot supination increases the transverse arch in the midfoot, providing an efficient fulcrum to the PL pull (Root et al., 1977; Valmassy, 1996). The PL everts the first metatarsal base under the rigid second metatarsal, providing sagittal stability. This mechanism is known as the forefoot locking mechanism (Johnson & Christensen, 1999; Perez et al., 2008). The first MTH is also stabilized against the ground, specifically against sesamoid bones, by the PL. The intrinsic muscles, especially abductor hallucis, produce active metatarsal plantarflexion, in addition to the PL and the windlass mechanism (Hicks, 1954; Valmassy, 1996).

If the first ray is considered as an isolated functional unit, the frontal plane motions are dorsiflexion coupled with inversion, and plantarflexion coupled with eversion (Hicks, 1953). In practice, when the whole foot is considered as a functional unit during forefoot eversion, inversion of the first ray, relative to lesser metatarsals, is hidden within the eversion of the whole foot. The net eversion of the foot is greater during the hindfoot pronation than during the inversion of the first ray, leading to an everted position of the first ray relative to the ground. However,
the amount of frontal plane eversion of the first ray is less than the eversion of the lesser metatarsals. This is due to the local inversion of the first ray. In summary, when the hindfoot is everted, the first ray is inverted relative to the rest of the foot, and vice versa (Hicks, 1954; Valmassy, 1996).

2.1.6 First metatarsophalangeal joint

The I MTPJ is composed of the articulations of the four bones within the single synovial joint capsule: the first MTH, the base of the proximal phalanx, and the medial and lateral sesamoid bones (Haines & McDougall, 1954). Motions in the I MTPJ are mechanically possible in the sagittal and transverse planes. The two distinct axes of this joint are the transverse and the vertical axis. Rotational motions are not possible without damaging forces to the joint, due to the condylar structure of the metatarsophalangeal joint articulations. The average passive dorsiflexion varies between 70 to 90 degrees. During a gait, 50 to 60 degrees of dorsiflexion is needed. The transverse axis shifts during sagittal plane motion: when the dorsiflexion increases, the transverse axis shifts dorsally and proximally within the first MTH. Three components of motion can be separated during the I MTPJ dorsiflexion: rolling motion; sliding motion, associated with the first ray plantarflexion; and compression at the end of motion. The dorsiflexion of the first ray (metatarsus elevatus) has been associated with a decrease in the sliding component and jamming of the I MTPJ during dorsiflexion (Valmassy, 1996).

The function of the I MTPJ has been described as a “dynamic acetabulum.” The anatomy of this joint is a concentration of soft-tissue attachments to the proximal phalanx. The first MTH is placed into this concave, soft-tissue surrounded cup. The tendon attachments and their function provide medial and lateral support to the joint to supplement that provided by the ligamentous structures (Perera, Mason, & Stephens, 2011; Valmassy, 1996). The proximal phalanx of the hallux is anchored to the foot with the FHL, the adductor hallucis oblique and transverse, and the flexor hallucis brevis with the sesamoid bones (Ferner & Staubesand, 1982). The abductor hallucis and the flexor hallucis brevis provide medial stability to the joint during propulsion (Valmassy, 1996). Normal function of the hallux requires three factors: stability and plantarflexion of the first ray, normal sesamoid function, and normal function of the stabilizing muscles of the I MTPJ (Root et al., 1977).

In the gait cycle, the I MTPJ is actively dorsiflexed, mainly by the extensor hallucis longus, during the terminal swing. This dorsiflexion continues until the ball under the first MTH contacts the ground. The toes relax during the loading response.
During the heel lift, the I MTPJ undergoes passive dorsiflexion (forefoot rocker). The toes are forced dorsally by the weight of the body advancement. The sesamoids and the first MTH combine to form a pulley for the FHL and brevis, and the plantar aponeurosis. The windlass effect tightens the plantar soft-tissue structures and increases the medial longitudinal arch during terminal stance and pre-swing. The hallux maintains the dorsiflexed position for the longest time, as the body weight rolls over the first ray. At the initial swing after toe-off, the metatarsophalangeal joints plantarflex, but they stay in a slightly dorsiflexed position to avoid contact with the ground during the swing phase of the limb. The extensor activity increases towards the terminal swing, to prepare the foot for the next gait cycle (Valmassy, 1996).

2.2 Pathoetiology and development of hallux valgus

The pathoetiology of HV is multifactorial. No single etiologic factor can solely explain the initiation and development of HV deformity (Easley & Trnka, 2007a; Perera et al., 2011). The generally accepted explanation is that HV develops gradually, on a background of several predisposing intrinsic and/or extrinsic factors. The failure of the medially supporting structures—the medial collateral ligament and medial sesamoid bone—is the initial mechanism needed for the development of HV. This enables the first MTH to drift medially and finally off the sesamoids. An unstable first tarsometatarsal joint encourages this process. The hallux is forced into a valgus, as it is anchored from its base to the sesamoids and rest of the foot with the flexor hallucis brevis, the deep transverse ligament, and the adductor hallucis. As the MTH drifts on the medial sesamoid, the malposition may wear out the cartilage and the plantar metatarsal crista. Footwear may cause friction to the medial bursa, and the thickening of the soft tissue increases the medial eminence, commonly known as a bunion. The bowstring effect of the extensor and the FHL tendons increases the valgus moment arm affecting the hallux. The abductor hallucis becomes dysfunctional, as it is shifted from the medial position downwards. The hallux is pulled into a pronated position by the adductor hallucis. The first metatarsal becomes increasingly unstable due to subluxation off the sesamoids, and it typically follows the first toe pronation forces. The instability of the first ray may transfer loading to the lesser metatarsals, and the mobile fifth metatarsal may also splay (Perera et al., 2011).

The progression of HV may wear out the joint surfaces (Haines & McDougall, 1954; Easley & Trnka, 2007a; Root et al., 1977). The flexibility of the HV
deformity is scarcely reported in the literature; the fixed HV deformity refers to the
degenerative changes in the joint (Easley & Trnka, 2007a). Generally, the flexibility
of the deformity is considered as a non-arthritic, reducible condition of the affected
joints (e.g., in the case of flexible flatfoot deformity); thus, the flexibility has an
impact on the available treatment protocols (Faldini et al., 2016). The idea that the
flexibility of the HV deformity would be the determining factor for the use of a
specific operating method has not been presented in the literature.

2.2.1 Epidemiology of hallux valgus

The prevalence of HV is higher among women. In the general population, the
prevalence of HV in females (30%) is 2.3 times higher than the estimate for males
(13%) (Nix et al. 2010). The sex ratio is 15:1 among the patients undergoing
corrective surgery for HV (Perera et al., 2011). Aging also increases the changes in
joint kinematics and plantar pressure, and the peak onset of HV is between 30 to
60 years. These factors all potentially increase the risk of HV. Nevertheless, the
initial changes leading to the development of HV start much earlier, even in
adolescence or childhood (Perera et al., 2011).

2.2.2 Genetic factors

Genetic factors have long been suspected to predispose persons to HV. Some
inheritable anatomic features may be relevant to HV; for example, the underlying
foot type and the hypermobility of the joints (Perera et al., 2011). In juvenile HV,
maternal transmission has been found in 94% of patients with a family history
(Coughlin & Jones, 2007a). A slight racial difference between whites and black
Africans has been found, with whites having a two times higher prevalence of HV
(Perera et al., 2011).

2.2.3 Footwear

The use of footwear has been shown to increase the prevalence of HV (Sim-Fook
& Hodgson, 1958). However, no clear evidence explains why the long-term use of
high-heeled shoes fails to cause HV in a significant number of people (Perera et al.,
2011). Indeed, HV has also been reported among non-shoe wearing populations
(Inman, 1974; Perera et al., 2011; Sim-Fook & Hodgson, 1958). Therefore,
footwear is not the sole factor in the development of HV (Inman, 1974). High-
heeled footwear increases forefoot loading and it therefore may be viewed as a contributing factor to HV as it increases the pronating forces to the hallux when the forefoot slides forward in the toe box (Perera et al., 2011).

### 2.2.4 Biomechanical factors

The biomechanics of the first ray is important in the pathoetiology and development of HV. No tendon attachments occur distally in the first metatarsal, and a stable and congruent metatarsophalangeal joint is required during propulsion. Due to the condylar structure of the metatarsophalangeal joint articulations, the joint reaction force of the metatarsosesamoid joint is normally sufficient to prevent subluxation of the sesamoids. The unloading of the metatarsosesamoid joint is required for the subluxation, and this may occur by elevation of the MTH or by the laterally loaded body weight (Perera et al., 2011).

The TA inverts the first ray, supinates the longitudinal axis of the Chopart’s joint, and increases the subtalar pronation. The TA should relax during the loading response. If the TA activation is prolonged to the mid stance, the lateral loading of the foot is increased due to the forefoot supination. The first ray plantarflexion is prevented (elevated first MTH) and the metatarsosesamoid loading is lost (Haines & McDougall, 1954; Valmassy, 1996). The inversion of the first ray opens the forefoot locking mechanism and increases the sagittal plane motion of the first ray (Perez et al., 2008). One third of the population chooses to supinate the forefoot during gait, and these persons are at the greatest risk for HV (Perera et al., 2011).

Reduced UAJ dorsiflexion and less hindfoot supination during the terminal stance have been reported in individuals with HV (Nix et al. 2013). Lifestyle factors (e.g., sleeping, sitting, walking, and sports activities) have been proposed as etiological factors creating the non-neurological, acquired muscular ankle equinus (AE) (Hill, 1995). This AE is a powerful destabilizer of the forefoot and a direct antagonist to the PL function in mid stance (Bierman, Christensen, & Johnson, 2001). The limitation of passive dorsiflexion at the UAJ is potentially compensated at the subtalar and the Chopart’s joint, causing excessive or prolonged pronation of the foot during mid stance (Hill, 1995; Valmassy, 1996). The AE, caused by the gastrocnemius or gastro-soleus complex, is one etiologic factor for limitation of passive UAJ dorsiflexion during mid stance (DiGiovanni et al., 2002, Hill 1995). The AE prevents the ankle rocker function and potentially increases the compensatory pronation of the foot (DiGiovanni et al., 2002; Hill, 1995), as well as increasing the hindfoot valgus moment arm in the pronated foot (Arangio,
Rogman, & Reid, 2009). The pronation of the foot produces a longitudinal rotation of the first ray in the closed kinetic chain, which alters the transverse axis of the I MTPJ in an oblique position relative to the floor (Inman, 1974). The deforming rotational forces may be increased by the shoe or by weight bearing (Inman, 1974), and the medial supporting structures of the I MTPJ ultimately fail.

In the closed kinetic chain, both the excessive hindfoot pronation and the forefoot supination disturb the PL function and the plantarfexion of the first ray (Valmassy, 1996). The windlass mechanism, including the plantar aponeurosis, is tightened, leading to the plantarfexor moment to the first proximal phalanx (Perera et al., 2011; Valmassy, 1996). Thus, the I MTPJ dorsiflexion is functionally restricted (functional hallux limitus) during the heel rise, and the compressive forces within the I MTPJ push the hallux laterally in the direction of least resistance (Perera et al., 2011).

In HV, frontal plane motion occurs in the first proximal phalanx and the medial stabilizing structures are shifted plantarward, so the hallux rotates into a pronated valgus position (Perera et al., 2011; Valmassy, 1996). The first MTH is able to shift medially due to the lack of medial stability at the I MTPJ (Perera et al., 2011; Valmassy, 1996). The FHL acts like a bowstring and predisposes the foot to the progression of HV (Faber et al., 1999; Lamur, Huson, Snijders, & Stoeckart, 1996; Perera et al., 2011). In HV, once the MTH starts to medialize, the initially stabilizing muscle attachments of the I MTPJ may become deforming forces (Perera et al., 2011).

When the HV deformity progresses, the crest under the first MTH degenerates and the condylar structure of the metatarsosesamoid joints disappears (Haines & McDougall, 1954; Root et al., 1977). Further progression of the deformity is enabled by this metatarsal joint plantar surface degeneration. The sesamoids continue shifting laterally, relative to the first ray (Haines & McDougall, 1954; Root et al., 1977). In HV, the stiffness of the deformity refers to the degenerative changes in the metatarsophalangeal joint (Easley & Trnka, 2007a).

