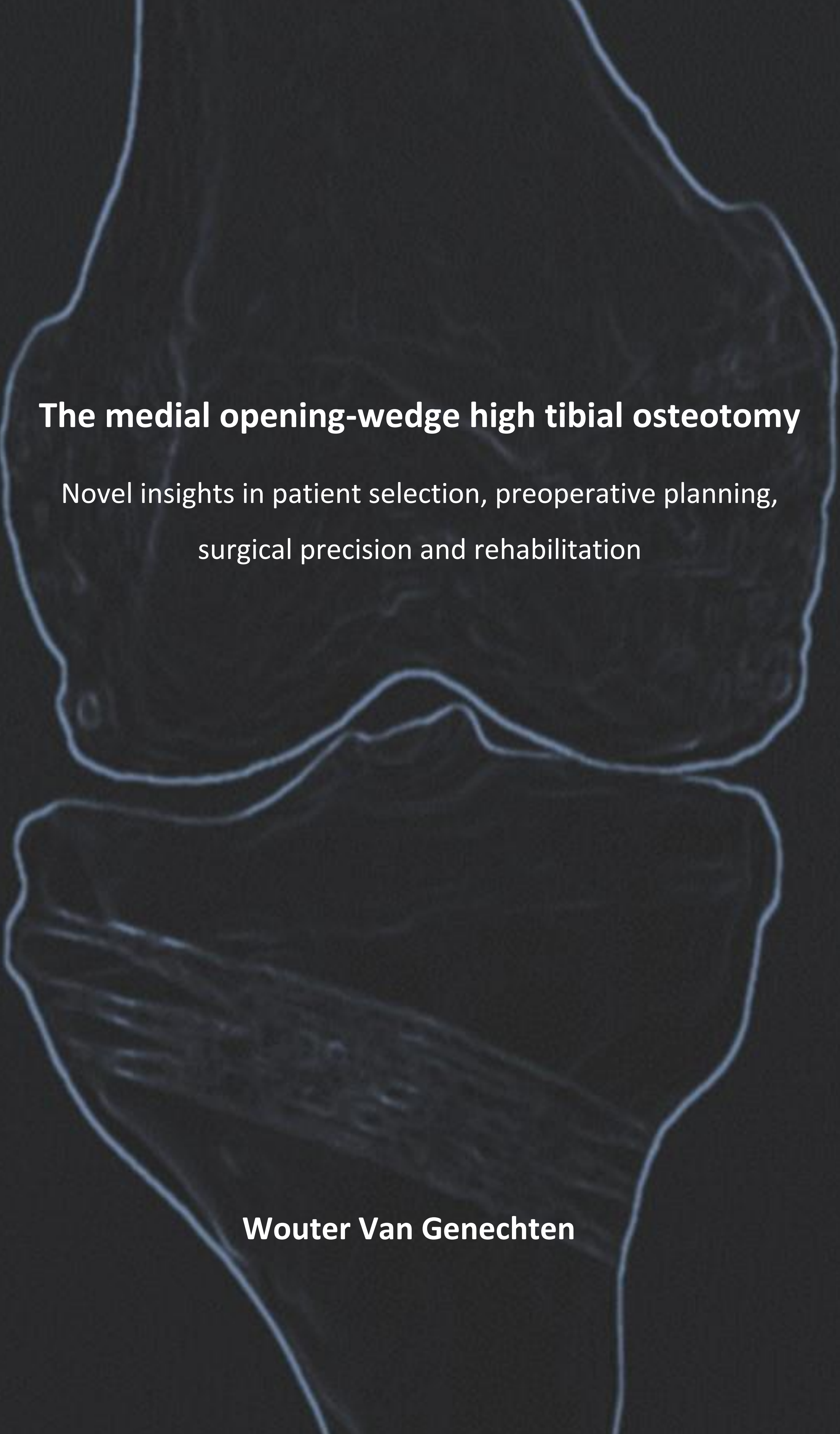


The medial opening-wedge high tibial osteotomy

Novel insights in patient selection, preoperative planning, surgical precision and rehabilitation

Wouter Van Genechten

Universiteit Antwerpen

Faculty of Medicine and Health sciences
Department of orthopaedic surgery

The medial opening-wedge high tibial osteotomy

Novel insights in patient selection, preoperative planning, surgical precision and rehabilitation

Thesis presented to obtain the degree of doctor in medical sciences at the University of Antwerp defended by Wouter Van Genechten

Promotor(s):
Jozef Michielsen, Peter Verdonk, Steven Claes, Johan Somville

Antwerp, 2023

Disclaimer

Preface

My primary motivation for starting a PhD was to exert a meaningful contribution to the scientific field regarding knee joint preservation strategies. The research topic of knee osteotomies was an obvious choice as I considered it as an extension of my bachelor (University of Hasselt) and master (University of Antwerp) thesis during my medical studies. During this ‘pre-PhD’ work, I was able to expose several gaps in knowledge about the medial opening-wedge high tibial osteotomy which are addressed in this PhD thesis.

Attempting a PhD is comparable with a hurdling race where you know from the start that reaching the finish line without touching a single hurdle will be impossible. One needs to have reliable supporters from the side line who encourage you to continue every time you are down. Looking back over the past 4 years, there have been many struggles and uncertainties I have dealt with. To me, a PhD was not simply a dive into answering 7 research questions, it was an ongoing personal learning process on how far limits can be pushed to obtain my goal. My expectations of a PhD thesis were more or less meeting with reality as I was able to write and publish articles not related to the PhD topic. However, I do admit that the final three years were long-lasting due to the full time combination of clinical work as an orthopaedic resident. On the other side, I must conclude that the alternating research work and clinics definitely improved my critical view on habits, traditions and the implementation of guidelines in the orthopaedic practice. Although this thesis occupied the majority of my spare time, it simultaneously served as an outlet for personal creativity in both designing of studies and the writing of manuscripts.

Finally, with this thesis, I would like to reach a broad audience that does not necessarily require extensive background knowledge about this topic. Therefore, this thesis is directed to every person with specific interest in joint preservation strategies of the knee and who might be involved in the perioperative setting of knee osteotomies. This includes, but is not limited to orthopaedic knee surgeons, orthopaedic residents, physiotherapists, radiologists, nurses, engineers and researchers.

Please enjoy.

‘The patient with early, symptomatic unicompartmental osteoarthritis will remain an ideal candidate for osteotomy’

- Mark Coventry (1973), Mayo Clinic, MN, USA -

Content

Summary

Year after year, the global population and average life expectancy continues to grow, which is associated with a higher prevalence of degenerative orthopaedic pathologies. The knee and hip joint are most commonly and severely involved due to their weight-bearing function, leading to symptomatic wear of the cartilage or osteoarthritis (OA). Regarding knee OA, isolated cartilage wear of the medial compartment forms the most common subtype. Progression of medial knee OA is associated with increasing varus malalignment (bow legs) of the lower limb leading to overload in the medial compartment. If this pathology becomes symptomatic in the young and active patient, and persists after conservative management, a corrective osteotomy around the knee is preferred to restore the alignment of the lower limb. The corrective osteotomy can either be performed at the level of the tibia, the femur or both, depending on the origin of deformity and the magnitude of varus. The medial opening-wedge high tibial osteotomy (MOWHTO) is the most commonly performed osteotomy technique in daily orthopaedic practice. During this procedure, an osteotomy is created on the medial side of the proximal tibia after which the distal tibia is gradually translated towards lateral. As such, the overall lower limb alignment will be restored and the medial diseased compartment will be unloaded during weight-bearing and functional activities.

Even though, this procedure has been successfully described for the first time by Jackson et al. in 1969 ('High tibial osteotomy for osteoarthritis of the knee'), several scientific gaps in knowledge are present in today's literature. This PhD thesis starts by formulating 7 critical research questions regarding patient selection, surgical planning and accuracy and early rehabilitation after MOWHTO. A chronologic structure containing 5 chapters is provided, equalizing the clinical pathway of the osteotomy patient.

Chapter 1 focusses on the surgical indication for MOWHTO with special interest for the multiplanar bony aspect of medial knee OA and the different varus phenotypes with their respective clinical outcome after MOWHTO. Retrospective analysis showed that medial knee OA in osteotomy candidates is exclusively induced and progressed by malalignment in the coronal plane (varus) in young patients. Bony malalignment in the sagittal or axial plane (rotations) did not show significant contribution to the medial OA process compared to healthy individuals.

Regarding corrective knee osteotomies, this means that unloading the medial knee compartment by strict corrections in the coronal plane remains key priority without further need for systematically investigating the sagittal or axial plane. Consequently, a closer look was taken on different varus phenotypes and the relation to MOWHTO. Historically, the MOWHTO has been performed on every varus phenotype, irrespective of the origin of deformity (femur, tibia, intra-articular or a combination) and the preoperative joint line obliquity. The study analyses were performed by using the CPAK classification ('coronal plane alignment of the knee'). The clinical 2-year follow-up results showed no difference in the effect of a MOWHTO on different varus phenotypes, however every varus phenotype did significantly improve. Surprisingly, patients with a varus deformity in the femur were numerically in favor of patients with a tibial varus deformity regarding the effect of a MOWHTO.

Chapter 2 describes the 2D and 3D planning modalities in MOWHTO with special attention for the position of the lateral tibial spine (LTS) on the tibial plateau. The LTS might be a useful planning target for aiming the weight-bearing axis on, although not much is known about its location and implications for MOWHTO planning. The 2D with 3D imaging study showed an average position of the LTS at 57-58% on the tibial plateau (0% medial, 100% lateral) with a maximal range of 10% (53-63%). A good correlation between 2D and 3D measurements was found. Consequently, the weight-bearing axis was planned through the LTS on 2D full-leg radiographs to investigate the implications on planned and postoperative mechanical alignment. A consistent planned and postoperative correction of 181-183° mTFA valgus was found while aiming the weight-bearing axis through the LTS. The lateral tibial spine can be considered a reliable landmark when aiming for slight valgus overcorrection in MOWHTO. Finally, this chapter contains a narrative review on the shift of 2D to 3D planning regarding knee osteotomies with discussion of our preferred 3D simulation technique in clinical practice.

Chapter 3 focusses on the surgical technics of the MOWHTO by a 3D simulation study. In 2016, we published a systematic review (Van den Bempt et al., 2016) which showed a surprisingly low accuracy of modern conventional MOWHTO techniques regarding the preoperative planning. It is suggested that this inaccuracy can be at least partially explained by the osteotomy and subsequent distraction itself because of unknown consequences in a 3-planar fashion. Therefore, this study simulates different osteotomy planes that vary in the coronal plane (start- and endpoint) and sagittal plane after which the axial rotation of the hinge axis is gradually adjusted. Realistic gap distractions of 5, 10 and 15mm were simulated to investigate the magnitude of correction on surgical accuracy. The difference in effect of osteotomy translations and hinge axis rotations are measured by the effective coronal bony correction and sagittal slope. Regarding coronal accuracy, the osteotomy depth forms the primary parameter while for sagittal accuracy, controlling the anterolateral hinge axis rotation is most important. The latter can be achieved by creating an equal osteotomy depth of the posterior and anterior cortices. Secondary, small tibias and large osteotomy corrections were bearing higher risk for inaccurate outcomes regarding the planned correction. Important to note is that the osteotomy plane orientation itself played a minimal role on achieving accurate corrections. Yet, most 3D guides designed for MOWHTO nowadays are focusing on reproducing the planned osteotomy plane during surgery…

Chapter 4 starts with a narrative review on existing 3D guides for MOWHTO in order to obtain more accurate outcomes. Our personal 3D technique, based on the implementation of customized structural bone allograft, was initially described in a pilot study in 2020 and was elaborated in this PhD thesis. After guide modifications, a novel prospective study was performed (30 cases in 2 centra) with biplanar surgical accuracy as primary outcome. The surgical accuracy was 60% between [-1°;+1°] and 90% between [-2°;+2°] regarding the correction goal. Moreover, a minimal increase in tibial slope was observed (1.2°±1.2). It was concluded that this 3D technique forms a viable alternative method for obtaining accurate MOWHTO corrections.

Chapter 5 is dedicated to early recovery after MOWHTO using structural bone allograft to fill the distraction gap. Despite satisfying clinical outcomes after MOWHTO, the procedure is considered to be invasive and painful with a long period of recovery for the patient. Since the MOWHTO and unicompartmental knee arthroplasty (UKA) do have some overlapping indications (isolated symptomatic ‘moderate’ OA), the UKA is often favored due to a short recovery period and resection of the arthritic tissue. The early rehabilitation period after MOWHTO bears the perception of being long and laborious compared to UKA, even though reliable research data on this topic are lacking. This high-volume prospective case series (n=103) renders early clinical outcome after MOWHTO when allowing patients to bear weight as tolerated from day 1 after surgery. Primary outcomes are pain and functional activities at 4 weeks and 3 months. The study showed a dramatic decrease in pain during the first 4 weeks while at 3 months, the large majority (98%) was able to walk > 500m without supportive measures. The conclusion was that (1) the use of structural impacted bone allograft seems beneficial in the early recovery phase after MOWHTO,

(2) the rehabilitation intensity after MOWHTO is overestimated by the perception of being painful and long-lasting, (3) immediate weight-bearing as tolerated by the patient is safe when locking plate systems are applied.

Samenvatting

Jaar na jaar blijft de bevolkingspopulatie en de gemiddelde levensverwachting stijgen wat onlosmakelijk verbonden is met een toename in degeneratieve gewrichtspathologieën. Het knie- en heupgewricht zijn hierbij het vaakst en ernstigst aangetast omwille van hun gewicht-dragende functie wat op termijn symptomatische ‘slijtage’ van het kraakbeen en osteoartrose (OA) genereert. Geïsoleerde artrose van het binnenste kniecompartiment is een vaak voorkomend subtype van knie OA. De toenemende ernst van OA in het binnenste kniecompartiment gaat gepaard met een progressieve scheefstand (O-been/varus) van het onderste lidmaat waardoor de overdruk alsmaar toeneemt. Indien deze pathologie symptomatisch is in jonge, actieve patiënten en resistent is aan conservatieve therapieën, wordt gekozen om een corrigerende osteotomie uit te voeren rond de knie. Een osteotomie kan uitgevoerd worden ter hoogte van de distale femur, de proximale tibia of van beiden, afhankelijk van de grootte van de as-afwijking en in welke botstructuur het malalignement zich bevindt. De mediale opening-wedge proximale tibia osteotomie (MOWHTO) is hierbij de techniek die het meest toegepast wordt in de hedendaagse orthopedische praktijk. Tijdens deze operatie wordt door middel van een osteotomie (doorzagen van bot) een laterale kanteling van de tibia uitgevoerd zodat het mediale zieke gewrichtscompartiment ontlast wordt tijdens steunname en activiteit. In feite wordt het ‘scheve’ onderste lidmaat terug ‘recht’ gezet met herverdeling van het gewicht over beide kniecompartimenten als gevolg.