In most cases, the tendon forces affecting the first ray and the net pronation of the foot drive the unstable first metatarsal into an everted position relative to the floor (Dayton, Feilmeier, Kauwe, & Hirshci, 2013; Oldenbrook & Smith, 1979; Perera et al., 2011; Scranton & Rutkowski, 1980; Valmassy, 1996). The tendon-pull of the hallux (e.g., the FHL) and the metatarsosesamoid ligaments (the so-called “drive-belt” effect) have been suggested as the root cause for the first metatarsal eversion seen in HV (Mortier, Bernard, & Maistro, 2012). However,
some controversy still exists; for example, Eustace et al. (1993) reported a minority of HV patients showed no first MTH eversion. A study by Mortier et al. (2012) showed that the sesamoids can evert without eversion of the first MTH. A weightbearing CT scan study showed that inversion of the first metatarsal occurs in HV, while healthy controls show a slight eversion in the mean position of the first MTH (Collan, Kankare, & Mattila, 2013). The position of the first metatarsal relative to the ground may also be affected by metatarsal torsion (Mortier et al., 2012). In HV, even if the first MTH can be either in an everted or inverted position relative to the ground, the first metatarsal is consistently in an inverted position relative to the sesamoids (Collan et al., 2013; Dayton et al., 2013; Eustace, O’Byrne, & Stack, 1993; Mortier et al., 2012; Oldenbrook & Smith, 1979; Perera et al., 2011; Scranton & Rutkowski, 1980; Valmassy, 1996).

2.2.5 Other factors

The rarer etiological factors of HV include trauma, inflammatory joint diseases, and any neurological conditions (i.e., cerebral palsy or Parkinson’s disease) affecting the foot and gait (Hansen, 2000).

2.3 Clinical examination of the hallux valgus patient

The clinical examination of a HV patient is a systematic inventory of patient history, symptoms and signs, and the clinical findings. The functional complexity of the foot and the uniformity of the patients’ symptoms necessitate a systematic physical examination, including inspection of the gait. The other investigations, if used as first line procedures without clinical context and understanding the significance of the findings, are usually unsuccessful. Despite possible other investigations, the physical examination always precedes treatment protocols (Biga, 2009).

In addition to systemic conditions, symptoms, and their duration, information about the use of nicotine products should be collected. Smokers have a 4.3 times higher risk for the complications, compared to nonsmokers, after forefoot surgery (Bettin et al., 2015). A HV patient typically complains about pain at the medial eminence or with the metatarsophalangeal joint motion, and the shoe problems (Easley & Trnka, 2007a).

During the clinical examination, the patient is barefoot. The pulses of the foot should be palpated. If the patient has a history of circulatory diseases, diabetes, or smoking, this is essential. The severity of HV and of possible pes planus is assessed.
while the patient is weightbearing (Easley & Trnka, 2007a). HV has been associated with a decreased balance range and functional ability in older people (Menz, Morris, & Lord, 2005), as the toe flexor activity may play an important role in balance maintenance (Menz et al., 2005). Thus, the toe flexor activity and digitus malleus deformities should be noted in quiet standing, as this may reflect a compensatory function of the foot to the decreased balance maintenance. The tibialis posterior function is evaluated with the single leg heel rise test (Biga, 2009).

In the gait cycle, prolonged activity of the TA is noted after the loading response; indeed, prolonged activity of the TA is a common finding among HV patients (Perera et al., 2011; Valmassy, 1996). The TA produces forefoot supination, lateral loading of the foot, and prevents normal PL function in mid stance. The extensors of the toes should also relax during the loading response. In mid stance, the foot pronation is registered. The pronatory motion (foot flat with a medial prominence) in the midfoot may reflect compensatory subtalar and Chopart’s joint dorsiflexion due to functional limitation of the dorsiflexion in the UAJ. Metatarsalgia and subtalar pain symptoms correspond with this finding. During late mid stance, the toe flexor activity is registered. Normally, the PL should plantarflex the first ray just before the heel rise. The early FHL initiation potentially elevates the first ray, thereby preventing normal dorsiflexion of the I MTPJ (Valmassy, 1996).

The passive dorsiflexion of the UAJ dorsiflexion is tested according to the principles presented by Silfverskiold (1924), with knee extended (gastrocnemius) and flexed (soleus). The foot arches are stabilized to the neutral position by the examiner and the patient does not actively help the dorsiflexion during examination (Biga, 2009; Hansen, 2000). The anterior muscles must be silent during the examination to ensure registration of the relevant gastrocnemius-soleus complex resting tone that is limiting the dorsiflexion (Biga, 2009). According to Hill (1995), less than 10 degrees of passive ankle dorsiflexion over the neutral 90 degrees foot–leg position is interpreted as a limitation of passive UAJ dorsiflexion, when examined with the knee straightened. DiGiovanni et al. (2002) proposed less than 5 degrees dorsiflexion to be clinically relevant gastrocnemius tightness with the foot patients, compared to a control group with a mean of 13 degrees passive dorsiflexion. The gastrocnemius tightness becomes more important in HV if a calcaneal eversion position is also noted (Arangio et al., 2009; Valmassy, 1996). The gastrocnemius equinus, combined with calcaneal eversion, increases compensatory subtalar pronation and prevents the midfoot locking mechanism, so
the first ray stabilization fails. The body weight is excessively shifted to the unstable medial column during the late stance phase (Valmassy, 1996).

The stability of the first ray is difficult to assess in clinical practice, due to the variable foot types and soft-tissue elasticity. The callosity of the second metatarsal refers to the insufficient loading capacity of the first ray. In addition to the sagittal plane instability, the transverse plane instability of the first ray (metatarsus primus varus) should be considered, as it reflects the rotational instability (Easley & Trnka, 2007a). The skin indicates excessive local pressure with callosities of the metatarsals in the plantar forefoot region (Spink, Menz, & Lord, 2009). Normally, the loading distribution is even across the two sesamoids of the first MTH and the four lesser MTHs during stance, and callosities do not exist in the normally functioning foot (Hansen, 2000; Morton, 1937). The localization of a callosity may confirm the result of gait evaluation. The physical examination should also include lesser ray evaluation; for example, metatarsalgia, toe deformities, or MTH overload symptoms, which are all often associated with HV (Easley & Trnka, 2007a).

The limitation in motion of the 1 MTPJ refers to degenerative changes in the joint. The possible osteoarthritic changes of the joint should be considered when the treatment of HV is planned (Easley & Trnka, 2007a). In theory, based on the biomechanical studies, a flexible HV deformity should be reducible by PL activation (Johnson & Christensen, 1999; Perez et al., 2008; Root et al., 1977; Valmassy, 1996). Nevertheless, weightbearing flexibility testing of HV deformity has not yet been presented in the literature.

### 2.4 Radiological evaluation of hallux valgus

The radiological evaluation of HV includes weightbearing radiographs with a lateral and a dorso-plantar projection (Easley & Trnka, 2007a). The hallux valgus angle (HVA, the angle between the longitudinal axes of the first metatarsal bone and proximal phalanx of the first toe) and IMA 1-2 (the angle between the longitudinal axes of the first and second metatarsal bones) are measured from the dorso-plantar image (Coughlin, Saltzman, & Nunley, 2002) (Figure 2).
Fig. 2. Hallux valgus angle and intermetatarsal angle 1-2.

The normal values for the HVA and IMA 1-2 are <15 degrees and <10 degrees, respectively. HV can be classified as mild (from 15 to less than 20 degrees), moderate (from 20 to less than 40 degrees), and severe (40 degrees or more), according to the HVA (Mann & Coughlin, 1999). The tibial sesamoid position relative to the first metatarsal bisector can also be evaluated from a dorso-plantar projection with LaPorta classification, ranging from normal 1 to most laterally shifted 7 (LaPorta, 1974) (Figure 3).
Fig. 3. LaPorta classification from 1 to 7. In LaPorta classification, hallux valgus is classified according to the medial sesamoid position, relative to the first metatarsal bisector. Position “1” is the normal. In this case, hallux valgus was classified as LaPorta 7.
Calcaneal pitch angle (the angle between the inferior surface of calcaneus and the line through the plantar surface of the sesamoids and the inferior calcaneus) and Meary’s angle (the angle between the longitudinal axes of the talus and the first metatarsal bone) are measured from lateral weightbearing radiographs (Coughlin & Jones, 2007a) (Figure 4).

![Fig. 4. Calcaneal pitch angle and Meary’s angle.](image)

The distal metatarsal articular angle (DMAA, the angle between the articular surface and the first metatarsal bisector) has often been used to evaluate the axial orientation of the first metatarsal distal joint surface in HV, even if it has been shown to have poor reproducibility (Chi, Davitt, Younger, Holt, & Sangeorzan, 2002; Coughlin & Freund, 2001; Lee et al., 2012; Robinson et al., 2006). Lee, Ahn, Chung, Sung, and Park (2012) suggested that increased DMAA is not a true deformity in dorso-plantar radiography, but a secondary projection of a rotational component of the first metatarsal malposition. Controversially, Pentikäinen, Piippo, Ohtonen, Junila, and Leppilahti (2015) reported excellent DMAA reliability for the radiologist (ICC 0.98), but only fair for the orthopedic surgeon (ICC 0.49).

### 2.5 Hallux valgus and gait

HV has an impact on gait (Canseco et al. 2010; Nix et al. 2013), and variable loading patterns have been reported (Nix et al. 2013). Due to HV, the first ray sagittal plane stability is compromised and load transfer occurs to the lesser toe MTHs, predisposing the patient to lesser toe metatarsalgia (Koller et al., 2014).

In the normal stance phase, the TA relaxes and the foot descends flat to the ground (heel rocker) and the subtalar joint pronates during the loading response (Perry & Burnfield, 2010; Valmassy, 1996). The foot becomes flexible, to enable adaptation to the ground and shock absorption. The body weight is shifted from the lateral calcaneus anteromedially to the forefoot. The knee straightens during mid
stance, producing external rotation to the subtalar joint, and the supination begins. Simultaneously, the body advancement occurs by UAJ passive dorsiflexion (ankle rocker). The subtalar supination stabilizes the Chopart’s joint, as the talar head moves laterally with the continuing external rotation of the limb during mid stance. The first ray plantarflexes and everts due to hindfoot supination. The tibialis posterior and PL activate in the late mid stance, locking the forefoot and further stabilizing the transverse and medial longitudinal arches of the foot. The gastrocnemius-soleus complex activates due to the muscle stretch produced by limb advancement over the stationary foot, and the heel lift occurs (forefoot rocker) (Valmassy, 1996). At this acceleration phase of the gait, 29% of the body weight is carried under the first MTH (Jacob, 2001). The metatarsophalangeal joints dorsiflex passively during propulsion. The UAJ plantarflexes and the windlass mechanism tightens, bringing the first MTH closer to the calcaneus. Just before toe-off, the foot is longitudinally twisted so that the hindfoot is in a supinated and the forefoot is in a pronated position. In this way, the foot functionally changes to a rigid lever arm (Valmassy, 1996).

Instability of the first ray is increased in HV (Perera et al., 2011), and the loading of the body weight on the forefoot is shifted laterally (Nix et al., 2013). Even a mild HV alters the gait to an apropulsive pattern, and central metatarsal loading is increased (Cancilleri et al., 2008). The windlass mechanism is functionally disrupted, and the first ray is unable to carry loading properly during the terminal stance and propulsion (Perera et al., 2011; Valmassy, 1996).

2.6 Operative treatment of hallux valgus

The operative treatment of HV is indicated when conservative treatment fails to relieve the pain in the I MTPJ (Easley & Trnka, 2007b). More than 130 different HV procedures have been described (Robinson & Limbers, 2005). The operative procedures can be divided to distal, midshaft, and proximal metatarsal osteotomies, arthrodesis, resection arthroplasty, and adjunctive soft-tissue procedures. Reasonable clinical outcomes for different types of procedures have been reported (Coetzee & Wickum, 2004; Deenik et al., 2008; Robinson, Bhatia, Eaton & Bishop, 2009; Torkki et al., 2001). The operative technique is chosen according to the severity of the HV deformity: a more proximal procedure is recommended for a more severe deformity (Easley & Trnka, 2007b).
2.6.1 First metatarsal osteotomies

The principle idea of all metatarsal osteotomies is to shift the first MTH laterally over the sesamoids, in addition to performing bony resection of the medial eminence of the distal first metatarsal in combination with medial capsular tightening. Distal metatarsal osteotomies are generally indicated for the treatment of mild-to-moderate HV deformities. The widely used distal metatarsal osteotomies are distal chevron osteotomy, also known as the Austin osteotomy (Austin and Leventen, 1981; Johnson, Cofield, & Morrey, 1979), Mitchell osteotomy (Robinson & Limbers, 2005), and Hohmann procedure (Faber et al., 2013).