Hoewel deze operatie al beschreven werd door Jackson et al. in 1969 (‘High tibial osteotomy for osteoarthritis of the knee’), bestaan er op heden nog tal van wetenschappelijke hiaten in de literatuur. Deze doctoraatsthesis start met het weergeven van 7 kritische onderzoeksvragen waarop een antwoord wordt gezocht aangaande patiëntenselectie, chirurgische planning en accuraatheid en de revalidatie voor een MOWHTO. Een chronologische opbouw aan de hand van 5 thesishoofdstukken werd voorzien, gelijkaardig aan het klinisch traject van een osteotomie-patiënt.

Hoofdstuk 1 gaat in op de chirurgische indicatiestelling voor een MOWHTO, met focus op het multiplanaire aspect van mediale knieartrose en de verschillende varus types met hun klinische uitkomsten na MOWHTO. Uit deze retrospectieve analyses blijkt dat artrose van het binnenste kniecompartiment uitsluitend geïnduceerd en onderhouden wordt door de asafwijking in het coronale vlak (varus) bij jonge patiënten. Beenderige afwijkingen in het sagittale of axiale vlak konden niet weerhouden worden als zijnde relevant voor mediale knieartrose in vergelijking met gezonde patiënten. Kaderend in correctieve knie-osteotomieën betekent dit dat ontlasting van het binnenste compartiment de hoofdzaak blijft door middel van een ascorrectie zuiver in het coronale vlak. Verder bouwend op deze conclusie werd vervolgens gekeken naar de verschillende varus phenotypes van het onderste lidmaat. Historisch werd een MOWHTO uitgevoerd bij elk varus phenotype, onafhankelijk van waar de afwijking zijn oorsprong kende (bovenbeen, onderbeen, kniegewricht of een combinatie). Ook met de preoperatieve scheefstand van het gewrichtsoppervlak werd geen rekening gehouden. De analyses werden uitgevoerddoor gebruik van de CPAK classificatie ('coronal plane alignment of the knee'). De klinische 2-jaars resultaten tonen dat er geen significant verschil is van het effect van een MOWHTO op de verschillende varus phenotypes. Elk varus phenotype kent wel een significante klinische verbetering op dit tijdspunt. Patiënten met een varus afwijking in het bovenbeen deden het numeriek zelfs beter dan patiënten met varus in het onderbeen, voor wie een MOWHTO net een zekere indicatie is.

Hoofdstuk 2 richt zich op de 2D en 3D planningsmogelijkheden van een MOWHTO met specifieke aandacht voor de ligging van de laterale tibiale spine (LTS), een referentiepunt op het tibia plateau dat als doel van correctie gebruikt zou kunnen worden. Deze 2D met 3D vergelijkende radiologische studie toont een gemiddelde LTS ligging van 57-58% op het tibia plateau (0% mediaal, 100% lateraal) met een maximale marge van 10% (53-63%). Een goede correlatie tussen 2D en 3D projecties werd aangetoond. Hierna werd op 2D full-leg radiografieën nagegaan wat de implicaties van deze variabele LTS positie is op de uiteindelijke mechanische correctie. Wanneer de gewricht-dragende as doorheen de LTS wordt gepland, kan een consistente correctie van 181-183° mTFA in valgus na MOWHTO verwacht worden. Tot slot wordt in dit hoofdstuk de opkomende shift van 2D naar 3D osteotomie planning uitgelegd en worden de persoonlijke preoperatieve 3D simulaties toegelicht die we in ons team gebruiken.

Hoofdstuk 3 gaat in op het chirurgisch technische aspect van een MOWHTO aan de hand van een 3D simulatie studie. In 2016 brachten we een systematisch review (Van den Bempt et al., 2016) uit, waaruit bleek dat moderne conventionele MOWHTO in de beschreven prospectieve studies een opvallend lage chirurgische accuraatheid kende ten opzichte van de preoperatieve planning. Er wordt gesuggereerd dat een deel van deze inaccuraatheid verklaard kan worden bij het maken en distraheren van de osteotomie zelf, omdat men niet exact weet wat er 3-dimensioneel op dat ogenblik gebeurd. De studie toont simulaties van osteotomie vlakken die variëren in het coronale (start- en eindpunt) en sagittale vlak waarbij finaal de hinge as stapsgewijs in het axiale vlak wordt geroteerd. Hierbij worden realistische correcties van 5, 10 en 15mm distractie gesimuleerd. Het verschil in effect van deze osteotomie verplaatsingen en grootte van ascorrectie wordt bekeken d.m.v. de effectieve beenderige coronale correctie en de sagittale slope. Voor coronale accuraatheid is de diepte van de osteotomie het meest belangrijk terwijl voor sagittale accuraatheid controle over anterolaterale rotatie van de hinge as het belangrijkst is. Die laatste kan bereikt worden door de posterieure cortex voldoende door te nemen ten opzichte van de anterieure. Bijkomend dragen kleine proximale tibia's en grote ascorrecties het hoogste risico op inaccurate uitkomsten t.o.v. de planning. Belangrijk te noteren is dat de oriëntatie van het osteotomie vlak zelf een minimale rol speelt voor het bereiken van een accurate correctie. De meeste 3D guides zijn tot op heden nochtans ingesteld op het reproduceren van het geplande osteotomievlak…

Hoofdstuk 4 start met een overzicht van de beschreven 3D guides beschikbaar voor het uitvoeren van een MOWHTO om de chirurgische accuraatheid te verbeteren. De eigen 3D techniek, die op een op maat gemaakte structurele botallogreffe is gebaseerd werd initieel in 2020 gepubliceerd als pilot studie en wordt in deze thesis verder uitgewerkt. Na enkele belangrijke modificaties aan de guide, werd een nieuwe prospectieve studie uitgevoerd (30 cases over 2 centra) met biplanaire accuraatheid als hoofduitkomst. Deze toonde een chirurgische accuraatheid van 60% tussen [-1°;+1°] en 90% tussen [-2°;+2°] rond het geplande doel. Bovendien werd slechts een beperkte toename in tibiale slope gezien (1.2°±1.2). Het besluit luidt dat deze 3D methode een valabel alternatief vormt voor accurate MOWHTO correcties.

Hoofdstuk 5 is toegewijd aan de vroege herstelperiode na een MOWHTO met gebruik van een structurele botallogreffe om de opening na distractie op te vullen. Ondanks de goede klinische uitkomsten na MOWHTO, wordt deze chirurgie vaak beschouwd als invasief en pijnlijk, gepaard gaande met een lange en moeizame revalidatie voor de patiënt. Aangezien MOWHTO en unicompartimentele prothesechirurgie (UKA) een overlappende indicatie kunnen hebben (geïsoleerde symptomatisch 'moderate' OA), gaat de chirurgische voorkeur vaak uit naar UKA omwille van de snelle revalidatie en resectie van het artrotisch weefsel. De revalidatieperiode na MOWHTO wordt naast die van UKA dus als lang en hardnekkig beschouwd, ook al bestaat hierrond bijzonder weinig wetenschappelijke evidentie. Deze prospectieve studie met hoog volume (n=103) geeft vroege klinisch uitkomsten weer wanneer steunname op pijn-geleide meteen is toegestaan. De hoofduitkomsten hier zijn pijn en functionele activiteiten op 4 weken en 3 maanden. De resultaten tonen een drastische vermindering in pijn gedurende de eerste 4 weken en op 3 maanden kon de ruime meerderheid (98%) > 500m stappen zonder hulpmiddelen. De conclusie is dat (1) het gebruik van structurele botallogreffe wordt aanbevolen voor een gunstig vroegtijdig herstel na MOWHTO, (2) de initiële herstelperiode na MOWHTO minder zwaar blijkt dan historische gedacht en (3) directe steunname na MOWHTO veilig is, mits gebruik van ‘locking plate’ systemen.

Introduction

Osteoarthritis (OA) of the knee joint is a common orthopaedic disease featured by pain and loss of function which can seriously affects the individuals' quality of life [73]. Secondary to cardiovascular diseases, knee OA is the most frequent cause for long-term disability [30]. Although age is a primary risk factor for OA development, a growing patient group between the age of 45-65 years suffering from knee OA is posing problems regarding durable therapeutic options as well as creating a major burden on society and insurance [15, 30, 73]. In the USA, half of the patients with symptomatic knee OA is younger than 65 years (7 million) [15]. This might cause a 53% loss on labor force with an estimated annual economic loss of US $ 5.46 billion [30].

A prevalent subset of knee OA is the isolated medial knee osteoarthritis (MKOA) in which the cartilage of the lateral and patellofemoral compartment remains largely unaffected [49]. The MKOA incidence is 5-10x higher than lateral compartment osteoarthritis, probably due to common constitutional varus alignment described by Bellemans et al. and unequal load distribution over the medial (60%) and lateral (40%) compartment in neutrally aligned patients [4, 38]. Degenerative changes of the medial knee compartment are typically graded by the Kellgren and Lawrence [42] or the Ahlbäck [1] radiographic classification. These grading systems are based on osteophyte formation, narrowing of the joint space, subchondral sclerosis and bone contour deformities in the medial compartment. MKOA is often associated with bowlegs, also known as varus malalignment, which can both be a cause and/or a consequence of degenerative changes in the medial compartment. Although several varus malalignment phenotypes have been identified, the baseline biomechanical principle of increasing peak forces in the medial compartment due to mechanical varus is true for every phenotype [34, 49, 70]. Varus malalignment typically accelerates mild-moderate MKOA, especially once a (partial) medial meniscectomy is performed which is even more aggravated in the presence of obesity [8, 71, 72]. There has been agreement after all that during walking, peak forces at the knee joint are approximately three times body weight [2]. So next to varus malalignment, obesity forms a major parameter in the equation towards MKOA progression [74].

Conservative management of MKOA should obviously first be exhausted prior to advancing into surgical options. Proven conservative therapies include lateral wedge insoles or a valgus unloader knee brace to unload the medial compartment, weight reduction, physiotherapy (quadriceps strength exercises), oral pain and anti-inflammatory medication and knee infiltrations (hyaluronic acid/platelet-rich plasma/stem cell therapy) [27, 28, 33, 56, 58, 68]. However, these therapeutic measures should preferably be combined in order to exert a meaningful benefit. The valgus unloader brace is often used both therapeutically and diagnostically to mimic the effect of realignment surgery. If conservative measures are deemed insufficient, MKOA patients are offered durable surgical solutions such a unicompartmental/total knee arthroplasty (UKA/TKA) or a corrective knee osteotomy, in which the knee joint can eventually be preserved.

Modern high tibial osteotomy (HTO) is an established surgical procedure for active patients suffering from isolated MKOA associated with varus deformity of the lower limb [57]. The aim of surgery is to redistribute load from the medial to the lateral knee compartment by performing a bony cut at the proximal tibia with subsequent tilting of the distal tibial part. Unloading the medial diseased compartment results in pain relief and functional improvement, delays the need for arthroplasty and has even shown to enable cartilage regeneration at 2 years postoperatively [40, 57].

The biomechanical principle of unloading a diseased knee compartment and correcting lower limb deformity goes back to the time of Hippocrates (460-370 BC) [64]. A distraction device called 'The Hippocratic Scamnum' was used to induce temporary unloading of the joint but without realigning the bone. It was only in the sixteenth century that primitive bony corrections were performed by breaking the bone, so called 'osteoclasia', and that fracture healing was intended by immobilisation into normal alignment [64]. The first published knee osteotomy (which deserves the name 'osteotomy' as in 'controlled cut of the bone') can be attribute to John Rhea Barton from Pennsylvania, USA (1794–1871). He performed a successful supracondylar femoral osteotomy in 1835 for an ankylosed knee joint. Ever since, techniques progressed rapidly (saw, chisel, manual drill) and experience was gained in both Western-Europe (Langenbeck, Louis Little, Volkmann, Barwell, Lister and Macewen) and the USA (Pancoast and Gross). Nevertheless, common complications of infection, loss of correction and stiffness were inevitable [64]. The main indications for realignment surgery were rachitis, genu recurvatum, and knee ankylosis but these were soon extended to (isolated) degenerative changes of the knee (1940). In 1958, Jackson published a small series of distal femoral and proximal tibial osteotomies for patients with disabling pain due to knee osteoarthritis (OA), which were complication-free [35]. Later on (1961), he published the first radiographic evidence of osteotomy healing while quantifying the amount of correction [36]. Large osteotomy series appeared soon by Coventry et al. (Mayo Clinic, USA) and Gariépy (Montreal, Canada) that showed delay in OA progression after healed osteotomies [12, 24]. Regarding internal fixation, it was Mark Conventry (1965) who introduced the staple for lateral tibial fixation but nevertheless there was the need for an additional immobilization period by casting the knee for 4-6 weeks [13]. Up to 1968, when the first successful total knee arthroplasty was performed, distal femoral and high tibial osteotomy were the primary, and actually the only surgical options for degenerative changes of the knee, despite its severe teething problems [64]. Due to good initial results after TKA, knee osteotomy performance dramatically decreased, even for its established indications at that time. Fortunately, a few osteotomy proponents such as Mark Coventry kept refining and publishing on surgical osteotomy indications and techniques resulting in more reproducible clinical outcomes [12]. Knee osteotomy revival was truly a fact with the widespread availability of locking plate systems at the beginning of this century. The effort by Staubli and Lobenhoffer must be admitted for this matter, especially for advancing osteotomy healing, facilitating early range of motion and safe partial weight-bearing while reducing general complication rates [6].

The medial opening-wedge HTO (MOWHTO), the lateral closing-wedge HTO (LCWHTO) or the dome-shaped HTO are well-described modern options for lower limb realignment. They all have technical pearls and pitfalls, while showing equal mid-term clinical outcomes and survival rates [17]. One could argue that the LCWHTO provides higher initial stability with favourable bone healing potential since the osteotomy plane is directly compressed. However, the LCWHTO seems technically more challenging since an additional osteotomy of the fibula or a release of the proximal tibiofibular joint is required and by imprecise determination of the desired bone wedge to resect [6]. The MOWHTO is therefore generally preferred for its ‘relative’ technique simplicity without the risk for damaging the peroneal nerve. Technically, an MOWHTO can be performed in a uniplanar (only horizontal cut) or a biplanar fashion (a horizontal cut with an ascending or descending transverse cut). The rationale of a biplanar osteotomy is that by increasing the total osteotomy surface, bone healing might accelerate while providing higher rotational stability due to optimal locking plate fixation [6]. However, clinical differences between both techniques are not proven upon today, which leaves the choice up to the surgeons experience.

Current survival rates after MOWHTO are estimated at 86-100% at 5 years, 64-97.6% at 10 years, 44-93.2% at 15 years and 46-85.1% at 20 years [37, 57]. HTO has been shown to restore normal biomechanics in gait analysis and secures high rates of return to sport (90-100%) and return to work (81-96%) [18, 47]. The baseline indication for HTO typically includes the young and active patient with isolated MKOA in the presence of significant varus malalignment (preferably tibia-driven) [10, 75]. Furthermore, many surgeons take into account BMI (interval 25-35), age (below 55 years), a minimum range of motion (ROM) of 0-100°, knee stability and MKOA severity (Kellgren and Lawrence grade 1-3) in decision-making [3]. However, the recent European Society of Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA) consensus statement (2022) about knee osteotomies considers no differences in clinical outcomes after knee osteotomy regarding sex and age (>< 55 years) [14]. A specific cut-off value for BMI could not be rendered, although a higher complication rate is observed in patients with BMI <21 and >30 [14]. Rheumatoid arthritis is generally considered a contraindication, unless well-controlled with medication [14]. Early degenerative changes of the patellofemoral and lateral compartment do not form a strict contraindication for HTO [14]. Nevertheless, the lateral meniscus and patellar height should be assessed before osteotomy planning in order to avoid respectively rapid degenerative changes laterally and anterior knee pain due to patella infra [14]. When patella infra is anticipated, adjustment of the osteotomy technique to a biplanar ascending cut or a LCWHTO is recommend. Smokers should be informed to stop three weeks before and after HTO and their increased risk for complications (wound infection, bone healing) should be discussed. However, they do not show inferior clinical outcomes after HTO compared to non-smokers [14]. So, MOWHTO is primarily indicated, but not limited to degenerative changes of the medial compartment. Other surgical indications include focal cartilage defects (and concomitant cartilage procedure), meniscus transplantation and ligamentous instability [20, 48]. However, these indications are falling beyond the scope of this thesis.

Although the importance of varus malalignment in the coronal plane for MKOA is now well understood, malalignment in the sagittal and axial plane are much less studied and might pose relevant information in the context of knee osteotomy surgery [8, 11, 32]. This is reflected by multiple guiding classifications in the coronal plane of healthy and diseased varus knees that differentiate for joint line obliquity, original site of the varus deformity and joint line (in)congruence between femur and tibia [34, 49, 54, 70]. With advancing (ultra) low-dose CT-scan protocols and widespread 3D software availability, the assessment of orthopedic malalignments on both upper and lower extremity has been improved [41]. This facilitates the standardization of sagittal and axial angles in large healthy populations as was recently shown for the femoral anteversion (FAVA (15.3 ± 9.5°)) and the tibial external rotation (TEVA (31.6 ± 6.3°)) [51]. Of note, Caucasians appeared to have less anteversion in the femur but more external rotation in the tibia compared to Asians, hereby highlighting the importance of ethnicity-specific research on this matter [51]. However, to date, no data regarding sagittal slope and tibial/femoral rotations are available in patients with symptomatic MKOA scheduled for knee osteotomy corrections. This might pose relevant information on both how to approach realignment surgery (uni- or biplanar correction) and might help in understanding the onset and progression of MKOA.

Bony corrections at the level of the tibia (medial opening-wedge or lateral closing-wedge) have long been the golden standard for correction of varus malalignment in the lower limb. Now, the primary contributing component to the overall varus malalignment (tibial, femoral or intra-articular (IA)) and preoperative joint line orientation was hereby long neglected, which could result in a high postoperative medial proximal tibial angle (MPTA) and joint line obliquity (JLO) with inferior clinical results [22, 53]. Recently, some authors therefore advocate to correct varus malalignment at the level of its deformity rather than always at the tibial level, mainly to avoid non-anatomical postoperative angles [22, 62]. Razak et al. found more femoral varus and equal tibial varus in patients scheduled for HTO compared to non-arthritic varus controls [62]. However, to date, no clinical outcomes are published regarding the effect on MOWHTO on several varus phenotypes, since clinical osteotomy studies commonly consider a mixture of varus entities in their study design.

The large majority of MOWHHTO procedures is currently planned on full-leg standing radiographs (FLSR) for which the Miniaci and Dugdale planning methods are most commonly applied [16, 19]. The target axis on which the final weight-bearing axis should be aimed at, is still a matter of debate [5]. The Fujisawa point located at 62% or 62.5% of the tibial plateau width has long been considered the gold standard in valgus-producing osteotomy surgery [5, 23]. Recent osteotomy consensus papers propose a rather individualized approach based on the indication for knee osteotomy (cartilage procedure, meniscal transplant, isolated MKOA…), size of preoperative malalignment and the severity of cartilage damage [14, 21, 65]. The absence of literature consensus and proper target guidelines leaves the chosen correction goal in clinical practice often subjected to individual preference and experience of the surgeon. Recently, more studies are using the lateral tibial spine (LTS) as an anatomical and radiographical landmark during MOWHTO. This point is supposed to produce slight overcorrection (valgus) as to the neutral axis [25, 45, 50, 60]. Although the position of the LTS was once estimated to correspond with 55% of the tibial plateau (1.7-1.9° mechanical tibiofemoral angle (mTFA) valgus) [50], thorough investigations about its position, variability and relevance in postoperative MOWHTO realignment were never performed on a large patient population.

A systematic review (2016) by our research team exposed fairly low accuracy outcomes relative to the planned correction in modern conventional HTO surgery. Eight out of 14 cohorts (57%) reported an accuracy rate below 75% within a self-defined accuracy interval [5]. The majority of inaccurate cases appeared to be under-corrected [5]. Ultimately, obtaining the planned correction in MOWHTO is considered a highly important factor as long-term clinical results depend on the accuracy of the lower limb realignment [29]. Reasons for low accuracy outcomes may lie in unprecise 2D planning of the osteotomy, the challenging translation of the planned correction, postoperative soft tissue rebalancing and loss of correction due to unstable hinge fractures [31, 60, 67]. Measuring errors during planning might not be surprising, given that the majority of MOWHTO planning is solely based on a single full-leg bipedal standing radiograph (FLSR) [55]. The introduction of computer navigation at the beginning of this century was promising for improving accuracy, yet not practically sufficient to become widespread among orthopaedic knee surgeons [63]. Moreover, not all surgical steps of the MOWHTO procedure itself have been investigated for their potential impact on surgical accuracy. Therefore, the availability of 3D software and low-dose CT-scan have enabled the conduction of osteotomy simulation studies that might provide clarity on relevant aspects of the osteotomy cut in MOWHTO.

Our research team has successfully hit the road on 3D osteotomy planning with the implementation of a 3D guide to customize structural bone allograft [26]. A pilot study describing this technique was published in 2020 and showed satisfying accuracy outcomes in the coronal plane while still encountering difficulties in maintaining the native tibial slope (addendum 2) [26]. Altogether, a deeper scientific dive was required to understand (1) what parameters determine the surgical accuracy at the level of the osteotomy itself and (2) to determine if both coronal and sagittal accuracy can be obtained with a modified 3D kit for bone allograft preparation while allowing early weight-bearing and mobilization after surgery.

Finally, considering patients with MKOA between 50-60 years old, the ‘willingness to pay’-threshold of 50.000 dollar per quality adjusted life year (QALY) is cost-effective for HTO in 57%, for TKA in 24% and for UKA in 19% [43]. Moreover, the risk of revising a primary TKA is higher in patients below 50 years due to periprosthetic infection (1.8x) or aseptic component loosening (4.7x) compared to patients above 65 years [52]. The Finnish arthroplasty registry (32.019 TKAs) similarly showed a 92% survival rate for patients <55 years compared to 97% for patients >65 years at 5 year follow-up, even after adjusting for sex, use of patellar component, type of TKA and the fixation method [39].

Despite these evidence-based advantages favouring realignment surgery in the middle-aged patient, the amount of HTO procedures performed in reality is largely outnumbered by UKA. This is indicated by comparing the United Kingdom Knee Osteotomy Registry (UKKOR) with the UK National Joint Registry (NJR) [59, 69]. Also, a recent meta-analysis of both treatments supports this statement [9]. In case of progressive osteoarthritis, HTO can be converted in total knee arthroplasty (TKA) without compromising outcomes and these procedures have been shown to demonstrate a lesser need for the use of revision TKA components compared to revision of UKA [20]. Surprisingly, this decreasing tendency of knee osteotomy performance seems merely a geographical trend (Western-Europa and USA), as exactly the opposite is observed in Asia. In Korea for example, the frequency of HTO performance has been increased by 6.5-fold over 10 years according to the Korean National Health Insurance database (2008-2018) [44]. More specifically, in the age category above 65 years, an increase by 8.2-fold was observed [44].

The fact that surgeons tend to opt more often for UKA instead of TKA nowadays, reflect a certain reluctance to perform HTO procedures. At least a part of this reluctance potentially originates from concerns associated with the early recovery after HTO e.g. pain, ambulation and complications [66]. Surely, osteotomies need time to achieve solid bony healing, generally considered to occur only after 12 weeks [7]. The burden of these restrictions probably is the most important factor determining attractiveness of HTO surgery in both patients’ and surgeons’ minds. Finally, our research team tried to address the issue of early postoperative pain and slow rehabilitation after MOWHTO by investigating a novel technique using structural bone allograft impaction.

Despite this reluctance for realignment procedures, the scientific field of knee osteotomies seems to grow year by year. On PubMed, the number of hits for ‘high tibial osteotomy’ have been doubled between 2016 (1605 hits) and 2023 (3095 hits). This indirectly proves both the growing interest for MOWHTO and the existing gap in knowledge, mainly occupied by unanswered questions regarding patient selection, osteotomy planning, accuracy and rehabilitation.

Therefore, this PhD thesis aims to contribute to the field of knee osteotomy by providing an evidence-based answer to each of the following research questions:

1. *Is symptomatic lower limb varus accompanied by structural bony malalignment in the sagittal (tibial slope) or axial plane (femoral or tibial rotation) in a male Caucasian osteotomy population?*
2. *What are the most prevalent varus phenotypes for MOWHTO and does the tibial-driven varus phenotype provides both superior radiological and short-term clinical outcomes compared to other phenotypes?*
3. *What is the 2D and 3D location of the lateral tibial spine on the tibial plateau in an eligible Caucasian MOWHTO population?*
4. *Is the lateral tibial spine a consistent and clinically relevant anatomical reference point for aiming the weight-bearing axis in MOWHTO planning and determination of postoperative accuracy of correction?*
5. *Which are the most relevant factors to take into account while making an opening-wedge osteotomy cut in order to obtain an accurate bony correction?*
6. *Can surgical accuracy of MOWHTO corrections be improved with 3D planning and by the availability of patient-specific instrumentation for preparing structural bone graft during surgery?*
7. *Does the implementation of structural impacted bone grafting enables fast rehabilitation and early pain relief after MOWHTO surgery?*

Each chapter provides a meaningful contribution to the existing literature regarding surgical indication, planning, surgical accuracy and rehabilitation of the medial opening-wedge high tibial osteotomy.

REFERENCES

1. Ahlbäck S (1968) Osteoarthrosis of the knee. A radiographic investigation. Acta Radiol Diagn (Stockh) (277):7–72

2. Amis AA (2013) Biomechanics of high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc 21(1):197–205

3. Batailler C, Gicquel T, Bouguennec N, Steltzlen C, Tardy N, Cartier JL, Mertl P, Pailhé R, Rochcongar G, Fayard JM (2022) A predictive score of high tibial osteotomy survivorship to help in surgical decision-making: the SKOOP score. Archives of Orthopaedic and Trauma Surgery Springer Berlin Heidelberg 143(8):4843-4851

4. Bellemans J, Colyn W, Vandenneucker H, Victor J (2012) The chitranjan ranawat award: Is Neutral Mechanical Alignment Normal for All Patients? The Concept of Constitutional Varus. Clin Orthop 470(1):45–53

5. Van den Bempt M, Van Genechten W, Claes T, Claes S (2016) How accurately does high tibial osteotomy correct the mechanical axis of an arthritic varus knee? A systematic review. Knee Elsevier B.V. 23(6):925–935

6. Brinkman JM, Lobenhoffer P, Agneskirchner JD, Staubli AE, Wymenga AB, Van Heerwaarden RJ (2008) Osteotomies around the knee: Patient selection, stability of fixation and bone healing in high tibial osteotomies. Journal of Bone and Joint Surgery - Series B 90(12):1548–1557

7. Brosset T, Pasquier G, Migaud H, Gougeon F (2011) Opening wedge high tibial osteotomy performed without filling the defect but with locking plate fixation (TomoFix^{TM}) and early weight-bearing: Prospective evaluation of bone union, precision and maintenance of correction in 51 cases. Orthop Traumatol Surg Res Elsevier Masson 97(7):705–711

8. Brouwer GM, Van Tol AW, Bergink AP, Belo JN, Bernsen RMD, Reijman M, Pols HAP, Bierma-Zeinstra SMA (2007) Association between valgus and varus alignment and the development and progression of radiographic osteoarthritis of the knee. Arthritis and

Rheumatism 56(4):1204–1211

9. Cao Z, Mai X, Wang J, Feng E, Huang Y (2018) Unicompartmental Knee Arthroplasty vs High Tibial Osteotomy for Knee Osteoarthritis: A Systematic Review and Meta-Analysis. J Arthroplasty 33(3):952–959

10. Capella M, Gennari E, Dolfin M, Saccia F (2017) Indications and results of high tibial osteotomy. Annals of Joint 2(6):33–33

11. Cerejo R, Dunlop DD, Cahue S, Channin D, Song J, Sharma L (2002) The influence of alignment on risk of knee osteoarthritis progression according to baseline stage of disease. Arthritis and Rheumatism 46(10):2632–2636

12. Coventry MB (1973) Osteotomy about the knee for degenerative and rheumatoid arthritis. J Bone Joint Surg Am 55(1):23–48

13. Coventry MB (1969) Stepped staple for upper tibial osteotomy. J Bone Joint Surg Am 51(5):10–11

14. Dawson MJ, Ollivier M, Menetrey J, Beaufils P (2022) Osteotomy around the painful degenerative varus knee: a 2022 ESSKA formal consensus. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 31(8):3041-3043

15. Deshpande BR, Katz JN, Solomon DH, Yelin EH, Hunter DJ, Messier SP, Suter LG, Losina E, Katz J (2016) The number of persons with symptomatic knee osteoarthritis in the United States: Impact of race/ethnicity, age, sex, and obesity. Arthritis Care Res (Hoboken) 68(12):1743–1750

16. Dugdale T, Noyes F, Styer D (1992) Preoperative planning for high tibial osteotomy. The effect of lateral tibiofemoral separation and tibiofemoral length. Clin Orthop (274):248–64

17. Duivenvoorden T, van Diggele P, Reijman M, Bos PK, van Egmond J, Bierma-Zeinstra SMA, Verhaar JAN (2017) Adverse events and survival after closing- and opening-wedge high tibial osteotomy: a comparative study of 412 patients. Knee Surg Sports Traumatol

Arthrosc Springer Berlin Heidelberg 25(3):895–901

18. Ekhtiari S, Haldane CE, De Sa D, Simunovic N, Musahl V, Ayeni OR (2016) Return to work and sport following high tibial osteotomy: A systematic review. J Bone Joint Surg Am 98(18):1568–1577

19. Elson DW, Petheram TG, Dawson MJ (2015) High reliability in digital planning of medial opening wedge high tibial osteotomy, using Miniaci's method. Knee Surg Sports Traumatol Arthrosc 23(7):2041–2048

20. Faber S, Zellner J, Angele P, Spahn G, Löer I, Zinser W, Niemeyer P (2020) Decision making for concomitant high tibial osteotomy (HTO) in cartilage repair patients based on a nationwide cohort study of 4968 patients. Archives of Orthopaedic and Trauma Surgery Springer Berlin Heidelberg 140(10):1437–1444

21. Feucht MJ, Minzlaff P, Saier T, Cotic M, S??dkamp NP, Niemeyer P, Imhoff AB, Hinterwimmer S (2014) Degree of axis correction in valgus high tibial osteotomy: proposal of an individualised approach. Int Orthop 38(11):2273–2280

22. Feucht MJ, Winkler PW, Mehl J, Bode G, Forkel P, Imhoff AB, Lutz PM (2020) Isolated high tibial osteotomy is appropriate in less than two-thirds of varus knees if excessive overcorrection of the medial proximal tibial angle should be avoided. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(10):3299-3309

23. Fujisawa Y, Masuhara K, Shiomi S (1979) The effect of high tibial osteotomy on osteoarthritis of the knee. An arthroscopic study of 54 knee joints. Orthop Clin North Am 10(3):585–608

24. Gariepy R (1964) Genu varum treated by high tibial osteotomy. In proceedings of the joint meeting of orthopaedic associations. J Bone Joint Surg Br 46:783–784

25. Van Genechten W, Van den Bempt M, Van Tilborg W, Bartholomeeusen S, Van Den Bogaert G, Claes T, Claes S (2020) Structural allograft impaction enables fast rehabilitation in opening-wedge high tibial osteotomy: a consecutive case series with one year follow-up.

Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 28(12):3747–3757

26. Van Genechten W, Van Tilborg W, Van Den Bempt M, Van Haver A, Verdonk P (2020) Feasibility and 3D Planning of a Novel Patient-Specific Instrumentation Technique in Medial Opening-Wedge High Tibial Osteotomy. J Knee Surg 34(14):1560–1569

27. Van Genechten W, Vuylsteke K, Martinez PR, Swinnen L, Sas K, Verdonk P (2021) Autologous micro-fragmented adipose tissue (Mfat) to treat symptomatic knee osteoarthritis: Early outcomes of a consecutive case series. Journal of Clinical Medicine 10(11):2231

28. Gohal C, Shanmugaraj A, Tate P, Horner NS, Bedi A, Adili A, Khan M (2018) Effectiveness of Valgus Offloading Knee Braces in the Treatment of Medial Compartment Knee Osteoarthritis: A Systematic Review. Sports Health 10(6):500–514

29. Hankemeier S, Mommsen P, Krettek C, Jagodzinski M, Brand J, Meyer C, Meller R (2010) Accuracy of high tibial osteotomy: comparison between open- and closed-wedge technique. Knee Surg Sports Traumatol Arthrosc 18(10):1328–1333

30. He M, Zhong X, Li Z, Shen K, Zeng W (2021) Progress in the treatment of knee osteoarthritis with high tibial osteotomy: a systematic review. Systematic Reviews Systematic Reviews 10(1):1–10

31. Heijens E, Kornherr P, Meister C (2016) The coronal hypomochlion: A tipping point of clinical relevance when planning valgus producing high tibial osteotomies. Bone Joint J 98(5):628–633

32. Heijink A, Gomoll AH, Madry H, Drobnič M, Filardo G, Espregueira-Mendes J, van Dijk CN (2012) Biomechanical considerations in the pathogenesis of osteoarthritis of the knee. Knee Surg Sports Traumatol Arthrosc 20(3):423–435

33. Hermans J, Bierma-Zeinstra SMA, Bos PK, Niesten DD, Verhaar JAN, Reijman M (2019) The effectiveness of high molecular weight hyaluronic acid for knee osteoarthritis in patients in the working age: A randomised controlled trial. BMC Musculoskeletal Disorders BMC

Musculoskeletal Disorders 20(1):1–10

34. Hirschmann MT, Moser LB, Amsler F, Behrend H, Leclerq V, Hess S (2019) Functional knee phenotypes: a novel classification for phenotyping the coronal lower limb alignment based on the native alignment in young non-osteoarthritic patients. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 27(5):1394–1402

35. Jackson JP (1958) Osteotomy for osteoarthritis of the knee. J Bone Joint Surg Br 40:826

36. Jackson JP, Waugh W (1961) Tibial Osteotomy for Osteoarthritis of the Knee. J Bone Joint Surg Br 43-B:746–751

37. Jin C, Song EK, Santoso A, Ingale PS, Choi IS, Seon JK (2020) Survival and Risk Factor Analysis of Medial Open Wedge High Tibial Osteotomy for Unicompartment Knee Osteoarthritis. Arthroscopy Arthroscopy Association of North America 36(2):535–543

38. Jones RK, Chapman GJ, Findlow AH, Forsythe L, Parkes MJ, Sultan J, Felson DT (2013) A new approach to prevention of knee osteoarthritis: Reducing medial load in the contralateral knee. Journal of Rheumatology 40(3):309–315

39. Julin J, Jämsen E, Puolakka T, Konttinen YT, Moilanen T (2010) Younger age increases the risk of early prosthesis failure following primary total knee replacement for osteoarthritis: A follow-up study of 32,019 total knee replacements in the Finnish Arthroplasty Register. Acta Orthop 81(4):413–419

40. Jung WH, Takeuchi R, Chun CW, Lee JS, Ha JH, Kim JH, Jeong JH (2014) Second-look arthroscopic assessment of cartilage regeneration after medial opening-wedge high tibial osteotomy. Arthroscopy Arthroscopy Association of North America 30(1):72–79

41. Keller G, Afat S, Ahrend MD, Springer F (2021) Diagnostic accuracy of ultra-low-dose CT for torsion measurement of the lower limb. European Radiology European Radiology 31(6):3574–3581

42. KELLGREN JH, LAWRENCE JS (1957) Radiological assessment of osteo-arthrosis. Annals of

the rheumatic diseases 16(4):494–502

43. Konopka JF, Gomoll AH, Thornhill TS, Katz JN, Losina E (2014) The cost-effectiveness of surgical treatment of medial unicompartmental knee osteoarthritis in younger patients a computer model-based evaluation. J Bone Joint Surg Am 97(10):807–817

44. Lee SH, Seo HY, Kim HR, Song EK, Seon JK (2021) Older age increases the risk of revision and perioperative complications after high tibial osteotomy for unicompartmental knee osteoarthritis. Sci Rep Nature Publishing Group UK 11(1):1–9

45. Lee SS, Lee H Il, Cho ST, Cho JH (2020) Comparison of the outcomes between two different target points after open wedge high tibial osteotomy: The Fujisawa point versus the lateral tibial spine. Knee Elsevier B.V. 27(3):915–922

46. Lim JBT, Chong HC, Pang HN, Tay KJD, Chia SL, Lo NN, Yeo SJ (2017) Revision total knee arthroplasty for failed high tibial osteotomy and unicompartmental knee arthroplasty have similar patient-reported outcome measures in a two-year follow-up study. Bone Joint J 99-B(10):1329–1334

47. Lind M, McClelland J, Wittwer JE, Whitehead TS, Feller JA, Webster KE (2013) Gait analysis of walking before and after medial opening wedge high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc 21(1):74–81

48. Liu JN, Agarwalla A, Gomoll AH (2019) High Tibial Osteotomy and Medial Meniscus Transplant. Clinics in Sports Medicine Elsevier Inc 38(3):401-416

49. MacDessi SJ, Griffiths-Jones W, Harris IA, Bellemans J, Chen DB (2021) Coronal Plane Alignment of the Knee (CPAK) classification a new system for describing knee phenotypes. Bone Joint J 103 B(2):329–337

50. Martay JL, Palmer AJ, Bangerter NK, Clare S, Monk AP, Brown CP, Price AJ (2018) A preliminary modeling investigation into the safe correction zone for high tibial osteotomy. Knee 25(2):286–295

51. Mathon P, Micicoi G, Seil R, Kacaoglu B, Cerciello S, Ahmad F, LiArno S, Teitge R, Ollivier M (2021) Healthy middle-aged Asian and Caucasian populations present with large intra- and inter-individual variations of lower limb torsion. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(4):1083–1089

52. Meehan JP, Danielsen B, Kim SH, Jamali AA, White RH (2014) Younger age is associated with a higher risk of early periprosthetic joint infection and aseptic mechanical failure after total knee arthroplasty. J Bone Jt Surg 96(7):529–535

53. Micicoi G, Grasso F, Kley K, Favreau H, Khakha R, Ehlinger M, Jacquet C, Ollivier M (2021) Osteotomy around the knee is planned toward an anatomical bone correction in less than half of patients. Orthop Traumatol Surg Res 107(4):102897

54. Mullaji A, Shah R, Bhoskar R, Singh A, Haidermota M, Thakur H (2021) Seven phenotypes of varus osteoarthritic knees can be identified in the coronal plane. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 30(8):2793-2805

55. Nguyen HC, Gielis WP, van Egmond N, Weinans H, Slump CH, Sakkers RJB, Custers RJH (2021) The need for a standardized whole leg radiograph guideline: The effects of knee flexion, leg rotation, and X-ray beam height. J Cartil Jt Preserv Elsevier B.V. 1(3):100022

56. Ogata K, Yasunaga M, Nomiyama H (1997) The effect of wedged insoles on the thrust of osteoarthritic knees. Int Orthop 21(5):308–312

57. Ollivier B, Berger P, Depuydt C, Vandenneucker H (2021) Good long-term survival and patient-reported outcomes after high tibial osteotomy for medial compartment osteoarthritis. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(11):3569–3584

58. Page CJ, Hinman RS, Bennell KL (2011) Physiotherapy management of knee osteoarthritis. International Journal of Rheumatic Diseases 14(2):145–151

59. Palmer H, Elson D, Baddeley T, Porthouse A (2018) The United Kingdom Knee Osteotomy Registry: the first annual report 2018.

60. van de Pol GJ, Verdonschot N, van Kampen A (2012) The value of the intra-operative clinical mechanical axis measurement in open-wedge valgus high tibial osteotomies. Knee 19(6):933–938

61. Ramappa M, Anand S, Jennings A (2013) Total knee replacement following high tibial osteotomy versus total knee replacement without high tibial osteotomy: a systematic review and meta analysis. Archives of Orthopaedic and Trauma Surgery 133(11):1587–1593

62. Razak HRBA, Micicoi G, Khakha RS, Ehlinger M, Faizan A, LiArno S, Ollivier M (2021) Patients with varus knee osteoarthritis undergoing high tibial osteotomy exhibit more femoral varus but similar tibial morphology compared to non-arthritic varus knees. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 30(2):680-687

63. Saragaglia D, Roberts J (2005) Navigated osteotomies around the knee in 170 patients with osteoarthritis secondary to genu varum. Orthopedics 28(10 Suppl):s1269–s1274

64. Smith JO, Wilson AJ, Thomas NP (2013) Osteotomy around the knee: Evolution, principles and results. Knee Surg Sports Traumatol Arthrosc 21(1):3–22

65. Snow M, Jermain P, Mandalia V, Murray J, Khakha R, McNicholas M, Dawson M (2021) A 2021 consensus statement on osteotomies around the knee by the UK Knee Osteotomy consensus Group (KOG). Knee Elsevier B.V. 33(December):73–83

66. Stukenborg-Colsman C, Wirth CJ, Lazovic D, Wefer A (2001) High tibial osteotomy versus unicompartmental joint replacement in unicompartmental knee joint osteoarthritis: 7-10-Year follow-up prospective randomised study. Knee 8(3):187–194

67. Takagawa S, Kobayashi N, Yukizawa Y, Oishi T, Tsuji M, Inaba Y (2020) Preoperative soft tissue laxity around knee was associated with less accurate alignment correction after hybrid closed-wedge high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 28(9):3022–3030

68. Tang JZ, Nie MJ, Zhao JZ, Zhang GC, Zhang Q, Wang B (2020) Platelet-rich plasma versus

hyaluronic acid in the treatment of knee osteoarthritis: A meta-analysis. Journal of Orthopaedic Surgery and Research Journal of Orthopaedic Surgery and Research 15(1):1–15

69. Ted Baker PLC (2013) National Joint Registry for England, Wales and Northern Ireland-10th Annual report. EPPO Bulletin, pp 534–545

70. Thienpont E, Parvizi J (2016) A New Classification for the Varus Knee. J Arthroplasty 31(10):2156–2160

71. Willinger L, Foehr P, Achtnich A, Forkel P, Voss A, Liska F, Lacheta L, Imhoff AB, Burgkart R (2019) Effect of Lower Limb Alignment in Medial Meniscus–Deficient Knees on Tibiofemoral Contact Pressure. Orthop J Sports Med 7(2):1–7

72. Willinger L, Lang JJ, Berthold D, Muench LN, Achtnich A, Forkel P, Imhoff AB, Burgkart R, von Deimling C (2020) Varus alignment aggravates tibiofemoral contact pressure rise after sequential medial meniscus resection. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 28(4):1055–1063

73. Yuqing Zhang, D.Sc and Joanne M. Jordan, MD M (2011) Epidemiology of Osteoarthritis. Clin Geriatr Med 26(3):355–369

74. Zheng H, Chen C (2015) Body mass index and risk of knee osteoarthritis : systematic review and meta-analysis of prospective studies. BMJ Open 5(12):e007568

75. Zuiderbaan HA, van der List JP, Kleeblad LJ, Appelboom P, Kort NP, Pearle AD, Rademakers M V. (2016) Modern Indications, Results, and Global Trends in the Use of Unicompartmental Knee Arthroplasty and High Tibial Osteotomy in the Treatment of Isolated Medial Compartment Osteoarthritis. Am J Orthop 45(6):E355–E361

Chapter 1 High tibial osteotomy indication

1.1 Multiplanar bony morphology of the symptomatic varus knee in Caucasian male candidates for high tibial osteotomy

Unpublished study

ABSTRACT

OBJECTIVES Although the importance of malalignment in the coronal plane is now well understood for medial knee osteoarthritis (MKOA), malalignment in the sagittal and axial plane are much less studied and might pose relevant information in the context of knee osteotomy surgery. The study aimed to determine and compare the multiplanar alignment of a symptomatic varus cohort (SVC) with a healthy neutral cohort (HNC) of Caucasian males. A young subset (age ≤45y) of the SVC was analyzed to investigate any relevant differences in the context of early onset MKOA. The hypothesis was that in addition to the varus malalignment in the coronal plane, other alignment differences existed on the axial or sagittal plane in symptomatic patients.