The distal chevron procedure is indicated for mild-to-moderate deformities, but it has also been used for correction of severe deformities (Pentikäinen, Ojala, Ohtonen, Piippo, & Leppilahti, 2012). After the capsulotomy and the bony bunionectomy, a V-shape saw cut is made to the distal metatarsal. The purpose of this V-shape (chevron) osteotomy is to narrow the forefoot by shifting the prominent distal MTH laterally in the transverse plane (Figure 5). According to anatomical study, a 5 to 6 mm lateral shift is possible, while still maintaining greater than 50% apposition of the bony fragments (Easley & Trnka 2007b). The shifted distal fragment may be fixed to a new position with a bioabsorbable rod or screw, but fixation is not necessary if the saw cut is stable (Pentikäinen et al., 2012). Recovery from the operation takes time, and pain may exist for several months postoperatively. According to Torkki (2004), 54 of 71 (76%) distal chevron treated patients reported pain in their operated feet for the past six months at the one-year follow-up. Still, this result was better when compared with the conservatively treated and the non-treated groups (Torkki, 2004). The advantage of the distal chevron osteotomy is that it involves minimal shortening of the first metatarsal (Bucioito, 2014).
The Mitchell osteotomy differs from the distal chevron osteotomy as it uses a double saw cut, leaving a step in the lateral cortex of the distal fragment. The purpose of this step is to stabilize the shifted MTH in its new position. When compared to the distal chevron, a comparable amount of correction was achieved for mild-to-moderate HV (Bucioto, 2014). However, in the Mitchell group, the rate of transfer metatarsalgia and symptomatic hammertoe were significantly higher due to shortening of the first metatarsal relative to the second metatarsal (Bucioto, 2014).

The Hohmann procedure is a medially closing distal metatarsal osteotomy, in which the distal fragment is displaced a few millimeters laterally and transfixed to the metatarsal shaft with a single percutaneous Kirschner wire (Grace, Hughes, & Klenerman, 1988). Although the worrisome long-term radiographic results have
been reported after the Hohmann procedure (Grace et al., 1988), Faber et al. (2013) reported good long-term results with the Hohmann procedure in comparison to the Lapidus procedure.

Midshaft osteotomies are indicated for moderate-to-severe HV. The Scarf osteotomy is a widely used midshaft osteotomy, with a complex Z-shape osteotomy technique (Easley & Trnka, 2007b). An equivalent correction in Scarf and distal chevron osteotomy has been reported, with a higher complication rate in the Scarf (Deenik et al., 2008). An oblique Ludloff osteotomy can be extended to the distal metatarsal, just proximal to the sesamoid complex. This modification of the proximal Ludloff osteotomy can be used for plantarization and rotational correction of a three-dimensional HV deformity (Easley & Trnka, 2007b).

Proximal metatarsal osteotomies are indicated for moderate to severe HV. They can be divided into closing wedge, opening wedge, and crescentic osteotomies. In HV, the frontal plane correction is generally neglected in the osteotomy techniques, but Okuda, Jotoku, and Shima (2013) described a proximal osteotomy technique with abduction-supination correction of the first metatarsal in adolescent HV patients. The closing wedge osteotomies have not gained general acceptance due to the risk of shortening and elevation of the first metatarsal. The complications of proximal closing wedge osteotomies include nonunion, dorsiflexion malunion, first metatarsal shortening, transfer metatarsalgia, and hallux varus (Easley & Trnka, 2007b). The proximal crescentic osteotomy includes a risk of dorsal malunion of 17 to 28%, depending on the study (Easley & Trnka, 2007b). The popularity of proximal opening wedge osteotomies has increased with the use of fixed angle plates, and the initial follow-up results seem satisfactory (Badekas, Georgiannos, Lampridis, & Bisbinas, 2013).

### 2.6.2 Resection arthroplasty and simple bunionectomy

The resection arthroplasty of the 1 MTPJ, generally known as the Brandes-Keller procedure, was originally described by Keller and Brandes (Vienne et al., 2006). Since its introduction in the beginning of last century, resection arthroplasty has gained popularity as a HV correction method (Vienne et al., 2006). In the Brandes-Keller procedure, one-third to one-half to two-thirds resection of the proximal part of the proximal phalanx has been recommended (Coughlin and Mann, 1987). Although good early results of the Brandes-Keller procedure have been reported, distal chevron osteotomy has been shown to produce better HVA, IMA, 1 MTPJ motion, and MTH position over the sesamoid complex (Easley & Trnka, 2007b).
The acceptable initial results of resection arthroplasty have been explained by ancillary procedures related to the surgery (Easley & Trnka, 2007b). The reported complications of the resection arthroplasty include recurrent HV, pain at the I MTPJ, excessive shortening of the hallux, development of lateral metatarsalgia, cock-up deformities, flail toe, first ray instability, and decreased capacity for weight bearing due to dramatically altered anatomical joint configuration (Coughlin & Mann, 1987; Vienne et al., 2006). The recommended procedure for failed Brandes-Keller is I MTPJ arthrodesis (Coughlin & Mann, 1987; Vienne et al., 2006). The correction of failed Brandes-Keller may be demanding, due to the often-needed bone autograft (Vienne et al., 2006). Thus, resection arthroplasty is reserved for elderly patients with low functional capacity, who may be at risk if corrective surgery is conducted (Easley & Trnka, 2007b).

Simple bunionectomy, in which only the medial eminence of the first MTH is excised, is currently not a common procedure. No recommendation can be made for the use of medial eminence resection in HV correction (Easley & Trnka 2007b).

2.6.3 Distal soft-tissue procedures

Distal soft-tissue procedures are commonly an adjunct in HV corrective procedures. The McBride procedure, based on the Silver bunionectomy procedure, is an isolated distal soft-tissue procedure for HV correction (Easley & Trnka, 2007b). The preservation of the lateral sesamoid bone was emphasized in the McBride modification due to the risk of hallux varus related to the original McBride procedure. In addition to resection of the medial eminence, the modified McBride includes lateral capsular release, adductor hallucis release, and the release of sesamoid ligaments, as well as medial capsular plication with controlled varus stress to the I MTPJ (Fraissler et al., 2016). Isolated use of the McBride procedure in HV correction is not recommended (Easley & Trnka, 2007b).

2.6.4 Lapidus and first metatarsophalangeal joint arthrodesis

In 1934, Paul W. Lapidus described first tarsometatarsal joint arthrodesis combined with the fusion of the bases of the first and second metatarsals and intercuneiform joint, bony exostectomy, soft tissue release, and repair of distal metatarsophalangeal joint (Lapidus, 1934). He emphasized the correction of primus metatarsus varus, rather than the rotational correction of first metatarsal (Lapidus, 1934). Several modifications of the original procedure have since been introduced
(Lapidus, 1956; Lapidus, 1960; Manoli & Hansen, 1990; Mauldin, Sanders, & Whitmer, 1990; Sangeorzan & Hansen, 1989). DiDomenico, Fahim, Rollandini, & Thomas (2014) reported a closed I MTPJ modification of the Lapidus procedure that included frontal plane rotational correction of the sesamoids. The technical description also demonstrated fixation between the first and second metatarsals (DiDomenico et al., 2014). Synostosis of the first and second metatarsals was originally described by Lapidus (1934). The Lapidus procedure is indicated for moderate to severe HV, for the treatment of the hypermobility of the first ray, for salvage of recurrent HV, and for adolescent HV (Clark, Veith, & Hansen, 1987; Coetzee, Resig, Kuskowski, & Saleh, 2004; Easley & Trnka, 2007b). Nonunion rates of 4 to 12% have been reported (Easley & Trnka, 2007b).

I MTPJ arthrodesis can be used for the correction of HV in a wide spectrum of patients. It is recommended for correction of severe and/or arthritic HV and for neurologic HV (Easley & Trnka, 2007b). It is also indicated for the treatment of failed HV due to prior surgery (Coughlin & Mann, 1987; Easley & Trnka, 2007b; Vienne et al., 2006). The I MTPJ arthrodesis produces good long-term results. The use of conventional shoewear is possible after arthrodesis, despite the stiff metatarsophalangeal joint (Easley & Trnka, 2007b).

### 2.6.5 Additional procedures

A closing-wedge osteotomy of the first proximal phalanx is called the Akin osteotomy. This osteotomy may be used as an adjunct to other HV surgery, to achieve a better alignment of the hallux relative to the first metatarsal. HV interphalangeus over 10 degrees is an indication for the Akin osteotomy (Fraissler et al., 2016).

A bunionectomy is commonly performed as part of the HV correction. In many techniques, such as metatarsal osteotomies and the McBride procedure, a bunionectomy is described as part of the procedure (Easley & Trnka, 2007b).

Distal soft-tissue procedures are widely used in osseous HV procedures. Metatarsal osteotomy combined with medial capsulotomy and subsequent medial capsular plication, and in some cases with lateral soft-tissue release, shows good overall results (Fraissler et al., 2016).

Operative treatment of AE in HV has been recommended if stretching exercises fail to restore passive UAJ dorsiflexion (Coughlin 1996). Conversely, the neglect of AE has not been reported to increase the recurrence rate of HV (Perera et al., 2011). Several operative techniques are available for elongation of the gastro-
soleus complex (Chen & Greisberg, 2009; Herzenberg, Lamm, Corwin, & Sekel, 2007). The principle idea is to direct the lengthening procedure to the tight muscle component (e.g., the gastrocnemius) instead of total Achilles tendon lengthening, when not necessary (Chen & Greisberg, 2009; Herzenberg et al., 2007). Overlengthening of the Achilles complex increases plantar pressure under the heel and produces gait problems (Chen & Greisberg, 2009). A grade B evidence-based recommendation ("fair") exists to support the use of gastrocnemius recession for the treatment of symptomatic midfoot/forefoot overload syndrome in adults (Cychosz, Phisitkul, Belatti, Glazebrook, & DiGiovanni, 2015).

2.7 Impact of hallux valgus surgery on gait

The impact of HV and the effect of surgical correction on the gait have been assessed in several studies (Brodsky et al., 2006; Cancilleri et al., 2008; King, Hamilton, & Ford, 2014; Koller et al., 2014; Nix et al., 2013; Schuh, Adams, Hofstaetter, Krismer, & Trnka, 2010; Waldecker, 2002; Yamamoto, Muneta, Asahina, & Furuya, 1996). The basic method is gait analysis, which can be used to characterize normal and pathological gaits, to study the biomechanical components of human gait and to objectively register the impact of a given treatment on gait (Mayich, Novak, Vena, Daniels, & Brodsky, 2014). The five main classes of parameters are temporo-spatial parameters, kinematic parameters, kinetic parameters, integrated biomechanics, and electromyography (Mayich et al., 2014). The kinetic parameters (ground reaction forces, center of pressure, plantar pressure distribution, joint moments, and joint mechanical powers) registered with force or pressure plates are commonly used for gait analysis in HV (Koller et al., 2014; Waldecker, 2002; Yamamoto et al., 1996).

The kinetic studies show that HV decreases force generation under the first ray and hallux, and increases load transfer over the lesser MTHs. When HV deformity progresses over time, the load is shifted from the medial to the lateral part of the foot (Koller et al., 2014; Waldecker, 2002). Lesser toe metatarsalgia symptoms and callosities under the lesser MTH are explained by the decreased loading capacity of the first ray (Cancilleri et al., 2008; Koller et al., 2014; Yamamoto et al., 1996). Historically, HV surgery was aimed at reducing the IMA and correcting the I MTPJ alignment parameters. Currently, the goal of HV correction is to restore the loading capacity of the first ray (Cancilleri et al., 2008; King et al., 2014).