METHODS A 3D osteotomy database (SVC) was compared to a healthy cohort (HNC) of asymptomatic neutrally aligned knees (±3°) and both retrospectively screened for relevant inclusion criteria (Age 18-70 years, male, Caucasian). Imaging parameters were measured on full-leg supine CT-scan and included the mechanical tibiofemoral angle (mTFA°), the lateral distal femoral angle (LDFA°), the medial proximal tibial angle (MPTA°), the medial and lateral tibial slope (TS°), the femoral anteversion angle (FAVA°) and the tibial eversion angle (TEVA°). The foot external rotation (FER°) was determined by subtracting FAVA° from TEVA°. Correlation testing was performed between the medial and lateral TS°, and between the FAVA° and TEVA°. Unpaired t-test or Mann-Whitney U test was used to compare cohorts. Alpha was set at 0.05.

RESULTS Sixty patients in the SVC (45.7y ±11.9, 100% male Caucasian) were found to be eligible and were compared to 104 individuals in the HNC (56.8y ±11.5, 100% male Caucasian). In the coronal plane, a significant difference was found for the LDFA° ($p<0.0001$), MPTA° ($p=0.001$) and the mTFA° ($p<0.001$). In the sagittal plane, no significant differences were found for the medial or lateral TS° between the SVC (resp. 94.7° ± 3.3 and 95.1° ± 3.4) and the HNC (resp. 94.1° ± 3.3 and

94.8° ± 3.2). In the axial plane, no significant difference was found for the FAVA°, TEVA° or FER° between cohorts. Both the interquartile range (IQR) and boxplot [5-95%] interval were fairly larger for the SC regarding FAVA° and TEVA°. Correlation testing revealed a 'medium' FAVA°/TEVA° correlation in the SVC (r=0.472) and 'few' positive correlation in the HNC (r=0.006). The young SVC (35.8y ± 7.2, 100% male Caucasian) was trending towards increased anteversion of the femur (FAVA 16.3° ± 10.4) compared to the HNC (FAVA 12.6° ± 7.1) (p=0.0841). The TEVA° was not significantly different. The FER° appeared to be significantly different between the young SVC (20.1° ± 9.8) and HNC (24.5° ± 8.3) (p=0.0497).

CONCLUSION In Caucasian males, symptomatic lower limb varus is not accompanied by structural malalignment in the sagittal (tibial slope) or axial plane (femoral or tibial rotation) compared to neutrally aligned healthy individuals. A profound large variability in FAVA° and TEVA° was observed with a medium positive correlation between these angles, which was both absent in healthy controls. A specified group of young Caucasian male patients (≤ 45y) with beginning MKOA did show a trend towards increased femoral anteversion (FAVA 16.3° ± 10.4 vs. 12.6° ± 7.1) and had definite decreased bony foot external rotation (FER 20.1° ± 9.8 vs. 24.5° ± 8.3). Altogether, when planning on knee realignment surgery for MKOA, correcting malalignment in the coronal plane remains key priority for clinical success.

KEYWORS: Knee – Osteoarthritis – Osteotomy – Indication – Morphology

INTRODUCTION

In the coronal plane, varus malalignment of the lower limb has been identified as a primary risk factor for medial knee osteoarthritis (MKOA) onset and progression [1, 3, 5]. Varus malalignment typically accelerates MKOA once a medial meniscectomy is performed, especially in obese patients [1, 18, 19]. Although the importance of malalignment in the coronal plane is now well understood for MKOA, malalignment in the sagittal and axial plane are much less studied. This is reflected by multiple guiding classifications in the coronal plane of healthy and diseased varus knees that differentiate for joint line obliquity, original site of the varus deformity and joint line (in)congruence between femur and tibia [6, 10, 12, 16]. The embedded standardization of 2D imaging techniques (full-leg standing radiographs) to determine varus/valgus alignment is prone to error if concomitant flexion or rotation of the limb is present and leaves the impossibility for further investigation in the remaining planes [13]. Therefore, associated femoral and tibial malalignment in the sagittal and/or axial plane seems underexposed in the understanding of MKOA and might pose relevant information in the context of knee osteotomy surgery and arthroplasty.

With modern (ultra) low-dose CT-scan protocols and 3D software availability, the assessment of orthopedic malalignments on both upper and lower extremity has been dramatically improved [7]. The main advantage is the measurement precision that can be performed in order to set for example angular benchmark values in large populations of healthy individuals [11, 15]. Regarding axial lower limb alignment, normal values in adults for the femoral anteversion angle (FAVA) have once been estimated on 15.6 ± 6.7° and the tibial external version angle (TEVA) on 23.5 ± 5.1° [9]. These values were recently reinvestigated in a healthy large population-based study and showed overall similar outcomes for the FAVA (15.3 ± 9.5°) but increased TEVA (31.6 ± 6.3°) as to previously known [11]. Further, Caucasians appeared to have less anteversion in the femur but more external rotation in the tibia compared to Asians, hereby showing the importance of ethnicity-specific research on this matter [11].

This study was conducted to determine and compare the multiplanar bony alignment of a symptomatic varus cohort (SVC) to a healthy neutral cohort (HNC), solely in a Caucasian male population. A young subset (age ≤45y) of the SVC was analyzed to investigate any relevant differences in the context of early onset MKOA. The hypothesis was that in addition to the varus malalignment in the coronal plane, other alignment differences existed in the axial or sagittal plane in symptomatic patients.

METHODS

For the SVC, a 3D knee osteotomy database of full-leg supine CT-scans was retrospectively screened for eligibility criteria: age 18-70 years, male sex, Caucasian race and a mechanical femorotibial angle (mTFA) ≤178° (varus). Subjects with previous bony surgery of femur or tibia, traumatic malalignment or the presence of an ankle/hip arthroplasty were excluded. CT-scans were derived from a past prospective 3D osteotomy study including two orthopaedic centres, that was earlier approved by the local and university ethical committees. All subjects underwent or were planned to undergo a valgus-producing knee osteotomy (high tibial osteotomy (HTO), distal femur osteotomy (DFO) or double-level osteotomy (DLO)).

For 3D measurements in the SVC, Digital Imaging and Communications in Medicine (DICOM) files from full-leg CT-scan (0.5-0.8mm knee slice thickness and spacing according to the Trumatch protocol by DepuySynthes®) were loaded into the segmentation software Mimics® 23.0 (Materialise, Leuven, Belgium) to separate the femur and tibia from surrounding soft tissue. Segmentation threshold was customized and set to a minimum of 130-200 Hounsfield units (HU) to gain adequate shaping of the complete bony model. The anatomical 3D model was then studied in 3-matic® 15.0 (Materialise, Leuven, Belgium). The hip center was first determined by marking the femoral head with subsequent fitting of a best fit sphere. The center of the distal tibia (pilon) was defined by measuring the anteroposterior and mediolateral middle of the tibial plafond surface. Correct positioning was visually controlled on an anteroposterior view. Landmarks around the knee joint were manually defined as earlier described by Victor et al. [17].

The anatomic plane of the femur was determined by connecting the medial and lateral epicondyle of the femur (=trans-epicondylar axis (TEA)) and the femoral head center. The mechanical femoral axis was created by connecting the femoral head center and the middle of the TEA. The anatomic plane of the tibia was then defined by the tip of the medial and lateral tibial spine and the pilon center. The mechanical tibial axis was created by connecting the center of the tibial pilon to the middle of the medial and lateral tibial spine distance. For the coronal angles, the mechanical tibiofemoral angle (mTFA°), lateral distal femoral angle (LDFA°) were determined in the anatomical femur plane while the medial proximal tibial angle (MPTA°) was measured in the anatomical tibial plane. A best fitting plane for the medial and lateral tibial plateau was determined and formed together with the mechanical tibial axis the medial and lateral tibial slope (TS°) angles. These were measured in the sagittal tibial plane, which was generated by comprising the mechanical tibial axis while being perpendicular to the anatomical tibial plane. The absolute difference between medial and lateral TS° was determined. Finally, the femoral anteversion angle (FAVA°) and tibial external version angle (TEVA°) were measured in an axial plane designed by the initial anatomical femoral plane. The femoral neck axis (FNA) was created by connecting the center of the hip to the most central point on the lateral femoral cortex (visual control) and formed together with the posterior condylar line (PCL) the FAVA°. The TEVA° was formed by the posterior line connecting the posterior borders of the medial and lateral tibial plateau and the line connecting the centers of the medial and lateral malleoli. The TEVA° was measured in the axial plane designed by the anatomical tibial plane. This method was previously used by Mathon et al. (TEVA° method 2) [11]. The foot external rotation (FER°) was determined by subtracting FAVA° from TEVA°. Correlation testing was performed between the MS° and LS°, and between the FAVA° and TEVA° per cohort. Additionally, a subgroup of young patients (age ≤45y) from the SVC was analyzed separately to identify any relevant bony morphology factors regarding early onset MKOA.

The neutral healthy cohort (HNC) was retrieved as a subgroup from the SOMA database (Stryker, Mahwah, New Jersey) [11] and used in this study with permission by the authors and by the owning company. This database was established by automatic CT-scan-based modeling using a validated software (Soma TM, Stryker, Mahwah, US). Reproducibility of angle measurement and reliable subject screening was earlier confirmed in the study by Mathon et al. (2020) using the same dataset [11]. All Caucasian males, aged 18-70 years with a neutral alignment (mTFA 180° ± 3°), were included in the HNC.

Statistics

Data outcomes were outlined as boxplots [5-95%] whereas descriptive outcomes were expressed as mean ± standard deviation (SD). Datasets were screened for outliers (Grubbs' test) and consequently removed. Assessment of normalized data by D'Agostino and Pearson omnibus normality test guided further statistics into parametric (P) or non-parametric tests (NP). Outcomes per cohort were compared by the Unpaired t-test (P) or the Mann-Whitney U test (NP). Welch's correction was applied in case of unequal variances. Correlation was assessed by the Pearson test (P) or Spearman test (NP) and expressed as correlation factor ‘r’. Alpha was set at 0.05 during all analysis. Measurements and analysis were performed by a single observer. Statistical tests were conducted in GraphPad Prism version 8.0.0 for Windows (GraphPad Software, San Diego, California USA, www.graphpad.com).

RESULTS

Sixty patients in the SVC (45.7y ± 11.9, 100% male Caucasian) were found to be eligible and were compared to 104 patients in the HNC (56.8y ± 11.5, 100% male Caucasian).

In the coronal plane, a significant difference was found for the LDFA° (resp. 88.2° ±2.0 and 86.5° ±1.4, $p<0.0001$), the MPTA° (resp. 85.2° ±2.5 and 86.4° ±1.7, $p=0.001$) and the mTFA° (resp. 174.6° ±2.2 and 179.0° ±1.3, $p<0.001$) (Figure 1). Mean differences between the SVC and HNC was 1.7° for the LDFA°, 1.2° for the MPTA° and 4.4° for the mTFA°.

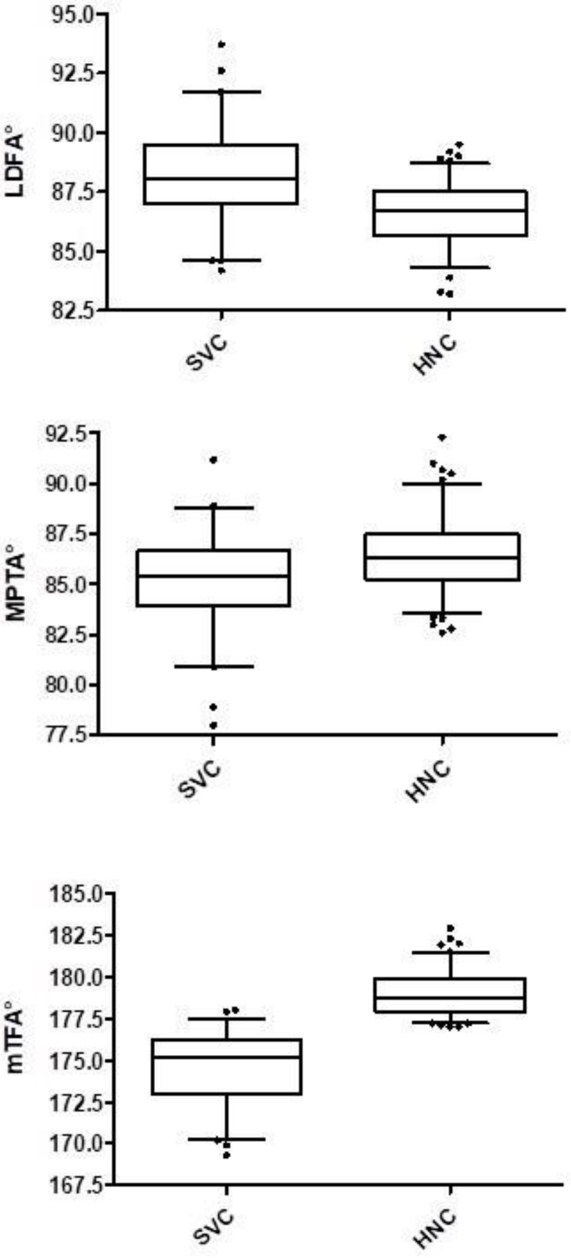


Figure 1. Angular differences in the coronal plane between the symptomatic varus cohort (SVC, n=60) and the healthy neutral cohort (HNC, n=104). All angles are significantly different between cohorts. LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle; mTFA, mechanical tibiofemoral angle.

In the sagittal plane, no significant differences were found for the medial or lateral TS° between the SVC (resp. 94.7° ±3.3 and 95.1° ±3.4) and the HNC (resp. 94.1° ±3.3 and 94.8° ±3.2) (Figure 2). The absolute difference between medial and lateral TS° was 2.8° ± 2.0 in the SC and 3.2° ± 2.0 in the HC, which was not significantly different. The medial and lateral TS° were 'medium' correlated in the SVC (r=0.436) and 'low' in the HNC (r=0.323).

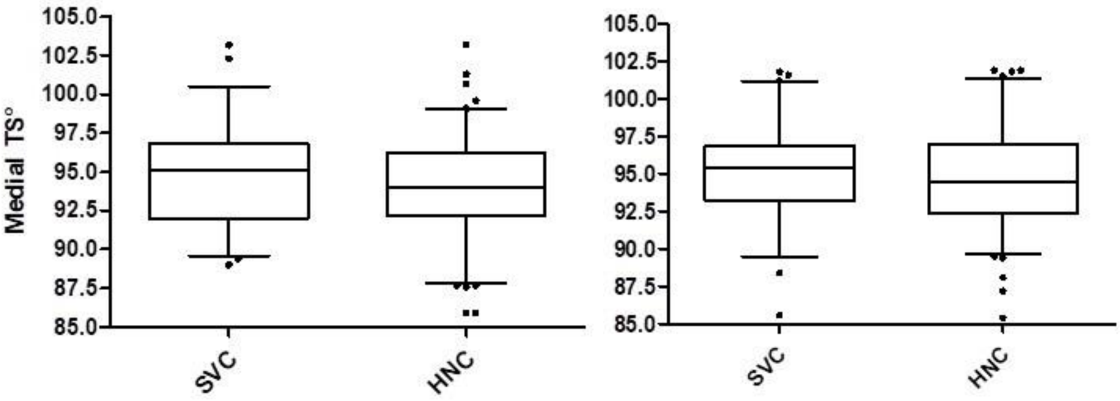


Figure 2. Angular differences in the sagittal plane between the symptomatic varus cohort (SVC, n=60) and the healthy neutral cohort (HNC, n=104). None of the angles was significantly different between cohorts. TS, tibial slope.

In the axial plane, no significant difference was found for the FAVA°, TEVA° or FER° between cohorts (Figure 3). Both the interquartile range (IQR) and boxplot [5-95%] interval were fairly larger for the SVC regarding FAVA° and TEVA°. Correlation testing revealed a 'medium' FAVA°/TEVA° correlation in the SVC (r=0.472, p=0.001) and 'few' positive correlation in the HNC (r=0.006, p=0.970) (Figure 4).

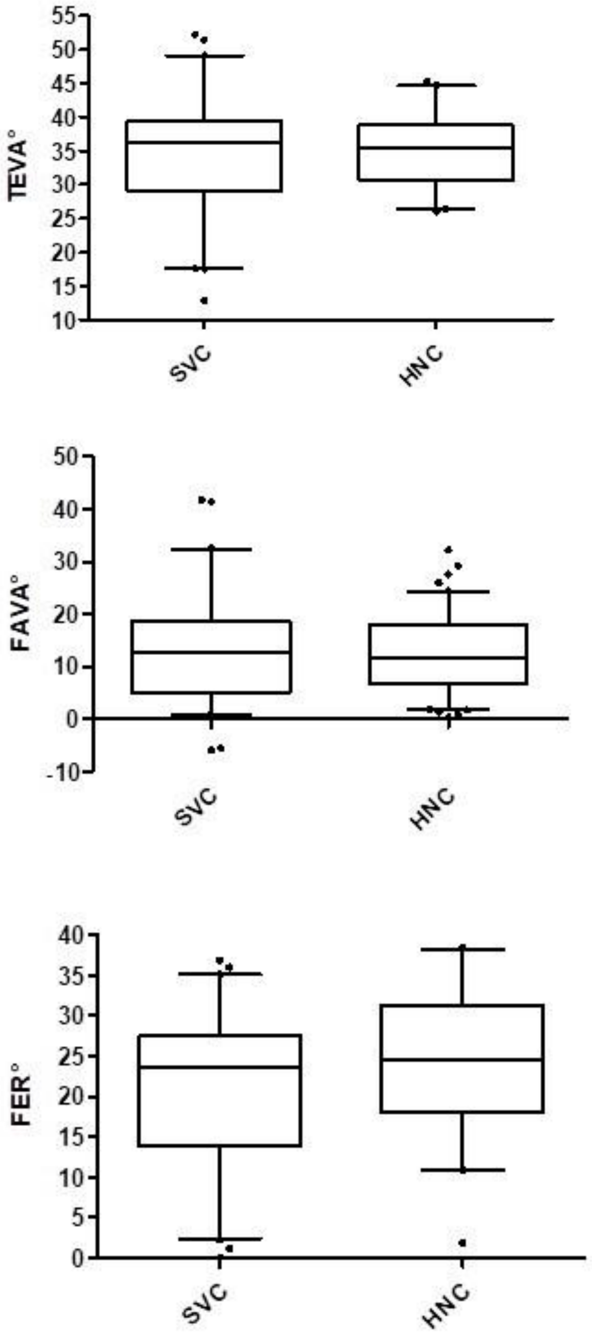


Figure 3. Angular differences in the axial plane between the symptomatic varus cohort (SVC, n=60) and the healthy neutral cohort (HNC, n=104 (TEVA and FER n=42)). None of the angles was significantly different between cohorts. FAVA, femoral anteversion angle; TEVA, tibia external version angle; FER, foot external rotation.

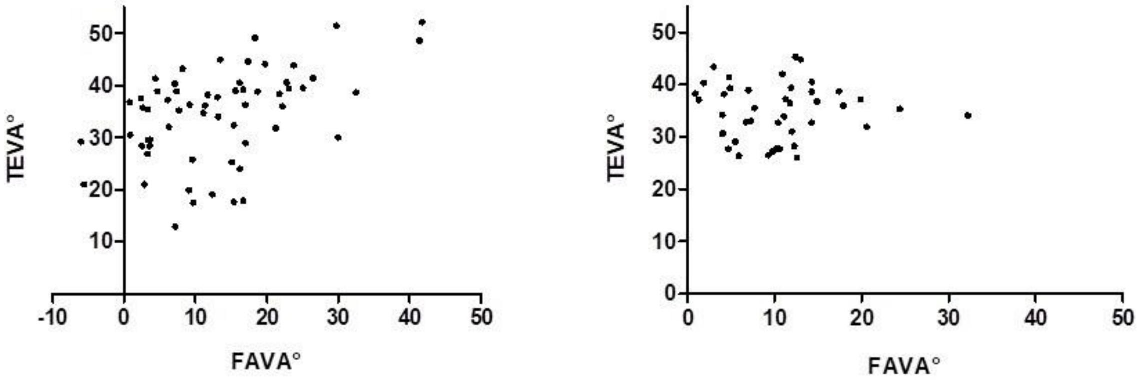


Figure 4. Correlation testing for the FAVA° and TEVA° per cohort; the symptomatic varus cohort (SVC, r=0.472) (Left) showed medial positive correlation; the healthy neutral cohort (HNC, r=0.006) (Right) showed no correlation.

The young SVC (35.8y ± 7.2, 100% male Caucasian) counted 28 patients for analysis and was compared to the HNC (n=104) (Table 1). Considering angles in the coronal and sagittal plane, outcomes with regards to the HNC were similar as for the complete SVC. In the axial plane, the young SVC was trending towards increased anteversion of the femur (FAVA 16.3° ± 10.4) compared to the HNC (FAVA 12.6° ± 7.1) (p=0.0841). The TEVA° was not significantly different. The FER° appeared to be significantly different between the young SVC (20.1° ± 9.8) and HNC (24.5° ± 8.3) (p=0.0497).

	Young SVC (n=28)	**HNC (n=104)**	**P**
Age (years)	35,8 ± 7,2	56,8 ± 11,5	<0,0001*
LDFA°	88,9 ± 2,3	86,5 ± 1,4	<0,0001*
MPTA°	84,8 ± 3,0	86,4 ± 1,7	0,0038*
mTFA°	173,8 ± 2,3	179,0 ± 1,3	<0,0001*
Medial TS°	94,8 ± 3,2	94,1 ± 3,3	0,2892
Lateral TS°	95,6 ± 3,3	94,8 ± 3,2	0,2945
Abs Slope Diff. (°)	2,9 ± 2,0	3,2 ± 2,4	0,7306
FAVA°	16,3 ± 10,4	12,6 ± 7,1	0,0841
TEVA°	36,3 ± 8,8	34,9 ± 5,3 (n=42)	0,4656
FER°	20,1 ± 9,8	24,5 ± 8,3 (n=42)	0,0479*

Table 1. Overview of angle differences between the young symptomatic varus cohort (SVC) and the healthy neutral cohort (HNC). LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle; mTFA, mechanical tibiofemoral angle; TS, tibial slope; FAVA, femoral anteversion angle; TEVA, tibia external version angle; FER, foot external rotation. *p<0.05.

DISCUSSION

The most important findings of this study are that in Caucasian males, no differences could be found in the sagittal or axial plane regarding tibial slope, FAVA°, TEVA° and foot external rotation between symptomatic varus patients and neutrally aligned healthy individuals. The study hypothesis was therefore not confirmed. In the SVC, a profound larger variability in FAVA° and TEVA° was observed with a medium positive correlation between FAVA° and TEVA°, which was completely absent in the HNC. Finally, young Caucasian male patients (≤ 45y) with MKOA necessitating HTO surgery did show a trend towards increased femoral anteversion (FAVA 16.3° ± 10.4 vs. 12.6° ± 7.1) and had definite decreased bony foot external rotation (FER 20.1° ± 9.8 vs. 24.5° ± 8.3) on top of a significant coronal varus malalignment in the femur and tibia.

The association of varus malalignment and MKOA is extensively investigated [1, 3, 5], while potential concomitant bony deformities in the sagittal and axial plane have been mostly ignored. This is the first study to explore 3D alignment parameters in symptomatic MKOA patients and compare them to a healthy neutral cohort. In the SVC, varus alignment was profound by intended cohort composition as per study protocol (symptomatic varus malalignment versus healthy neutrally aligned individuals). Larger LDFA (+1.7°) and smaller MPTA (-1.2°) in the SVC contributed to the overall varus malalignment (mTFA). Even though, the mean rotation of the femur and tibia was not statistically different between the SVC and HNC, larger variations were observed in the SVC. Especially for the TEVA°, the SVC [5-95%] interval was almost double [17.5°-49.0°] of the HNC [26.0°-44.0°]. Moreover, TEVA values were moderately correlated with FAVA values and vice versa in the SVC (r=0.472, p=0.001), which was completely absent in the HNC (r=0.006, p=0.970). It is suggested that this 'compensatory-like' observation can be attributed to maintain foot external rotation within normal ranges, hereby preserving normal gait. Nevertheless, these data should evoke a certain awareness that symptomatic varus malalignment can be associated with excessive rotational malalignment of the femur or tibia which is considered highly relevant information regarding knee osteotomy or arthroplasty planning [2, 8, 14]. Surprisingly, in the young SVC, the foot external rotation was significantly smaller (20.1° ± 9.8) compared to the HNC (24.5° ± 8.3) (p=0.0497). This was mainly resulting from an increased, but not significant FAVA (16.3° ± 10.4) found in the young SVC.

Overall, we can conclude that the contribution to the overload process of MKOA can largely be attributed to the presence of mechanical coronal plane varus in first place [1, 3, 5]. With regards to knee osteotomy planning in the symptomatic varus knee with MKOA, the primary focus should remain to correct the coronal plane malalignment.

Clear differences in bony alignment have been identified between ethnicities and sexes [11, 15]. The decision for only including Caucasian males was based on three arguments; first the 3D osteotomy database consisted mainly of males (87%) of Caucasian origin (97%), as this seems clinically the most relevant population for knee osteotomy. Second, healthy females exhibit more femoral valgus [15] and femoral anteversion [11] compared to males. Third, Asians show more anteversion on the femur but less on the tibia compared to Caucasians [11]. Including females and a non-Caucasian race could have scattered data in the coronal and axial plane, potentially resulting in false conclusions. Therefore, the authors strongly advocate to differentiate for ethnicity and sex regarding future research on bony lower limb alignment.

Some limitations need to be addressed to the study. Angle parameters were not measured by a single observer over both cohorts. The HC was derived from the automated SOMA database (Stryker®) for which the authors were unable to repeat measurements personally. Methodology of point, line and plane definition as well as angle measurements were mimicked for the SC as described by Siboni et al. and Mathon et al. for the SOMA database [11, 15]. The major difference was that anatomic landmarks were pre-defined in SOMA whereas for the SC, the landmarks were determined manually by a single observer. Nevertheless, it has been shown that manual landmark determination on CT-based 3D models of knee have high reproducibility [17]. Missing data in the HC formed truly an issue for the TEVA and FER values. Unfortunately, more than 50% of included cases in the HC did not have these required data points. Therefore, the references values (HNC) on TEVA and FER should be interpreted with caution. Finally, it is known that measurements of the FAVA and TEVA may vary based on the used methodology to determine the respective femoral neck axis (FNA) and posterior line of the tibial plateau [4, 11]. In this study, the FNA (mainly the lateral femoral landmark) was determined under visual control as 'best fit' according to the observer. The authors are aware that more so-called objective methods are described for FAVA, although still with large inter- methodology variability [4].

CONCLUSION

In Caucasian males, symptomatic lower limb varus is not accompanied by structural malalignment in the sagittal (tibial slope) or axial plane (femoral or tibial rotation) compared to neutrally aligned healthy individuals. A profound large variability in FAVA° and TEVA° was observed with a medium positive correlation between these angles, which were both absent in healthy controls. A specified group of young Caucasian male patients (≤ 45y) with beginning medial OA did show a trend towards increased femoral anteversion (FAVA 16.3° ± 10.4 vs. 12.6° ± 7.1) and had definite decreased bony foot external rotation (FER 20.1° ± 9.8 vs. 24.5° ± 8.3). Altogether, when planning on knee realignment surgery for MKOA, correcting malalignment in the coronal plane remains key priority for clinical success.

CONFLICT OF INTERST

The authors declare to have no conflict of interest.

FUNDING

No funding was received for this study.

ACKNOWLEDGEMENT

None.

REFERENCES

1. Brouwer GM, Van Tol AW, Bergink AP, Belo JN, Bernsen RMD, Reijman M, Pols HAP, Bierma-Zeinstra SMA (2007) Association between valgus and varus alignment and the development and progression of radiographic osteoarthritis of the knee. Arthritis and Rheumatism 56(4):1204–1211

2. Castelli CC, Falvo DA, Iapicca ML, Gotti V (2016) Rotational alignment of the femoral component in total knee arthroplasty. Annals of Translational Medicine 4(1):2–10

3. Cerejo R, Dunlop DD, Cahue S, Channin D, Song J, Sharma L (2002) The influence of alignment on risk of knee osteoarthritis progression according to baseline stage of disease. Arthritis and Rheumatism 46(10):2632–2636

4. Van fraeyenhove B, Van Haver A, Grammens J, Mestach G, Verhaegen J, Verdonk P (2021) The Quest For Optimal Femoral Anteversion Angle Measurements: A Comparative Advanced 3D Study. 2021 ISAKOS Biennial Congress Paper

5. Heijink A, Gomoll AH, Madry H, Drobnič M, Filardo G, Espregueira-Mendes J, van Dijk CN (2012) Biomechanical considerations in the pathogenesis of osteoarthritis of the knee. Knee Surg Sports Traumatol Arthrosc 20(3):423–435

6. Hirschmann MT, Moser LB, Amsler F, Behrend H, Leclerq V, Hess S (2019) Functional knee phenotypes: a novel classification for phenotyping the coronal lower limb alignment based on the native alignment in young non-osteoarthritic patients. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 27(5):1394–1402

7. Keller G, Afat S, Ahrend MD, Springer F (2021) Diagnostic accuracy of ultra-low-dose CT for torsion measurement of the lower limb. European Radiology European Radiology 31(6):3574–3581

8. Kfuri M, Crist BD, Stannard JP (2022) Preoperative Planning and Preservation of the Knee with Complex Osteotomies. Missouri medicine 119(2):144–151

9. Luís NM, Varatojo R (2021) Radiological assessment of lower limb alignment. EFORT Open Reviews 6(6):487–494

10. MacDessi SJ, Griffiths-Jones W, Harris IA, Bellemans J, Chen DB (2021) Coronal Plane Alignment of the Knee (CPAK) classification a new system for describing knee phenotypes. Bone Joint J 103 B(2):329–337

11. Mathon P, Micicoi G, Seil R, Kacaoglu B, Cerciello S, Ahmad F, LiArno S, Teitge R, Ollivier M (2021) Healthy middle-aged Asian and Caucasian populations present with large intra- and inter-individual variations of lower limb torsion. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(4):1083–1089