Controversial opinions exist about the HV correction method that can most effectively offload the central metatarsals. Coughlin and Jones (2007b) concluded
that distal soft-tissue realignment combined with proximal crescentic osteotomy restored the stability of the first ray without need for the first tarsometatarsal joint arthrodesis. Controversially, Brodsky et al. (2006) reported in their gait analysis study that proximal crescentic osteotomy did not restore the first ray postoperative loading capacity, but increased pressure under the second MTH. According to Faber et al. (2013), Hohmann distal metatarsal osteotomy and Lapidus operations produced similar long-term results, and the hypermobility in the first tarsometatarsal joint made no difference to the outcomes. King et al. (2014) compared distal chevron osteotomy and a modified Lapidus procedure in terms of loading characteristics and concluded that both methods corrected the HV deformity, but the Lapidus procedure also had positive effects on the forefoot loading distribution. Cancilleri et al. (2008) compared the postoperative loading characteristics of standard distal chevron osteotomy and triplanar modification of distal chevron osteotomy, in which the distal MTH was plantarized and shortened with oblique osteotomy line. The loading characteristics did not differ significantly between the groups, but the lesser metatarsal callosities were reduced with the triplanar modification when compared to the standard distal chevron osteotomy (Cancilleri et al., 2008). Robinson, Cullen, Chhaya, Sri-Ram, and Lynch (2009) reported a better resolution of the plantar callosities and transfer lesions with the Scarf osteotomy compared to Ludloff osteotomy (p<0.001) at the one-year follow-up.

There are indications that postoperative physical rehabilitation may improve the loading capacity of the first ray after HV correction (Schuh et al., 2010). Even if a HV operation corrects the foot geometry and the hallux kinematics, the more proximal kinematics of the foot and limb may not be improved (Canseco et al., 2012).

**Biomechanical aspects**

None of the previously described HV correction techniques are aimed at correcting all the biomechanical aspects, including the forefoot locking mechanism and the rotational component of the first ray. Theoretically, HV correction could be possible in flexible deformity without interventions to the I MTPJ. This could potentially prevent postoperative scar-tissue formation and limit the stiffness and/or pain of the I MTPJ. Additionally, the eversion correction could mimic the PL function during propulsion phase of the gait. According to Johnson and Christensen (1999) and Perez et al. (2008), the eversion of the first metatarsal increases the sagittal
stability of the first ray with the forefoot eversion locking mechanism, normally created by PL pull. In HV deformity, the dynamic stabilizing function of the PL and the windlass mechanism is disrupted (Rush, Christensen, & Johnson, 2000).
3 Aims of the thesis

The aims of the present thesis were:

1. to describe a novel FTJDA technique for flexible HV and to demonstrate a new test to identify the flexible HV (I).
2. to report the mid-term radiological and clinical follow-up results of the new operative technique for flexible HV (II).
3. to study the effect of new operative method on first metatarsal dynamic loading capacity and radiological and clinical follow-up results, in comparison to distal chevron osteotomy (III).
4 Patients and methods

The research was conducted at the Division of Orthopaedic and Trauma Surgery, Department of Surgery, Oulu University Hospital, Medical Research Center Oulu, Oulu, Finland, in co-operation with the Division of Operative Care, Department of Diagnostic Radiology, Department of Physical and Rehabilitation Medicine, Terveystalo, Oulu and Pohjola Sairaala Oy, Helsinki.

4.1 Patients (I-III)

The patients were adults with symptomatic HV, referred to the orthopedic outpatient clinic of Oulu University Hospital for clinical evaluation and planning of treatment. The research was based on two previously operated HV cohorts:

4.1.1 First tarsometatarsal joint derotational arthrodesis patients (FTJDA group) (I-III)

A specific clinical test was developed for the new operative method to identify the patients with flexible HV. This test, called the peroneus longus activation test, was initially based on a clinical finding whereby in a case of flexible HV, the patient is able to reduce the HV with a change in the standing balance maintenance mechanism while weightbearing, despite the severity of the deformity. Specifically, the patient stands still and lifts toes off the floor, thereby increasing the contact under the first MTH. With this maneuver, FHL activation is reduced and PL activation is increased, and in the case of flexible HV, the deformity is reduced both rotationally and axially (Figure 6). During this test, the PL activation can be seen as a muscle contraction on the lateral side of the leg, and the PL tendon becomes visible behind the fibula. In case of a fixed deformity, the HV deformity is not corrected, despite the peroneus activation. The idea for the PL activation test was based on the dysfunction of the PL in HV (Johnson & Christensen, 1999; Root et al., 1977; Rush et al., 2000; Valmassy, 1996). No pilot studies were conducted for the test, as it was initially developed for clinical purposes to identify flexible HV.

Between 2003 and 2009, 70 consecutive patients with 88 flexible HV feet underwent operations with the FTJDA procedure at Oulu University Hospital. The inclusion criterion for the operation was a flexible HV reducible with the PL activation test (Figure 6).
The exclusion criteria were limitation in the preoperative reduction of HV deformity and/or an injured windlass mechanism. The windlass was assessed as uninjured when the flexor hallucis brevis, sesamoids, and plantar fascia were intact (i.e., there was no history of resection arthroplasty or plantar fascia operation). Five of the feet had undergone previous operations for HV. Two distal chevron osteotomies and three bunionectomies had been performed in four patients as primary surgery. Patients with a history of rheumatoid arthritis or other inflammatory joint diseases were not included in this research, as they were further referred to the rheumatoid orthopedic outpatient clinic.

In the clinical examination, the passive UAJ dorsiflexion was examined systematically with the principles described by Silfverskiold (1924) and Hansen (2000). The passive UAJ dorsiflexion of ≥90 degrees foot-leg angle was interpreted as AE. If AE was noted, stretching exercises were advised by the physical therapist. In the preoperative examination, the residual AE was registered.
and additional gastrocnemius elongation was programmed as an adjunctive procedure, if needed.

The baseline patient data were collected retrospectively from patient records, and preoperative radiological variables were measured from dorso-plantar and lateral weightbearing radiographs. Sixty-six consecutive patients with 84 feet were enrolled in retrospective radiologic analysis according to available pre- and six-week postoperative radiographs for the measurements (I) (Table 1).

Table 1. Demographic data of 66 patients with 84 FTJDA operated HV feet.

<table>
<thead>
<tr>
<th>Variable</th>
<th>n* (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y mean (SD)</td>
<td>48 (SD 10)</td>
</tr>
<tr>
<td>Women/men, n</td>
<td>62/4</td>
</tr>
<tr>
<td>Smoker, n (%)</td>
<td>11/84 (13)</td>
</tr>
<tr>
<td>Diabetes, n (%)</td>
<td>0/84 (0)</td>
</tr>
<tr>
<td>Ankle equinus</td>
<td></td>
</tr>
<tr>
<td>Initially, n (%)</td>
<td>65/84 (77)</td>
</tr>
<tr>
<td>Pre-operatively, n (%)</td>
<td>58/84 (69)</td>
</tr>
<tr>
<td>Hallux valgus angle, pre-operative, mean (SD)</td>
<td>30 (SD 7)</td>
</tr>
<tr>
<td>Intermetatarsal angle 1-2, pre-operative, mean (SD)</td>
<td>13 (SD 3)</td>
</tr>
<tr>
<td>Meary’s angle &lt; 0.0 ° (pronation type), n (%)</td>
<td>60/77 (78)</td>
</tr>
<tr>
<td>Meary’s angle &gt; 0.0 ° (supination type), n (%)</td>
<td>17/77 (22)</td>
</tr>
</tbody>
</table>

*lateral weightbearing radiographs missing in 7 cases.

The severity of the HV (based on HVA) was not considered as a primary indication for the FTJDA procedure: three feet had mild HV (HVA less than 20°), 70 feet had moderate HV (HVA 20° to 39°), and eight feet had severe HV (HVA 40° or more).

Fifty-eight patients (76 feet, 90.5%) of the original patient cohort were available for the late follow-up at mean of 5.1 years after surgery (range 3.0 to 8.3) (II-III). A senior orthopedic surgeon examined all the patients for the mid-term follow-up. A research nurse, who did not participate the treatment of the patients, assisted the subjects with the questionnaires at the late follow-up visit.
4.1.2 Distal chevron osteotomy patients (chevron group) (III)

The chevron group consisted of 100 patients (100 feet) from a previous prospective randomized controlled trial comparing two distal chevron osteotomy techniques (no osteotomy fixation versus bioabsorbable rod fixation) and two postoperative regimens (soft cast versus elastic bandage). The patients underwent operations between 1998 and 2002 at the Oulu University Hospital. All the feet (100%) in the chevron group were operated on by a single surgeon. Inclusion criteria for radiographic analysis were age between 20 and 50 years, presence of a painful bunion with HVA of 50 degrees or less, and IMA 1-2 21 degrees or less. The exclusion criteria were previous bunion surgery, limitation of ROM of the I MTPJ, flatfoot, rheumatoid disease, and pregnancy. Seventy-seven of 100 patients participated the late follow-up, with a mean of 7.9 years (range 5.8 to 9.4).

The radiological, clinical, and gait analysis results of the distal chevron and FTJDA operated feet were compared in a matched-pair analysis (III). Both the chevron group and the FTJDA group were examined with gait analysis for plantar loading measurements at the latest follow-up. Two separate matchings (A and B) were made. In the matching A, the chevron and FTJDA groups (77 and 76 feet, respectively) were matched between preoperative HVA and a follow-up time maximum of 24 months apart. The two-year difference between follow-up times was evaluated as clinically acceptable, considering the lengths of mean follow-up times (mean of 7.9 years, range 5.8 to 9.4 and mean of 5.1 years, range 3.0 to 8.3, respectively). Matching criteria gave initially 39 pairs, but nine patients in the chevron group lacked gait analysis measurements, which gave 30 matched pairs included in this study (Table 2).
Table 2. The demographic data of the paired groups according to the preoperative hallux valgus angle (n=30). The secondary criteria for matching was follow-up time (difference ≤ 24 months).

<table>
<thead>
<tr>
<th>Variable</th>
<th>FTJDA</th>
<th>Distal chevron</th>
<th>Mean difference (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preop. HVA, mean, degrees (SD)</td>
<td>29.3 (5.8)</td>
<td>29.2 (6.2)</td>
<td>0.1 (-0.3 to 0.5)</td>
</tr>
<tr>
<td>Follow-up time, mean, months (SD)</td>
<td>72.4 (11.8)</td>
<td>86.1 (10.3)</td>
<td>13.7 (10.2 to 17.2)</td>
</tr>
<tr>
<td>Age, mean, years (SD)</td>
<td>51.3 (9.2)</td>
<td>37.6 (7.0)</td>
<td>13.7 (8.8 to 18.6)</td>
</tr>
<tr>
<td>Sex, female/male, n</td>
<td>29 / 1 (96.7)</td>
<td>30 / 0 (100)</td>
<td>-</td>
</tr>
</tbody>
</table>

Abbreviations: FTJDA = first tarsometatarsal joint derotational arthrodesis, Preop. HVA = preoperative hallux valgus angle, SD = standard deviation.

The matching B was made to examine the effect of residual HV on dynamic forefoot loading between the groups. The matching criteria were postoperative HVA at the latest follow-up and follow-up time difference maximum of 24 months. Thirty-one pairs were matched accordingly. Only relative impulses were analyzed from matching B (Table 3).

Table 3. The demographic data of the paired groups according to the postoperative hallux valgus angle (n=31). The secondary criteria for matching were follow-up time (difference ≤ 24 months).

<table>
<thead>
<tr>
<th>Variable</th>
<th>FTJDA</th>
<th>Distal chevron</th>
<th>Mean difference (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Postop. HVA, mean, degrees (SD)</td>
<td>16.9 (7.4)</td>
<td>16.8 (7.2)</td>
<td>0.1 (-0.2 to 0.3)</td>
</tr>
<tr>
<td>Follow-up time, mean, months (SD)</td>
<td>74.1 (12.3)</td>
<td>85.7 (10.4)</td>
<td>11.6 (8.5 to 14.7)</td>
</tr>
<tr>
<td>Age, mean, years (SD)</td>
<td>51.2 (8.9)</td>
<td>38.9 (6.9)</td>
<td>12.3 (8.3 to 16.4)</td>
</tr>
<tr>
<td>Sex, female/male, n</td>
<td>31 / 0 (100)</td>
<td>31 / 0 (100)</td>
<td>-</td>
</tr>
</tbody>
</table>

Abbreviations: FTJDA = first tarsometatarsal joint derotational arthrodesis, Postop. HVA = postoperative hallux valgus angle, SD = standard deviation.
4.2 Operative technique (I-III)

4.2.1 First tarsometatarsal joint derotational arthrodesis

In FTJDA, the patient was placed in a supine position and a tourniquet was applied above knee level to allow an adjunctive gastrocnemius elongation, if needed. The toes were left visible.

The incision was made dorso-medially, starting proximal to the first tarsometatarsal joint, above the dorsal margin of the tendon TA, and ending proximal to the I MTPJ capsule. The medial dorsal cutaneous nerve was protected. The first tarsometatarsal joint was exposed. A straight chisel was placed into the first tarsometatarsal joint for orientation to the joint line. The joint line orientation was maintained to avoid excessive plantarization of the first metatarsal when an oscillating saw was used to cut the cuneiform joint surface. Sawing began from the cartilage surface to avoid shortening of the first ray. The saw cut was directed perpendicular or in a slightly proximal direction to the second metatarsal to achieve enough axial correction of the IMA 1-2. The bean-shaped, convex cuneiform cartilage was removed. The first metatarsal base was placed firmly against the medial cuneiform. Maximal eversion of the first metatarsal was applied by handheld compression of the bunion to imitate PL tendon pull. The IMA 1-2 was also corrected in this manner. The amount of eversion correction depended on the individual’s anatomy and the initial severity of the HV deformity, as the second metatarsal base limited the amount of eversion correction. The exact amount of applied eversion was not measured. A parallel cut to the cuneiform joint line was made as proximally as possible to the base of the first metatarsal (proximal to the ridge at the base of the first metatarsal). A small joint distractor was placed into the first tarsometatarsal joint and the resected joint cartilage was removed. The distal insertion of the PL tendon could be seen attached to the base of the first metatarsal at the bottom of the first tarsometatarsal joint. The resected joint surfaces were perforated with multiple cannulated screw guide wire drills. The first metatarsal was positioned and held by hand, as previously described, and the first tarsometatarsal joint was fixed axially with guide wire, starting dorsally and approximately two to three centimeters distal to the first tarsometatarsal joint line. Fluoroscopy was used to check the guide wire positioning. The tip of the guide wire should have remained in the medial cuneiform. Initial correction of the HV could be seen at this point. Single screw fixation was used (Acutrak 4/5, Acumed® Corp., Portland, Oregon, USA). A measurement was taken for the screw length. Drilling
was then performed to match the screw length and the cannulated screw (typical screw length varies between 40 and 50 millimeters) was introduced while holding the corrected metatarsal position by hand. The axial clockwise rotation and the bite of the screw enhanced the rotational correction of the first metatarsal in the right foot, but made it more difficult in the left foot. Therefore, a temporary Kirschner wire fixation could have been used to maintain rotational correction during screw fixation in the left foot. No opening of the I MTPJ was required after the FTJDA, if the patient selection had been successful. The wound was closed with subcutaneous absorbable sutures and skin closure was made with wound staples or intracutaneous sutures. (Figure 7).

The postoperative regimen consisted of the use of a removable soft-cast geisha shoe and non-weightbearing for the first 6 postoperative weeks. Immediate postoperative radiographs were taken with the operated foot in the non-weightbearing attitude. Passive range of motion exercise of the I MTPJ was conducted ten days following the operation. The weightbearing radiographs were obtained at 6 weeks postoperatively. The PL and intrinsic muscle exercises were advised, along with a gastrocnemius stretching program at the 6-week postoperative control.

4.2.2 Distal chevron osteotomy

In distal chevron osteotomy, bunionectomy was performed after medial incision and capsulotomy. A V-shape cut was made with a 60-degree metal guide to the
distal metatarsal, and the MTH was shifted laterally 3 to 4 mm. The distal fragment was fixed, according to randomization, with a bioabsorbable rod or with no fixation. Lateral capsular release was not performed. Distal soft-tissue realignment was performed, with medial capsular tightening in all the operated feet.

Postoperative treatment consisted of an elastic bandage or soft-cast geisha shoe, depending on the result of randomization. Weightbearing on the heel was allowed immediately after the operation. Plantigrade walking was allowed after three weeks.

4.3 Radiological measurements (I-III)

Both groups underwent similar radiological measurements. In the FTJDA group, the measurements were made or supervised by the senior radiologist, who did not participate in the clinical examination or the treatment of the patients. In the distal chevron group, a senior orthopedic surgeon who also operated on the patients analyzed all the radiographs. HVA and IMA 1-2 were measured from dorso-plantar images according to the guidelines of the American Orthopedic Foot and Ankle Society ad hoc Committee on Angular Measurements (Coughlin et al., 2002) (Figure 2). The calcaneal pitch angle and Meary’s angle (the angle between the longitudinal axes of the talus and the first metatarsal) were measured from lateral weight bearing radiographs (Coughlin & Jones, 2007) (Figure 4). The tibial sesamoid position from 1 to 7 was evaluated using the LaPorta classification (LaPorta, 1974) (Figure 3).

4.4 Clinical outcome measurements (II-III)

Both HV groups were studied for the American Orthopaedic Foot and Ankle Society (AOFAS) metatarsophalangeal–interphalangeal (MTP-IP) clinical outcome score (Kitaoka et al., 1994). Due to the retrospective nature of the FTJDA group, AOFAS (MTP-IP) clinical outcome score data were acquired only at the latest follow-up. Additionally, in the FTJDA group, the patients completed the visual analog scale (VAS) for pain (from 0 for no pain to 10 points for worst pain), and for function (from 0 for no restrictions to 10 points for worst restriction) at the latest follow-up. A non-validated patient questionnaire was also completed at the latest follow-up by the FTJDA patients with the assistance of a research nurse, who did not participate the treatment of the operated patients. The questionnaire included the following questions: “How would you evaluate your current ability to perform (normal / nearly normal / abnormal / strongly abnormal)?”; “Did the
operation help your HV problem (yes / no)?”; “Would you be willing to receive the same operative treatment again under similar circumstances (yes / no)?”; “Have you had other operations to the same foot after the HV operation (yes / no. If yes, what was the operation)?”; and “Was there any complication related to the HV operation (superficial wound infection / deep wound infection / nerve injury / venous thrombosis / something else, what was it)?” The data of complications were also collected from the patient records.

4.5 Plantar loading measurements (III)

The patients walked barefoot at their most comfortable speed for about ten minutes without breaks and a gait analysis was performed using the RSscan Footscan 7.96 3D Gait Scientific 2m system pressure plate, with non-top-layer protocol (Xu, Wen, Huang, Shang, Yang, Yan, & Lei, 2017). Acceleration and deceleration phases were avoided during data collection. A few minutes of familiarization walk over the plate was performed before the recording was started. The pressure and impulse screens were viewed and the recording was started after the walking seemed to be comfortable. All the measurements and analyses were made by one examiner. Both the time-based gait symmetry characteristics, including velocity, and loading parameters such as plantar pressures, forces, and impulses (force–time integrals) were recorded using the pressure sensor plate (Koller et al., 2014, Mayich et al., 2014). The measuring area was 33 × 195 cm and foot loading was measured by 16,384 conductive polymer sensors of size 5 × 7 mm and sensitivity 0.27-127 N/cm². The measurements were made at a recording speed of 125 Hz (Xu et al., 2017). The weight calibration measurement was made daily before the measurement sessions using the calibration screen of the program. Every step was checked before analysis and the automatic zone selection was corrected manually, where needed.

The forefoot impulse (force–time integral, Ns) distribution was investigated. The relative impulse distribution was calculated so that the distal metatarsals (MTH 1–MTH 5) and the first toe together equaled 100 %. The gait analysis results of each foot were the mean of 10 steps. Plantar loading measurements and analyses were performed blinded, as the examiner did not know the matching results of the groups.
4.6 Statistical methods (I-III)

Summary measurements are presented as mean and standard deviation (SD) or as median with 25th-75th percentiles. Comparisons between pre- and post-operative values were performed by a paired samples t-test or the Wilcoxon signed rank test. The 95% confidence interval (95% CI) is presented with the mean change.

In the mid-term follow-up study, a linear mixed model (LMM) was used for repeatedly measured data. If the LMM showed significant change over time ($p_{\text{time}} < 0.05$), pairwise comparisons were performed. In the LMM analyses, the patient was set as a random effect to take into account that the operation was performed on both feet for some of the patients. The 95% confidence interval (95% CI) is presented as the mean change. Student’s t-test was used for group-wise comparisons.

In the matched-pair analysis comparing the FTJDA and the distal chevron osteotomy, comparisons between matched pairs were performed using a paired samples t-test. Three different subgroups were created according to adjunctive procedures for the FTJDA group, and subgroup analyses were performed: 1) gastrocnemius elongation vs. no elongation, 2) hammertoe correction (with or without Weil osteotomy) vs. no lesser toe procedure, and 3) either of the previous adjunctive procedures vs. no adjunctive procedures. Student's t-test was used for subgroup comparisons.

For all three studies, two-tailed p-values are presented and analyses were performed using SPSS for Windows (versions 16.0, 20.0 and 21.0. Armonk, NY: IBM Corp.) and SAS (version 9.3, SAS Institute Inc., Cary, NC, USA).

4.7 Ethics

The studies (I-III) were approved by the local ethics committee.
5 Results

5.1 First tarsometatarsal joint derotational arthrodesis operative technique and initial radiological results (I)

A preoperative lateral view was available for 77 feet, of which 60 (78%) were pronation-type and 17 (22%) were supination-type (negative or positive Meary’s angle, respectively). The mean HV correction angle between preoperative and follow-up radiographs was 19.8° (p < 0.001). The mean Meary’s angles were −3.9° pre-operatively and 8.1° postoperatively, with a mean change of 12.0° (p < 0.001). Between preoperative and follow-up, the average decrease in IMA 1-2 was 8.9° (p < 0.001) (Table 4).

Table 4. Effect of the operation on radiological parameters.

<table>
<thead>
<tr>
<th>Radiological parameter</th>
<th>Pre-operative</th>
<th>Post-operative</th>
<th>Mean difference (95% CI)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hallux valgus angle, mean (SD)</td>
<td>30.5 (SD 7.3)</td>
<td>10.7 (SD 5.6)</td>
<td>19.8 (18.1 to 21.4)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Intermetatarsal angle 1-2, mean (SD)</td>
<td>13.2 (SD 2.7)</td>
<td>4.3 (SD 2.6)</td>
<td>8.9 (8.3 to 9.6)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Calcaneal pitch angle, mean (SD)</td>
<td>20.1 (SD 4.4)</td>
<td>22.2 (SD 4.8)</td>
<td>2.1 (1.5 to 2.7)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Meary’s angle, mean (SD)</td>
<td>-3.9 (SD 6.8)</td>
<td>8.1 (SD 7.7)</td>
<td>12.0 (10.2 to 13.7)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

The LaPorta classification was used to measure the rotational correction of the first metatarsal bone along its longitudinal axis. From preoperative to follow-up, the median decrease in LaPorta classification was 2.5 units (25th-75th percentile, 2-3; p < 0.001). Postoperatively, no patients were in LaPorta group six or seven.

In all cases, a single, headless, fully threaded cannulated compression screw was used to fix the first tarsometatarsal joint arthrodesis. In 63 feet (75%), additional procedures were included (gastrocnemius/Achilles elongation n=57, Weil osteotomy n=9, and flexor digitorum longus transposition n=16); a total of eight feet had complications (nonunion n=2, suspected infection n=4, verified infection n=2). Three feet were re-operated due to the complications. The data regarding complications were collected from the patient records up to one year postoperatively.
5.2 Mid-term follow-up results of the first tarsometatarsal joint derotational arthrodesis operated feet (II)

Fifty-eight (87.9%) patients with 76 (90.5%) feet of the initial 84 feet were included in the late follow-up, with a mean of 5.1 years (SD 1.38, range 2.96 to 8.32) of follow-up time. Eight patients (eight feet; two men and six women) were lost during follow-up. Two of the nonparticipants could not be reached, three were not able to participate, and three declined. There were two reoperations among nonparticipants: one corrective osteotomy of the first metatarsal because of malunion (declined follow-up) and one screw removal because of a too-long screw (was not able to participate in follow-up).