12. Mullaji A, Shah R, Bhoskar R, Singh A, Haidermota M, Thakur H (2021) Seven phenotypes of varus osteoarthritic knees can be identified in the coronal plane. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 30(8):2793-2805

13. Nguyen HC, Gielis WP, van Egmond N, Weinans H, Slump CH, Sakkers RJB, Custers RJH (2021) The need for a standardized whole leg radiograph guideline: The effects of knee flexion, leg rotation, and X-ray beam height. J Cartil Jt Preserv Elsevier B.V. 1(3):100022

14. Reif TJ, Humphrey TJ, Fragomen AT (2022) Osteotomies About the Knee: Managing Rotational Deformities. Operative Techniques in Sports Medicine Elsevier Inc. 30(3):1–11

15. Siboni R, Vialla T, Joseph E, LiArno S, Faizan A, Martz P, Ollivier M (2022) Coronal and sagittal alignment of the lower limb in Caucasians: Analysis of a 3D CT database. Orthop Traumatol Surg Res Elsevier Masson SAS 108(3):103251

16. Thienpont E, Parvizi J (2016) A New Classification for the Varus Knee. J Arthroplasty 31(10):2156–2160

17. Victor J, Van Doninck D, Labey L, Innocenti B, Parizel PM, Bellemans J (2009) How precise can bony landmarks be determined on a CT scan of the knee? Knee Elsevier B.V. 16(5):358–365

18. Willinger L, Foehr P, Achtnich A, Forkel P, Voss A, Liska F, Lacheta L, Imhoff AB, Burgkart R (2019) Effect of Lower Limb Alignment in Medial Meniscus–Deficient Knees on Tibiofemoral Contact Pressure. Orthop J Sports Med 7(2):1–7

19. Willinger L, Lang JJ, Berthold D, Muench LN, Achtnich A, Forkel P, Imhoff AB, Burgkart R, von Deimling C (2020) Varus alignment aggravates tibiofemoral contact pressure rise after sequential medial meniscus resection. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 28(4):1055–1063

1.2 Outcome stratification after medial opening-wedge high tibial osteotomy by means of the CPAK classification

Study under review in KSSTA

ABSTRACT

OBJECTIVES Clinical studies regarding medial open-wedge high tibial osteotomy (MOWHTO) often analyse a mixture of varus entities without differentiating for its primary varus-inducing component. This study aims to compare the radiological and clinical outcomes of the most prevalent varus malalignment phenotypes by means of the CPAK classification.

METHODS Accurate MOWHTO cases with minimal 2 year clinical follow-up were retrospectively selected from a knee osteotomy database (2016-2020). Based on the medial proximal tibial angle (MPTA) and lateral distal femoral angle (LDFA), subjects were allocated to the correct CPAK phenotype, both pre- and postoperatively. Clinical outcomes were NRS, KOOS and therapeutic response rate (TRR) at 2 year follow-up. Inter-observer correlation coefficient (ICC) and unpaired student t-test was performed for cross-cohort comparison.

RESULTS 135 subjects were found eligible (53,0y ±9,6 [19-77], 72% male, 53% left sided). The most prevalent preoperative phenotype was CPAK 1 (n=70 (52%)) and postoperative phenotype was CPAK 6 (n=66 (49%)). All CPAK phenotypes improved significantly relative to baseline but cross-cohort comparison yielded no significant differences in clinical outcome. The TRR at two year was 67% for CPAK 1, 69% for CPAK 2 and 87% for CPAK 4. The TRR for CPAK 6 was 64% compared to 80% for the CPAK 9, which was not significantly different.

CONCLUSION At 2 year follow-up, no clinical significant differences are observed between different CPAK phenotypes. Accurate MOWHTO corrections (180-184° mTFA) provide significant clinical improvement even in the femoral-driven varus knee (CPAK 4) and the constitutional varus knee dominated by intra-articular wear (CPAK 2).

KEYWORDS: High tibial osteotomy – Indication – Outcome – Knee – Alignment – Varus

INTRODUCTION

Valgus producing lower limb realignment surgery for medial knee osteoarthritis (OA) has historically been treated at the level of the tibia by performing high tibial osteotomy (HTO) surgery [1, 5, 11]. These tibial corrections towards valgus have been performed regardless of the primary contributing component to the overall varus malalignment (tibial, femoral or intra-articular (IA)) and preoperative joint line orientation. Such an 'all at the tibia' approach may result in high postoperative joint line obliquity (JLO) or abnormally high non-anatomical medial proximal tibial angles (MPTA) [8, 20]. According to Nakayama et al., a postoperative JLO > 5° induces excessive laterally directed shear stress on the cartilage on 3D finite element analysis [23]. Moreover, Kim et al. concluded that a postoperative MPTA >95.2° was associated with more valgus overcorrection resulting in both inferior radiological and clinical outcomes [14].

While the actual long-term consequences of these high post-osteotomy angles are still debated [30], it is now understood that the tibial bony varus phenotype as primary underlying reason for the overall varus malignment and medial OA has been overestimated [8, 20, 25]. Razak et al. found more femoral varus and equal tibial varus in patients scheduled for high tibial osteotomy (HTO) compared to non-arthritic varus controls [25]. In order to avoid excessive postoperative JLO, Feucht et al. showed that isolated HTO surgery is indicated in only 57% of the symptomatic varus knees if a postoperative MPTA up to 95° is accepted [8]. In addition, his study suggested a double-level osteotomy (DLO) in 33% and a single distal femoral osteotomy (DFO) in 8% [8]. Moreover, the prevalence of a true tibial varus deformity (MPTA <85°) was only present in 28% of cases. These studies clearly advocate for bony corrections at the level of the deformity rather than the 'all at the tibia' principle. Despite this fact, most clinical MOWHTO studies report outcomes on a mixture of varus entities without differentiating for its primary inducing varus component. Consequently, the therapeutical response rate (TRR) and clinical outcome of MOWHTO on different varus knee phenotypes is an underexposed research area that might possess relevant information regarding patient selection.

The coronal plane alignment of the knee (CPAK) classification, introduced by MacDessi et al. in 2021, forms an easy applicable tool for preoperative varus, neutral or valgus phenotype categorization of the osteoarthritic knee [19]. It contains a three by three matrix and includes the parameters of overall alignment (varus, neutral, valgus) and joint line obliquity (sum of the lateral distal femoral angle (LDFA) and the MPTA). Consequently, the postoperative realignment of a valgus-producing osteotomy could also be categorized according to this classification system into one of the neutral or valgus phenotypes.

Therefore, this study wants to verify and compare the most prevalent preoperative and postoperative alignment phenotypes with their respective radiological and clinical outcomes before and after MOWHTO by means of the CPAK classification. The hypothesis was that tibial varus deformities with or without a moderate intra-articular varus component (CPAK 1) have favourable short-term clinical and radiological outcomes and that cases with an overcorrected MPTA would have an inferior clinical outcome.

METHODOLOGY

A single-centre knee osteotomy database (2016-2020) was retrospectively screened by a single observer for the following eligibility criteria:

- Valgus producing unilateral MOWHTO surgery
- Patient age at time of surgery between 18-80 years
- Availability of baseline patient reported outcome measures (PROMs) and minimal two year clinical follow-up

The selected cases were then subjected to specific radiological inclusion criteria:

- The availability of a valid preoperative (within one year before surgery) and postoperative (three months) full leg bipodal standing radiograph and a Schuss view knee radiograph
- Preoperative mechanical varus alignment of 170-177.5° mTFA
- Osteoarthritis severity grade 1-3 (Kellgren and Lawrence)
- Postoperative valgus alignment of 180-184° mTFA

Study demographics consisted of patient age, treated side, sex, osteoarthritis severity, % concomitant knee arthroscopy procedure with MOWHTO, the need for hardware removal, the conversion rate to arthroplasty and the need for secondary knee arthroscopy. Primary clinical outcomes were represented by the numeric rating scale (NRS) for pain (0-100) at rest and during activity and the Knee Injury and Osteoarthritis Outcome Score (KOOS) at baseline and two year.

The threshold for determining the therapeutic response rate (TRR%) was set at 15 points absolute improvement on overall KOOS relative to baseline [12]. This research study was conducted retrospectively from data obtained for clinical purposes and all the procedures being performed were part of the routine care.

Radiological measurement on pre-and postoperative full leg radiographs included the LDFA°, MPTA°, mTFA°, and JLCA°. OA severity was scored following the Kellgren and Lawrence classification on Schuss radiographs [13]. Radiological data were measured by two blinded observers and the interobserver reliability was determined. A common case-by-case review decided if a second measurement round was necessary in case large discrepancies were detected.

The CPAK classification [19] was used to allocate the included cases into the correct preoperative and postoperative phenotype (Figure 1). The following definitions were applied to determine the correct CPAK phenotype; overall alignment (arithmetic hip-knee-ankle angle (aHKA) = MPTA° – LDFA°): Varus ≤ -2°, Neutral -2 to 2° or Valgus ≥ 2°. The Joint line obliquity (JLO = MPTA° + LDFA°) was classified as with the apex distally (JLO≤177°), the apex neutrally (JLO = 177°-183°) or the apex proximally (JLO≥ 183°). Important to note is that CPAK only refers to bony alignment categorization while ignoring the JLCA (or intra-articular wear). However, the aHKA has shown to provide an excellent estimation of the constitutional alignment of the lower limb previously, especially in overall varus malalignment <8° mTFA [3, 18].

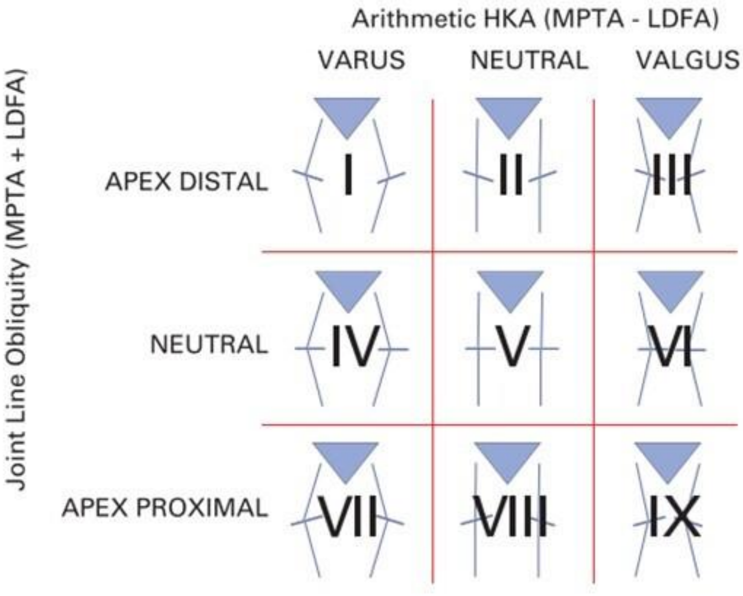


Figure 1. The knee phenotype classification according to MacDessi et al. (2021) (used with permission from the authors and Bone and Joint Journal).

Radiological parameters and clinical outcome at two year follow-up were first determined for the entire population, followed by inter-phenotype comparison of:

A. Preoperative CPAK 1, CPAK 2 and CPAK 4
B. Postoperative CPAK 6 and CPAK 9
C. Postoperative CPAK 5/6 and CPAK 8/9

CPAK phenotypes with ≤ 15 cases were excluded for comparative analysis due to the low sample size.

<u>Statistics</u>

Descriptive statistics were displayed as mean ± standard deviation (SD) [minimum (min);maximum(max) values]. Radiological data were measured by two observers for which the interobserver correlation coefficient (ICC) was determined. In general, outliers were first removed by the Grubbs test and normal distribution was assessed by the D'Agostino and Pearson test. Parametric or non-parametric statistics were performed depending on normal distribution testing. For radiological parameters, the interobserver reliability was determined by correlation testing r (Spearman or Pearson test). The paired t-test or the Wilcoxon matched pairs test was applied to assess differences in pre- and postoperative radiological and clinical parameters for the entire population. For inter-phenotype parameter comparison of three groups, One-way ANOVA testing was performed by the One-way analysis of variance (with post-hoc Bonferroni test) in case of normalized data, the Kruskal-Wallis test (with post-hoc Dunn's test) was used otherwise. For inter-phenotype parameter comparison of two groups, the unpaired t-test was used in normal distributed data and the Mann-Whitney U test as non-parametric alternative. A Welch's correction was applied if unequal variances were detected. Differences in TRR% were determined by the Fischer's exact test. Alpha was set at 0.05 to define statistical significance. Statistical tests were conducted in Graphpad 8.0. (IBM Co., Armonk, NY, USA).

RESULTS

135 subjects were found eligible for analysis (53.0±9.6 years [19-77], 72% male, 53% left sided). Osteoarthritis severity was equally distributed; grade 1 (30%), grade 2 (29%) and grade 3 (41%). A concomitant knee arthroscopy was performed in 9% of cases. Postoperatively, the implant was removed in 48%. Ten (10) percent needed an additional knee arthroscopy within two years. None of the osteotomies was converted to arthroplasty. Pre- and postoperative radiological outcomes are outlined in table 1. Overall, an excellent inter-observer correlation ($r \geq 0.90$) was observed for the determined parameters. All postoperative parameters were significantly different compared to preoperatively ($p < 0.0001$) while the LDFA° was only measured on preoperative radiographs. The average correction size was 7.3°±2.8 (ΔmTFA°). Regarding clinical outcomes, the NRS rest and activity and the KOOS significantly improved 2 year after surgery (Figure 2). An overall TRR of 69% was found at 2 year follow-up.

	Preoperative	**Postoperative**	**ICC preoperative/postoperative**	**P**
LDFA°	88,8 ±1,9	-	0.90/-	-
MPTA°	85,9 ±2,0	92,5 ±2,2	0.92/0.96	<0,0001*
mTFA°	174,7 ±1,8	182,0 ±1,3	0.97/0.93	<0,0001*
JLCA°	2,5 ±1,5	2,0 ±1,4	0.92/0.93	<0,0001*
JLO° (calculated)	174,7 ±3.4	181.2 ±3.5	-	<0,0001*
aHKA° (calculated)	-2.9 ±2.0	3.7 ±2.2	-	<0,0001*

Table 1. The pre- and postoperative radiological outcomes of the entire cohort (n=135). Except for the LDFA, all parameters were significantly different. LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle; mTFA, mechanical tibiofemoral angle; JLCA, joint line convergence angle; JLO, joint line obliquity; aHKA, arithmetic hip-knee-ankle; ICC, interobserver correlation coefficient.