The mean correction of HVA from preoperative to follow-up period values was 13.4° (95% CI 11.6 to 15.1, p < .001), and the mean IMA 1-2 correction was 4.5° (95% CI 3.7 to 5.2, p < 0.001), respectively (Table 5).

**Table 5. Radiological results.**

<table>
<thead>
<tr>
<th>Radiological parameter</th>
<th>Preoperatively</th>
<th>6 weeks</th>
<th>Follow-up*</th>
<th>ptime*</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVA (°)</td>
<td>30.1 (SD 7.0)</td>
<td>10.6 (SD 5.5)</td>
<td>16.7 (SD 7.9)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>IMA 1-2 (°)</td>
<td>13.3 (SD 2.7)</td>
<td>4.3 (SD 2.6)</td>
<td>8.6 (SD 3.5)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>LaPorta (Class 1-7)</td>
<td>5.3 (SD 1.0)</td>
<td>2.8 (SD 1.0)</td>
<td>4.0 (SD 1.1)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Calc. pitch (°)</td>
<td>20.2 (SD 4.4)</td>
<td>22.4 (SD 4.7)</td>
<td>20.7 (SD 4.4)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Meary’s angle (°)</td>
<td>-3.7 (SD 6.8)</td>
<td>8.2 (SD 7.8)</td>
<td>1.7 (SD 6.8)</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

Abbreviations: HVA = hallux valgus angle, IMA 1-2 = intermetatarsal angle between the 1st and 2nd metatarsals, Calc. pitch = calcaneal pitch angle.

*The average follow-up time was 5.1 years (SD 1.4, range 3.0 to 8.3).

*ptime ~p value for the change over time, according to a linear mixed model.

The tibial sesamoid position relative to the metatarsal bisector (LaPorta classification) was degraded by 1.1 units (95% CI 0.9 to 1.4, p < 0.001) from 6 postoperative weeks to the end of follow-up. One (1.3%) foot was classified as LaPorta 7 when preoperatively 10 (12.7%) feet were in this group (Table 6).
Table 6. Effect of the operation on LaPorta classification in the mid-term follow-up.

<table>
<thead>
<tr>
<th>LaPorta classification</th>
<th>Preoperative n (%)</th>
<th>Follow-up n (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 (0)</td>
<td>2 (3)</td>
</tr>
<tr>
<td>2</td>
<td>0 (0)</td>
<td>4 (5)</td>
</tr>
<tr>
<td>3</td>
<td>5 (6)</td>
<td>19 (25)</td>
</tr>
<tr>
<td>4</td>
<td>8 (10)</td>
<td>28 (37)</td>
</tr>
<tr>
<td>5</td>
<td>34 (43)</td>
<td>18 (24)</td>
</tr>
<tr>
<td>6</td>
<td>22 (28)</td>
<td>4 (5)</td>
</tr>
<tr>
<td>7</td>
<td>10 (13)</td>
<td>1 (1)</td>
</tr>
</tbody>
</table>

LaPorta classification could be assessed from 79 feet preoperatively and from 76 feet in follow-up.

The AOFAS (MTP-IP) clinical outcome score was excellent or good in 55 (72%) of the 76 operated feet at the latest follow-up. Fifteen (20%) feet were reported as fair and six (8%) as a poor result in the AOFAS (MTP-IP) scores. There were no re-operated feet due to complications among the excellent or good outcomes. When the study cohort was divided into two groups by severity according to preoperative HVA (≤30° or > 30°), the mean postoperative AOFAS scores were 88.9 (SD 11.5) and 84.8 (SD 14.8), respectively (p = 0.19). The I MTPJ motion (dorsiflexion plus plantarflexion) was normal or mildly restricted (ROM 75° or more) in 72 (94.7%) of 76 operated feet according to the AOFAS (MTP-IP) clinical examination. The VAS showed a median of 0.2 points in pain (mean of 1.4 points; SD 2.4) and a median of 0.3 points (mean of 1.3 points; SD 2.1) in function as a follow-up result. For 66 (88.0%) of the 75 operated feet, patients reported a willingness to choose a similar operative treatment under similar circumstances. Patients evaluated their postoperative functional capability as normal or nearly normal in 66 (88.0%) of the 75 feet. Overall, patients with 69 of the 73 feet (94.5%) reported that the operation had helped their HV problem.

Altogether, seven (9.2%) feet needed eight (10.5%) reoperations during follow-up: three nonunions, one malunion, two hardware removals, and two recurrent HV. The complications also included three superficial wound infections and one sural nerve hyperesthesia related to the initial surgery.
5.3 The effect of first tarsometatarsal joint derotational arthrodesis on first ray dynamic stability compared to distal chevron osteotomy (III)

In the matching A (preoperative HVA), the FTJDA group had higher relative impulses in MTH 1 (8.2%, p < 0.001), whereas the chevron group had higher relative impulses in MTH 3 (4.3%, p = 0.001) and MTH 4 (3.2%, p = 0.022) (Table 7).

**Table 7. Relative loading distribution (%) of the distal metatarsals (1 to 5) and the first toe at the late follow-up. The force–time integral (impulse) was measured at the levelled gait. Values are presented as a percentage of the total loading (100%). Pairs (n = 30) were matched according to preoperative hallux valgus angle and follow-up time difference ≤ 24 months.**

<table>
<thead>
<tr>
<th>Region</th>
<th>FTJDA Mean (SD)</th>
<th>Distal chevron Mean (SD)</th>
<th>Mean difference (95% CI)</th>
<th>p Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTH 1</td>
<td>23.4 (10.3)</td>
<td>15.2 (5.1)</td>
<td>8.2 (4.2 to 12.3)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>MTH 2</td>
<td>27.0 (6.0)</td>
<td>27.3 (4.8)</td>
<td>-0.3 (-3.2 to 2.6)</td>
<td>0.839</td>
</tr>
<tr>
<td>MTH 3</td>
<td>20.8 (6.8)</td>
<td>25.2 (3.0)</td>
<td>-4.3 (-6.9 to -1.8)</td>
<td>0.001</td>
</tr>
<tr>
<td>MTH 4</td>
<td>14.4 (6.2)</td>
<td>17.6 (3.9)</td>
<td>-3.2 (-6.0 to -0.5)</td>
<td>0.022</td>
</tr>
<tr>
<td>MTH 5</td>
<td>9.0 (5.3)</td>
<td>7.2 (3.0)</td>
<td>1.8 (-0.5 to 4.2)</td>
<td>0.124</td>
</tr>
<tr>
<td>T 1</td>
<td>5.4 (4.3)</td>
<td>7.7 (4.0)</td>
<td>-2.3 (-4.5 to 0.1)</td>
<td>0.055</td>
</tr>
</tbody>
</table>

*Abbreviations: FTJDA = first tarsometatarsal joint derotational arthrodesis, MTH 1 = first metatarsal head, MTH 2 = second metatarsal head, MTH 3 = third metatarsal head, MTH 4 = fourth metatarsal head, MTH 5 = fifth metatarsal head, T 1 = first toe, SD = standard deviation.

*p Value = significance, reported as two-tailed p value.

In the matching B (postoperative HVA), the FTJDA group had higher relative impulses in MTH 1 (10.6%, p < 0.001) and MTH 5 (2.6%, p = 0.049), whereas the chevron group had higher impulses in MTH 3, MTH 4, and the first toe, at 4.8%, (p = 0.005), 3.7% (p = 0.018), and 3.7% (p = 0.001), respectively (Table 8).
The operation improved the HVA mean of 6.6 degrees (SD 5.6) in the chevron group and a mean of 12.9 degrees (SD 7.0) in the FTJDA group in matching I. The mean difference of the HVA at the latest follow-up was 6.2 degrees (95% CI 3.0 to 9.5, *p* = 0.001).

The latest follow-up results in IMA 1-2 (*p* = 0.964), Meary’s angle (*p* = 0.750), calcaneal pitch angle (*p* = 0.467), and LaPorta (*p* = 0.662) did not differ significantly between the groups. However, the difference in the change in the achieved correction (preoperative vs. latest follow-up) between the groups in the calcaneal pitch angle (*p* < 0.001) and Meary’s angle (*p* < 0.001) were statistically significant (Table 9, Figure 8).

### Table 8. Relative loading distribution (%) of the metatarsal heads (1 to 5) and the first toe at the late follow-up. Relative impulse (relative force – time integral, %) was measured during contact phase of gait. Pairs (*n* = 31) were matched according to residual hallux valgus angle (late follow-up hallux valgus angle) and follow-up time difference ≤ 24 months.

<table>
<thead>
<tr>
<th>Region</th>
<th>FTJDA</th>
<th>Distal chevron</th>
<th>Mean difference (95% CI)</th>
<th>p Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTH 1</td>
<td>22.6 (SD 10.9)</td>
<td>12.0 (SD 5.1)</td>
<td>10.6 (6.0 to 15.2)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>MTH 2</td>
<td>27.0 (SD 6.0)</td>
<td>28.0 (SD 5.1)</td>
<td>- 1.1 (-3.8 to 1.6)</td>
<td>0.427</td>
</tr>
<tr>
<td>MTH 3</td>
<td>21.4 (SD 7.7)</td>
<td>26.1 (SD 2.7)</td>
<td>- 4.8 (-8.0 to -1.5)</td>
<td>0.005</td>
</tr>
<tr>
<td>MTH 4</td>
<td>14.4 (SD 6.7)</td>
<td>18.1 (SD 4.1)</td>
<td>-3.7 (-6.7 to -0.7)</td>
<td>0.018</td>
</tr>
<tr>
<td>MTH 5</td>
<td>9.4 (SD 6.0)</td>
<td>6.8 (SD 3.4)</td>
<td>2.6 (0.0 to 5.1)</td>
<td>0.049</td>
</tr>
<tr>
<td>T 1</td>
<td>5.2 (SD 4.7)</td>
<td>8.9 (SD 4.2)</td>
<td>-3.7 (-5.7 to -1.6)</td>
<td>0.001</td>
</tr>
</tbody>
</table>

Abbreviations: FTJDA = first tarsometatarsal joint derotational arthrodesis, MTH 1 = first metatarsal head, MTH 2 = second metatarsal head, MTH 3 = third metatarsal head, MTH 4 = fourth metatarsal head, MTH 5 = fifth metatarsal head, T 1 = first toe.

*p* Value = significance, reported as two-tailed *p* value.
Table 9. Radiological results for groups matched by follow-up time and preoperative HVA.

<table>
<thead>
<tr>
<th>Radiological parameter</th>
<th>Preoperative Mean (SD)</th>
<th>Follow-up Mean (SD)</th>
<th>Change, Preoperative-Follow-up (SD)</th>
<th>Mean difference1 (95% CI)</th>
<th>p1</th>
<th>Mean difference2 (95% CI)</th>
<th>p2</th>
</tr>
</thead>
<tbody>
<tr>
<td>FTJDA HVA</td>
<td>29.3 (5.8)</td>
<td>16.4 (7.9)</td>
<td>12.9 (7.0)</td>
<td>-6.2 (-9.5 to -3.0)</td>
<td>0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevron</td>
<td>29.2 (6.2)</td>
<td>22.6 (7.5)</td>
<td>6.6 (5.6)</td>
<td>6.3 (3.2 to 9.3)</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMA1-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTJDA IMA1-2</td>
<td>12.9 (2.9)</td>
<td>8.0 (4.0)</td>
<td>5.3 (4.0)</td>
<td>0.2 (-1.6 to 2.0)</td>
<td>0.86</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevron</td>
<td>13.0 (3.1)</td>
<td>7.8 (3.2)</td>
<td>5.3 (3.1)</td>
<td>0.0 (-1.7 to 1.8)</td>
<td>&gt;0.90</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meary’s angle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTJDA Meary’s angle</td>
<td>-4.8 (6.7)</td>
<td>2.2 (7.0)</td>
<td>-6.7 (6.4)</td>
<td>-0.5 (-3.6 to 2.6)</td>
<td>0.75</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevron</td>
<td>4.0 (7.1)</td>
<td>2.7 (7.0)</td>
<td>0.5 (2.2)</td>
<td>-7.1 (-9.8 to -4.5)</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Calc. pitch</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTJDA Calc. pitch</td>
<td>20.0 (4.1)</td>
<td>20.9 (4.1)</td>
<td>-1.3 (2.1)</td>
<td>0.9 (-1.5 to 3.3)</td>
<td>0.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevron</td>
<td>21.4 (5.3)</td>
<td>20.0 (5.0)</td>
<td>1.4 (1.4)</td>
<td>-2.4 (-3.5 to -1.4)</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LaPorta 1-7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FTJDA LaPorta 1-7</td>
<td>5.1 (1.1)</td>
<td>3.7 (1.3)</td>
<td>1.6 (1.5)</td>
<td>0.1 (-0.5 to 0.75)</td>
<td>0.66</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chevron</td>
<td>4.5 (0.9)</td>
<td>3.6 (1.0)</td>
<td>1.1 (1.0)</td>
<td>0.5 (-0.1 to 1.2)</td>
<td>0.087</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: FTJDA = first tarsometatarsal joint derotational arthrodesis, HVA = hallux valgus angle, IMA 1-2 = intermetatarsal angle between the 1st and 2nd metatarsals, Calc. pitch = calcaneal pitch angle, LaPorta 1-7 = LaPorta classification 1 to 7, SD = standard deviation, CI = confidence interval. 

p1 = P-value for the mean difference at follow-up. 
p2 = P-value for the mean difference for the change (from preoperative to follow-up results) between the matched pairs.
The AOFAS (MTP-IP) clinical outcome scores were a mean value of 81 (SD 7) in the chevron group and 86 (SD 16) in the FTJDA group at the latest follow-up (p=0.128).

According to subgroup analyses, in the FTJDA group, feet with lesser toe procedures had a significantly lower relative impulse in MTH 2 in both matching A and B (22.6% [SD 6.5] vs. 28.3% [SD 5.3] [p = 0.025] and 21.7% [SD 6.4] vs. 28.3% [SD 5.5] [p = 0.009], respectively). Furthermore, feet with either lesser toe or gastrocnemius lengthening procedures had a higher relative impulse in MTH 5 in matching A (11.4% [SD 6.2] vs. 5.8% [SD 3.2], p = 0.012). In the FTJDA group, the relative impulse distribution did not differ significantly between the gastrocnemius elongation vs. no elongation groups (data not shown).
6 Discussion

6.1 General considerations

The idea for the new HV correction technique originated from the existing biomechanical knowledge of the foot function, and specifically from the excessive foot pronation, typical compensatory mechanisms and the PL dysfunction common in HV (Bierman et al., 2001; DiGiovanni et al., 2002; Johnson & Christensen, 1999; Root et al., 1977; Rush et al., 2000; Valmassy, 1996). The development of the FTJDA would not have been possible under laboratory conditions (e.g., with a cadaver study) because post mortem stiffness of the joints does not allow flexible HV. The ethical background for the in vivo use of the FTJDA technique in flexible HV was based on the reduction of unnecessary surgery of the distal first ray and thus, avoiding the risks of possible infection and pain problems related to the distal wound and the scar-tissue formation.

The obvious limitation of the studies I-III was that the data of the FTJDA operated feet were collected retrospectively from the patient records. Originally, no plans were made for clinical studies of the FTJDA operated patients, and the patients were not enrolled in any specific study protocol. For this reason, the clinical outcome score or the gait analysis was not studied preoperatively.

The bias in patient selection is a concern, especially when retrospective patient material is analyzed. In this study, the FTJDA cohort consisted of consecutive series of 84 feet operated with the new technique between 2003 and 2009. Patients were initially selected for the new operative method by the flexibility, not primarily by the severity, of the deformity. Preoperatively, the weightbearing radiographs were used routinely and the flexibility of the deformity was examined systematically. The previously used modified Lapidus procedure was subsided by the FTJDA when the flexibility of the deformity and the possibility to correct flexible HV without any additional distal procedures was recognized in the clinic. The Lapidus procedures were focused mainly on one surgeon at the Oulu University hospital, due to the steep learning curve related to the procedure. For this reason, the HV patients were treated consistently with the FTJDA procedure instead of the Lapidus, or its known modifications, when the deformity was determined to be flexible. In this respect, the bias of patient selection and the chosen treatment modality may be considered low.
In the current study, the pre- and postoperative sesamoid positions, relative to the first MTH, were evaluated with LaPorta classification measured from dorso-plantar weightbearing radiographs (LaPorta, 1974). The weakness of LaPorta classification is that it does not consider the overall pronation of the foot, which affects the projection of the first MTH relative to the sesamoids. Furthermore, the LaPorta classification does not reliably give the sesamoid location against the metatarsal joint facets. For these reasons, it would have been preferable to analyze the sesamoid reduction with the weightbearing computed tomography scan, but the technical application to do this was not available at the time of the initial treatment of these patients.

The strength of the study was that the HV patients were referred to the Oulu University Hospital foot and ankle outpatient clinic and both the preoperative and follow-up examination were systematic and comprehensive. Additionally, the preoperative and follow-up clinical data were restored in electronic patient records. Thus, the availability and the quality of the demographic data may be considered reliable.

In the follow-up study (II), the follow-up time was relatively long, with a mean of 5.1 years. The rate of participation was also high: 76 (90.5%) feet of the initial 84 feet were available for the late follow-up. However, the comparison of the FTJDA follow-up results to the others have limitations. Due to the retrospective patient material, preoperative outcome scores were not available for the FTJDA follow-up study. The flexibility of HV was not tested in the other studies, whereas in the FTJDA cohort, all the feet had flexible HV (Coetzee & Wickum, 2004; Faber et al., 2013; Pentikäinen et al., 2012).

In the matched-pair analysis (III), the clinical examination protocol differed between the groups: in the chevron group, the AE was not examined or treated. In the FTJDA group, HV deformities were flexible, but this was not specifically tested in the chevron group. The FTJDA group also included additional procedures: gastrocnemius lengthening, digitus malleus corrections and Weil osteotomies, which were not performed in the chevron group. For this reason, subgroup analyses were conducted on the FTJDA group. The results showed some evidence of different relative impulse distribution between the operated feet, with and without adjunctive procedures, in the FTJDA group. However, the statistical power was insufficient for a full investigation of this finding. The matched-pair analysis may be considered as a comparison of two different treatment strategies. The distal chevron, as an isolated procedure, is aimed at correcting the HVA, whereas the
FTJDA, with additional procedures, is focusing on restoring the biomechanical loading properties of the first ray and the foot.

In study III, the strengths were the exact matching of the HVAs (mean differences of both preoperative and residual HVA matchings were 0.1 degrees), a good number of matched pairs (30 and 31 pairs) and the relatively long follow-up times in both groups (mean of 5.1 in FTJDA and 7.9 years in distal chevron). In both groups, the operations were mostly performed by a single surgeon (88% and 100%, respectively). The gait was analyzed in the same unit by the same examiner, who did not know the matching results of this matched-pair analysis.

6.2 First tarsometatarsal joint derotational arthrodesis and other techniques (I-II)

The FTJDA is the first operative technique for HV in which the I MTPJ or surrounding soft-tissue structures are not touched and the correction of the deformity is made in all three planes. Lapidus (Lapidus, 1934) introduced a HV correction technique based on a Silver-type distal exostectomy and combined with first tarsometatarsal joint arthrodesis and the synostosis between the first and the second metatarsal base (Lapidus, 1934). Several modifications have been published since the original Lapidus procedure, but they have all included a metatarsophalangeal joint procedure (Bednarz & Manoli, 2000; Lapidus, 1956, Lapidus, 1960, Sangeorzan & Hansen, 1989). The Lapidus procedure is aimed at correcting the IMA 1-2, but does not highlight the rotational correction of the first metatarsal. The only analogy between the Lapidus procedure and the FTJDA is the tarsometatarsal arthrodesis.

The FTJDA reduced HVA from a preoperative mean value of 30.1 degrees to 16.7 degrees at a mean follow-up time of 5.1 (SD 1.4, range: 3.0-8.3) years postoperatively. The IMA 1-2 was reduced from a preoperative mean value of 13.3 degrees to 8.6 degrees. The LaPorta score degraded by 1.1 units during follow-up to a mean value of 4.0 at the latest check-up.

In a prospective study, with mean of 3.7 years follow-up time, the Lapidus procedure corrected HVA from 37 degrees to 16 degrees (Coetzee & Wickum, 2004). With the distal chevron procedure, Pentikäinen et al. (2012) reported a reduction in HVA from 26 to 20 degrees at the mean follow-up time of 7.9 years. Faber et al. (2013) compared the Hohmann osteotomy and the Lapidus procedures in a prospective follow-up study with a mean of 9.3 years follow-up time. The Hohmann osteotomy improved HVA from 32 degrees to 11, whereas the Lapidus
procedure corrected HVA from 35 to 14 degrees at the latest follow-up (Faber et al., 2013). The mean age of the patients in the reported studies were 41, 39, 41 and 43 years, whereas in the present study the mean age was higher, 48 years (Coetzee & Wickum, 2004; Faber et al., 2013; Pentikäinen et al., 2012). In the current study, the HVA was improved by 13.4 degrees in the late follow-up, which is in a good agreement with the previously reported results (Coetzee & Wickum, 2004; Faber et al., 2013; Pentikäinen et al., 2012).

In the previously reported studies, the achieved mean corrections of IMA 1-2 were 10 degrees with the Lapidus, 5 degrees with the distal chevron, 6 degrees with the Hohmann and 8 degrees with the Lapidus procedures (Coetzee & Wickum, 2004; Faber et al., 2013; Pentikäinen et al., 2012). The achieved correction of IMA 1-2 with the FTJDA was a mean of 4.7 degrees (ptime < 0.001) at the latest check-up.

The LaPorta classification was not reported in the previously mentioned studies (Coetzee & Wickum, 2004; Faber et al., 2013; Pentikäinen et al., 2012). In the present study, the LaPorta score was significantly (p < 0.001) corrected.

The commonly used HV procedures alter the shape of the first metatarsal due to bunionectomy and/or metatarsal osteotomy. The impact of the non-anatomical shape of the first metatarsal on the reliability of the axial measurements should be considered critically.

Inman (1974) noted that HV is caused by foot pronation. The radiological results in the present study indicate that the underlying foot type varies in terms of the flexible HV. A pronation (Meary’s angle negative) was noted in four-fifths of the operated feet and one-fifth were the supination-type feet (Meary’s angle positive). The result suggests that, in the certain types of cavus feet, HV may develop to compensate for an initially plantarized first ray. Compensatory etiology of HV should be considered when HV is corrected in a supination-type foot, to avoid postoperative cavus deformity.

In the present study, the AOFAS (MTP-IP) outcome score was 86.4 out of 100 at the latest follow-up. The mean AOFAS score did not differ significantly, when the operated feet were divided into two groups according to the preoperative HVA of ≤30 degrees and >30 degrees. This finding suggests that the initial severity of the HV is less important than the flexibility of the deformity.

The median VAS for pain was 0.2 points (mean of 1.4) and for function 0.3 points (mean of 1.3) at the late FTJDA follow-up. The Lapidus VAS for pain was 1.3 at the 3.7 years follow-up (Coetzee & Wickum, 2004). In the Hohmann and
Lapidus groups, a mean late follow-up VAS for pain was 1 and 2 points, respectively (Faber et al., 2013).

The complications included eight re-operations altogether in seven feet: three nonunions (4.0%), one malunion, one too-long screw removal, and one late fixation material removal after a nonunion operation. Two feet were re-operated with I MTPJ arthrodesis due to a recurrent HV. The nonunion rate (4.0%) is low in the present study, when compared to early reports of 10 to 12% nonunion rates with the Lapidus procedure (Easley & Trnka, 2007b). The FTJDA procedure is a powerful correction method; therefore, it carries a risk for malpositioning and/or excessive shortening of the first metatarsal. Three-dimensional HV correction is a demanding procedure and the learning curve may be steep, especially if the operator is not familiar with the first tarsometatarsal joint arthrodesis.

If HV is not reduced with the PL activation test, the limitation of motion indicates degenerative changes in the metatarsophalangeal joint (Easley & Trnka, 2007a). In addition to degeneration of cartilage, the limitation of motion in HV may arise from stiffness and/or swelling of the soft-tissue surrounding the I MTPJ, e.g. the tendons, the ligaments and the joint capsule. The predictability and efficacy of the HV correction method on a postoperative result should be valued. In the degenerated, fixed HV, the predictable and effective procedure is the I MTPJ arthrodesis (Easley & Trnka, 2007b). Considering this, early stage preventative measures (e.g., rehabilitative exercises) are recommended to improve the foot function before HV progresses to a painful, degenerative state.

In the new operative FTJDA technique, the windlass is reduced without the metatarsophalangeal joint procedures and the eversion correction of the first metatarsal potentially increases the stability of the first ray.

The FTJDA procedure is an efficient and safe correction technique for flexible HV that leaves the I MTPJ and the surrounding soft tissue untouched. In the mid-term follow-up, the radiological and clinical results were comparable to the best reported follow-up result achieved with different operative techniques (Coetzee & Wickum, 2004; Faber et al., 2013; Pentikäinen et al., 2012).

6.3 The matched pair-analysis comparing first tarsometatarsal joint derotational arthrodesis and distal chevron osteotomy (III)

In the FTJDA group, dynamic forefoot loading distribution (relative impulse, %) indicated an 8.2% (p<0.001) higher loading capacity under the first MTH during the contact phase of the gait when compared to the chevron group. This result was
maintained when the effect of recurrent HV (the matching B) on dynamic forefoot loading distribution was examined between the groups. The first toe impulse was also 2.3% higher in the chevron group. This finding may indicate a tendency to increase FHL activity as an attempt to compensate for the weaker first ray dynamic stability or that first toe flexion forces are increased due to windlass pull and dynamic hallux limitus.

The matching B showed a higher relative impulse under the fifth MTH in the FTJDA group (p = 0.049). However, the relative impulse value diminished gradually from the second metatarsal to the lateral metatarsals in the FTJDA group. For this reason, the higher relative impulse under the fifth MTH was not considered as an indicator of the lateral loading pattern but was viewed as a result of a more evenly distributed forefoot loading compared to the chevron group. The results of the matching B suggest that if recurrent HV develops, FTJDA still maintains a better first ray dynamic stability when compared to the distal chevron procedure.

The relative impulse (relative force–time integral, %) distribution of the forefoot region (first toe, MTH 1-5) was chosen as the gait parameter in this study because the impulse tells the total loading instead of momentary pressure or force peaks. The relative impulse distribution describes the cumulative dynamic load directed at the forefoot during the gait. The forefoot region was chosen as the area of interest because HV has been shown to produce apopulsive loading patterns (Cancellieri et al., 2008).

According to Jacob (2001), in the normal gait, 29% of the body weight should be placed under the first MTH during the early heel rise. In principle, this demand may also be fulfilled with osteotomy correction. Conversely, the central dynamic forefoot loading distribution seen in the chevron group may be considered as a risk factor for overload symptoms, such as lesser toe metatarsalgia and painful plantar callosities (Cancellieri et al., 2008).

Coughlin and Jones (2007b) reported that distal soft-tissue realignment combined with proximal crescentic osteotomy increased the stability of the first ray without a need for first tarsometatarsal joint arthrodesis. According to Faber et al. (2013), the Hohmann distal metatarsal osteotomy and the Lapidus operation produced similar long-term results and the presence or absence of hypermobility in the first tarsometatarsal joint made no difference to the outcomes. Neither the radiological results, specifically the change achieved in Meary’s angle and the calcaneal pitch angle between the groups, nor the dynamic loading measurements seen in the present study support the conclusions of Coughlin and Jones (2007b) and Faber et al. (2013). However, the conclusions based on the results of different
osteotomy techniques (distal chevron, proximal crescentic osteotomy and the Hohmann procedure) used in these studies should be considered carefully.

In HV, the relative contribution of the first tarsometatarsal joint mobility to the total first ray mobility is greater in the medial than in the dorsal direction (Faber et al. 1999). The PL pull has a significant stabilizing effect against dorsal angular displacement (Faber et al., 1999). In the FTJDA procedure, the eversion correction, mimicking the PL function, may explain the higher relative impulse under the first MTH when compared to the distal chevron. Perez et al. (2008) described the stabilizing effect of the eversion locking mechanism to the dorsal mobility of the first metatarsal. In the FTJDA, the eversion locking mechanism is fully benefitted with the first metatarsal eversion correction. Considering this, the FTJDA may produce better first ray sagittal stability than is achieved with the modified Lapidus, where the stability is based on the first tarsometatarsal joint fusion and realignment. The classic version of the modified Lapidus does not address the rotation. When the modified Lapidus procedure is considered, we recommend testing the flexibility of the HV preoperatively with the PL activation test. If the HV is flexible, we recommend proceeding with the FTJDA instead of the modified Lapidus because, according to the results of the present study, the distal soft-tissue procedures and bunionectomy are needless. The medial capsular reefment is also not needed in the FTJDA, despite the medial capsular attenuation of the I MTPJ.

In the Lapidus procedure, the instability of the first ray is often used as the determining factor for the procedure. However, clinically relevant first ray instability may be difficult to estimate in practice (e.g., due to general joint laxity). In the FTJDA, the flexibility of the HV deformity is the main indication for the use of the procedure. The concept of a “flexible HV” also includes a possible instability of the first ray.

The FHL force resists dorsal angular displacement but also increases the medial angular displacement of the first tarsometatarsal joint (metatarsal primus varus), making it a potential factor for the recurrence of HV (Faber et al., 1999). In the FTJDA, the fusion of the first tarsometatarsal joint efficiently prevents the adverse foot widening effect, unlike the case with the distal chevron in which postoperative medial angular displacement is possible. The FHL overuse may compromise the windlass mechanism and the mechanical properties of the first ray, thereby leading to an increased risk of recurrent HV. Our results support this theory because the relative impulse under the first toe, relative to the first MTH, was higher in the chevron group than in the FTJDA group. The overuse of the FHL may also be a
compensatory mechanism caused by the insufficient first metatarsal dynamic stability.

The operative treatment of HV should be aimed at restoring the propulsion function of the first ray, regardless of the selected correction method. The progression of HV deformity predisposes the I MTPJ to degenerative changes (Easley & Trnka, 2007a; Root et al., 1977). Thus, the ideal HV correction method corrects the three-dimensional deformity and restores the propulsion function of the foot without intervening with the I MTPJ, thereby avoiding unnecessary surgery with scar tissue formation and residual pain problems in the I MTPJ.

The first tarsometatarsal joint arthrodesis has been reported to improve the PL function in the closed kinetic chain (Bierman et al., 2001). In the FTJDA, the eversion correction of the first metatarsal, in addition to IMA 1-2 correction, further improves the sagittal stability of the first ray by mimicking the PL function and the forefoot locking mechanism during the late stance phase (Bierman et al., 2001; Perez et al., 2008). The overall pronation of the foot typically places the first metatarsal into an everted position relative to the floor. Nevertheless, the hallux and the sesamoids are systematically placed in a more everted position relative to the first MTH. This can be seen as lateralized sesamoids relative to the first MTH in a weightbearing antero-posterior radiograph. After the eversion correction of the first metatarsal in the FTJDA procedure (chasing the sesamoids axially and rotationally with the first metatarsal), the stability of the first ray is increased and the overall foot pronation is decreased. The AE treatment further decreases the pronation forces affecting the foot during the late stance phase. The result of this decreased overall pronation of the foot (increased postoperative Meary’s angle and calcaneal pitch angle) is correction of the position of the first MTH relative to the floor and the sesamoids.

The occurrence of AE has been linked to varying foot pathologies, including HV (DiGiovanni et al., 2002; Nix et al., 2013). In addition to increasing the forefoot loading, AE reduces the influence of PL on the first ray (Johnson & Christensen, 2005). The tightness in the gastro-soleus muscle complex is the most common cause of AE among otherwise healthy individuals (DiGiovanni et al., 2002; Hill, 1995). The clinically relevant gastrocnemius equinus, tested with the knee in full extension, has been proposed to be less than 5 to 10 degrees dorsiflexion over the neutral 90degree position (i.e., >80 to 85 degrees for the foot–leg angle) (DiGiovanni et al., 2002; Hill, 1995; Nix et al., 2013). In the present study, the passive UAJ motion of ≥90 degrees foot–leg angle was interpreted as AE. All the patients with gastrocnemius, or gastro-soleus tightness, were advised to do the
preoperative stretching exercises. If the AE had not resolved with conservative treatment, the gastrocnemius lengthening procedure was added to the FTJDA procedure. In the present study, for seven feet (8%), the stretching exercises resolved the equinus. However, the overall patient compliance to perform the given stretching exercises was not studied. Stretching has been shown to improve ankle ROM in healthy individuals (Young, Nix, Wholohan, Bradhurst, & Reed, 2013).

The FTJDA significantly increased the postoperative stability of the first ray according to radiological and gait parameters. If a HV patient has underlying AE, it may be worsened by the increased forefoot stability after FTJDA correction. In cases of neglected AE, the distal chevron osteotomy may still produce a misleadingly asymptomatic result in the first ray region, but it also potentially increases the risk for overload symptoms in the lesser metatarsal area, as well as detrimental and excessive foot pronation during gait due to the weaker dynamic stability of the first ray.

### 6.4 Clinical implications

Based on study I, HV includes a flexible subtype that can be easily detected with a simple clinical test called the PL activation test. This test also enables patients with a flexible HV to see the expected postoperative result preoperatively. A flexible deformity can be corrected with the FTJDA procedure without any additional procedure to the I MTPJ. In this respect, the flexibility of the deformity becomes the determining factor, rather than the severity alone, for the choice of the proper treatment modality. For example, if the Lapidus was considered for a patient with a flexible HV, the FTJDA would be a better recommendation than the classic Lapidus or its well-known modifications. The flexibility of the HV may contribute to the other correction techniques in the form of better postoperative results; thus, it should be examined systematically in HV feet.

Study II shows that the results of the FTJDA are maintained in the mid-term follow-up, and the results are comparable with the best results of other reported techniques. The FTJDA is a safe and efficient method for the correction of flexible HV.

The matched pair-analysis indicated that the FTJDA produces better first ray dynamic loading capacity, more even impulse distribution between the MTHs and better radiological follow-up results when compared to the distal chevron.
6.5 Future studies

The three-dimensional deformity correction of flexible HV and the impact of different, commonly used correction techniques on overall foot architecture and the dynamic foot function need prospective comparative studies with weightbearing CT-scan and gait analysis. The current technology still limits the available image size in the weightbearing CT-scan. Ideally, the whole foot would fit into the weightbearing CT-scan image for profound analysis of the three-dimensional effect of a given treatment modality on the foot architecture. Additionally, the exact amount of the applied rotational correction of the first metatarsal in FTJDA could be studied with the weightbearing CT-scan. Gait analysis should be expanded to cover the interaction of the joints as well in the more proximal kinetic chain.

The PL activation test was developed for clinical use to identify the flexible HV. However, further studies are needed to validate this test.

In the present study, the various foot types, like supination and pronation types, were demonstrated to exist as one etiological factor in HV. Larger epidemiologic studies would enlighten the pathoetiology of HV as related to the different etiological foot types.

The prevalence of flexible HV in the general population, or its proportion in all HV deformities, has not been reported in the literature. Large population studies are needed to estimate the prevalence of flexible HV.

A longitudinal study is required to determine if the flexibility is permanent property or just a passing feature occurring during progression of the HV deformity.
7 Conclusions

I The novel FTJDA technique corrects flexible HV deformity without any bone or soft-tissue procedures to the I MTPJ. Flexible HV is identified with the peroneus longus activation test. Examination and treatment of ankle equinus is essential part of the FTJDA procedure.

II The clinical and radiological results indicate that the FTJDA is an effective and safe procedure for the correction of flexible HV and it produces satisfactory mid-term results.

III The FTJDA produced better postoperative dynamic loading capacity of the first ray and better HVA correction when compared to distal chevron osteotomy.
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Tero Klemola

FLEXIBLE HALLUX VALGUS

RESULTS OF A NEW SURGICAL TECHNIQUE