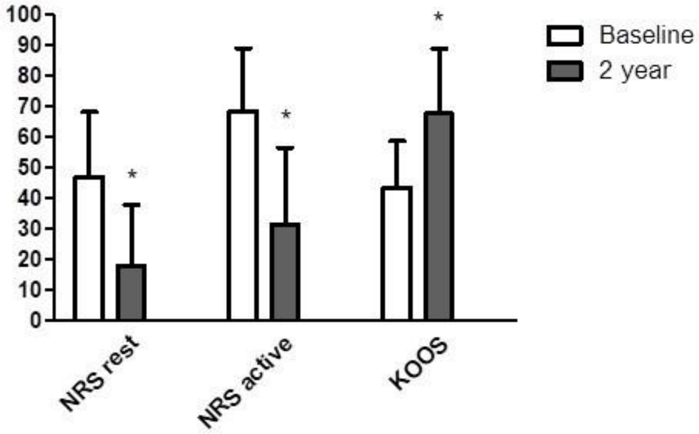


Figure 2. The pre- and postoperative clinical outcomes after medial opening-wedge high tibial osteotomy (MOWHTO). All outcomes improved significantly at 2 year follow-up. *p<0.05.

A. Preoperative CPAK 1, CPAK 2 and CPAK 4

The most prevalent preoperative phenotype was CPAK 1 (n=70 (52%)), featured by a varus malalignment (174,0° ±1,8 mTFA) which was mostly tibia driven (MPTA 84,6° ±1,5) while having a JLO≤177° (apex distally). The overall pre- and postoperative CPAK distribution is outlined in figure 3.

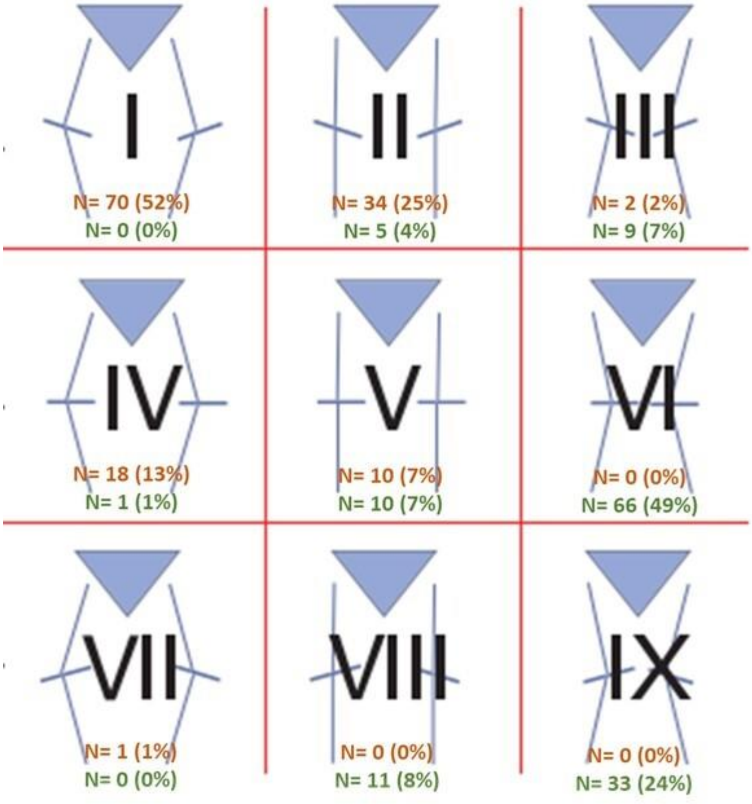


Figure 3. The pre- (red) and postoperative (green) distribution of knee phenotypes undergoing an accurate MOWHTO according to the CPAK classification.

Inter-phenotype comparison between CPAK 1, CPAK 2 (n=34 (25%)) and CPAK 4 (n=18 (13%)) revealed significant differences between each phenotype for the LDFA° (p<0.0001) (Table 2). Femoral varus was most prominent in CPAK 4 (91.4° ±1.1 LDFA). The MPTA° in CPAK 1 (84.6° ±1.5) differed significantly from CPAK 2 (86.5° ±1.3) and CPAK 4 (87.7° ±1.0) (p<0.0001). Small overall varus was found in CPAK 2 (175.9 ±0.8 mTFA) compared to CPAK 1 (174.0 ±1.8) and CPAK 4 (174.1 ±1.8) (p<0.0001) which was mainly determined by the difference in preoperative JLCA° between these phenotypes (p<0.0001). Postoperative realignment showed an 94.3° ±2.0 MPTA in CPAK 4 that significantly differed from CPAK 1 (91.9° ±1.9) and CPAK 2 (92.1° ±2.2) (p<0.0001). Similar to the preoperative JLCA, the postoperative JLCA was significantly higher in CPAK 2 (2.6° ±1.9) compared to CPAK 1 (1.5° ±1.2) and CPAK 4 (1.5° ±1.5). Regarding clinical outcomes, no significant differences were observed between pre – or postoperative NRS or KOOS outcomes between CPAK 1, 2 or 4 (Figure 4). The TRR at two year was 67% for CPAK 1, 69% for CPAK 2 and 87% for CPAK 4 which showed no statistical significant difference.

Preoperative CPAK		**CPAK 1**	**CPAK 2**	**CPAK 4**	**P**
N (%)		**70 (52%)**	**34 (25%)**	**18 (13%)**	-
LDFA°	Preoperative	88,7 ±1,4	87,3 ±1,2	91,4 ±1,1	<0.0001*
	Postoperative	-	-	-	-
MPTA°	Preoperative	84,6 ±1,5	86,5 ±1,3	87,7 ±1,0	<0,0001*
	Postoperative	91,9 ±1,9	92,1 ±2,2	94,3 ±2,0	<0,0001*
mTFA°	Preoperative	174,0 ±1,8	175,9 ±0,8	174,1 ±1,8	<0,0001*
	Postoperative	181,9 ±1,2	182,2 ±1,3	182,0 ±1,1	0.4514
JLCA°	Preoperative	2,0 ±1,4	3,3 ±0,9	2,3 ±1,5	<0,0001*
	Postoperative	1,5 ±1,2	2,6 ±1,1	1,5 ±1,5	<0,0001*
aHKA°	Preoperative	-4.1 ±1.4	-0.8 ±0.6	-3.7 ±1.3	<0,0001*
	Postoperative	3.2 ±2.1	4.8 ±1.9	2.9 ±2.4	<0,0001*
JLO°	Preoperative	173.3 ±2.5	173.7 ±2.4	179.1 ±1.7	<0,0001*
	Postoperative	180.5 ±2.7	179.3 ±3.0	185.7 ±2.0	<0,0001*

Table 2. The pre- and postoperative radiological outcome comparison of CPAK 1, CPAK 2 and CPAK 4. LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle; mTFA, mechanical tibiofemoral angle; JLCA, joint line convergence angle; aHKA, arithmetic hip-knee-ankle angle; JLO, joint-line obliquity.

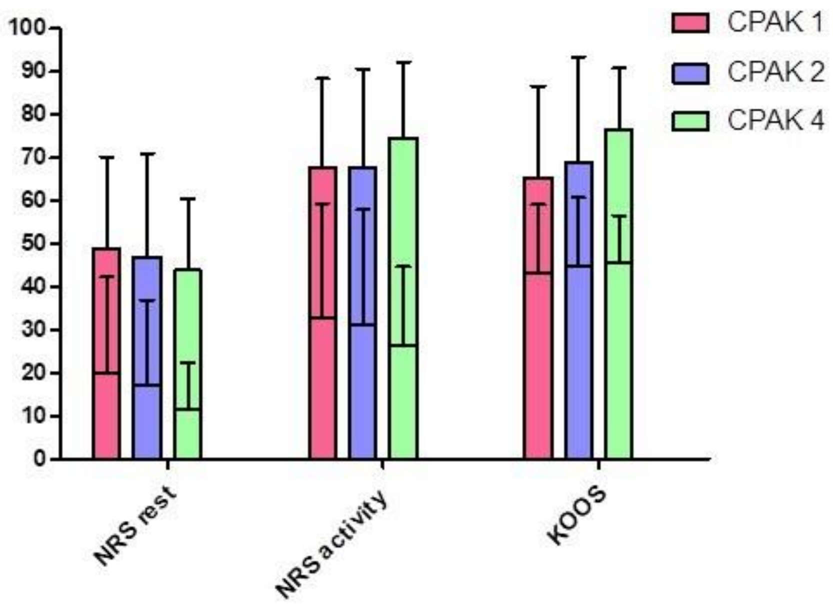


Figure 4. The pre- and postoperative clinical outcomes by preoperative inter-phenotype comparison between CPAK 1, CPAK 2 and CPAK 4. None of the outcomes were significantly different.

B. Postoperative CPAK 6 and CPAK 9

The most prevalent postoperative phenotype was CPAK 6 (n=66 (49%)), featured by a valgus realignment of 182,2° ±1,3 mTFA, a postoperative MPTA of 92,4° ±1,3 and a JLO between 177-183° (apex neutral). Outcomes of CPAK 6 were compared to CPAK 9 (n=33 (24%)) and showed significant difference regarding preoperative LDFA° (p<0.0001), MPTA° (p<0.0001) and mTFA° (p=0.0089) and the postoperative MPTA° (p<0.0001) (Table 3). CPAK 9 showed more femoral varus (90.3° ±1.0 LDFA) compared to CPAK 6 (88.0° ±1.1 LDFA) but less preoperative tibial varus (87.3° ±1.0 vs. 85.6° ±1.0 MPTA). Overall preoperative alignment differed 1° (p=0.0089). Postoperatively, only the MPTA° was significantly higher for CPAK 9 compared to CPAK 6 (94.9° ±1.3 vs. 92.4° ±1.3) (p<0.0001). No significant differences were found for pre- or postoperative clinical outcomes (Figure 5). The TRR for CPAK 6 was 64% compared to 80% for the CPAK 9, which was not significantly different.

Postoperative CPAK		CPAK 6	CPAK 9	P
N (%)		66 (49%)	33 (24%)	-
LDFA°	Preoperative	88.0 ±1,1	90.3 ±1,0	<0.0001*
	Postoperative	-	-	-
MPTA°	Preoperative	85.6 ±1,6	87.3 ±1,0	<0,0001*
	Postoperative	92.4 ±1,3	94.9 ±1,3	<0,0001*
mTFA°	Preoperative	175.0 ±1,5	174.0 ±1.9	0.0089*
	Postoperative	182.2 ±1,3	182,5 ±1,0	0.4514
JLCA°	Preoperative	2,6 ±1,5	2.9 ±1.2	0.137
	Postoperative	2.1 ±1,3	2,5 ±1,4	0.137
aHKA°	Preoperative	-2.4 ±1.8	-3.0 ±1.7	0.1053
	Postoperative	4.4 ±1.7	4.6 ±1.4	0.5148
JLO°	Preoperative	173.6 ±2.0	177.5 ±2.3	<0,0001*
	Postoperative	180.4 ±1.5	185.1 ±1.8	<0,0001*

Table 3. The pre- and postoperative radiological outcome comparison of CPAK 6 and CPAK 9. LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle; mTFA, mechanical tibiofemoral angle; JLCA, joint line convergence angle; aHKA, arithmetic hip-knee-ankle angle; JLO, joint-line obliquity.

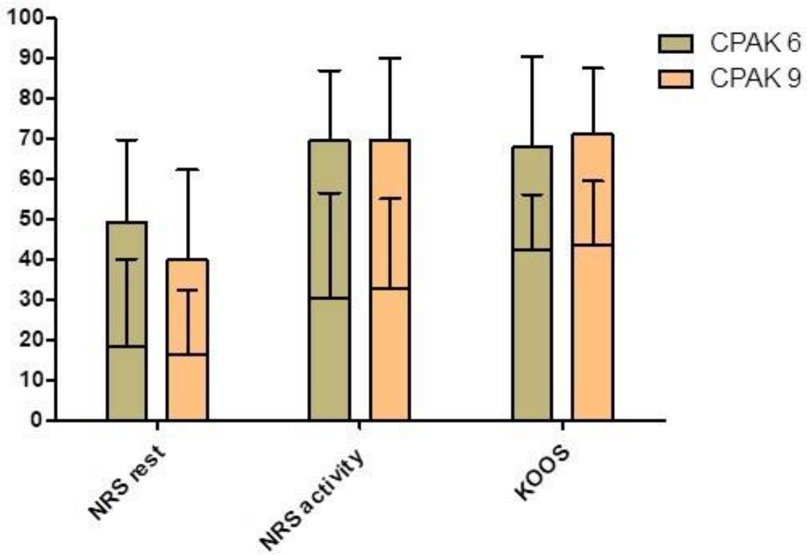


Figure 5. The pre- and postoperative clinical outcomes by postoperative inter-phenotype comparison between CPAK 6 and CPAK 9. None of the outcomes were significantly different.

C. Postoperative CPAK 5/6 and CPAK 8/9

By merging the postoperative CPAK 5 with CPAK 6 (total n=76 (56%)) and CPAK 8 with CPAK 9 (total n=44 (32%)), outcomes regarding postoperative JLO difference could be assessed (apex neutral or apex proximal). Radiological comparison showed significant difference regarding preoperative LDFA° (p<0.0001), MPTA° (p<0.0001) and mTFA° (p=0.0089) and the postoperative MPTA° (p<0.0001) (Table 4). CPAK 8/9 showed more femoral varus (90.7° ±1.3 LDFA) compared to CPAK 5/6 (88.2° ±1.1 LDFA) but less preoperative tibial varus (87.2° ±2.0 vs. 85.6° ±1.5 MPTA). Overall preoperative mechanical alignment differed 1.2° (p=0.0005). Postoperatively, only the MPTA° was significantly higher for CPAK 8/9 compared to CPAK 5/6 (94.3° ±1.6 vs. 92.1° ±1.5) (p<0.0001). No significant differences were found for pre- or postoperative clinical outcomes (Figure 6). The TRR for CPAK 5/6 was 64% compared to 76% for the CPAK 8/9, which was not significantly different.

Postoperative CPAK		**CPAK 5/6**	**CPAK 8/9**	**P**
N (%)		**76 (56%)**	**44 (32%)**	-
LDFA°	Preoperative	88,2 ±1,1	90.7 ±1,3	<0.0001*
	Postoperative	-	-	-
MPTA°	Preoperative	85.6 ±1,5	87.2 ±2.0	<0,0001*
	Postoperative	92.1 ±1,5	94.3 ±1.6	<0,0001*
mTFA°	Preoperative	175.1 ±1,8	173.9 ±2.0	0.0005*
	Postoperative	182.1 ±1,2	182,1 ±1,2	0.859
JLCA°	Preoperative	2,4 ±1,6	2.6 ±1.3	0.442
	Postoperative	1,9 ±1,4	2,0 ±1,6	0.596
aHKA°	Preoperative	-2.6 ±1.8	-3.5 ±2.0	0.0092*
	Postoperative	3.9 ±2.1	3.6 ±2.3	0.3932
JLO°	Preoperative	173.8 ±2.0	177.9 ±2.7	<0,0001*
	Postoperative	180.2 ±1.6	185.0 ±1.9	<0,0001*

Table 4. The pre- and postoperative radiological outcome comparison of CPAK 5/6 and CPAK 8/9. LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle; mTFA, mechanical tibiofemoral angle; JLCA, joint line convergence angle; arithmetic hip-knee-ankle angle; JLO, joint-line obliquity.

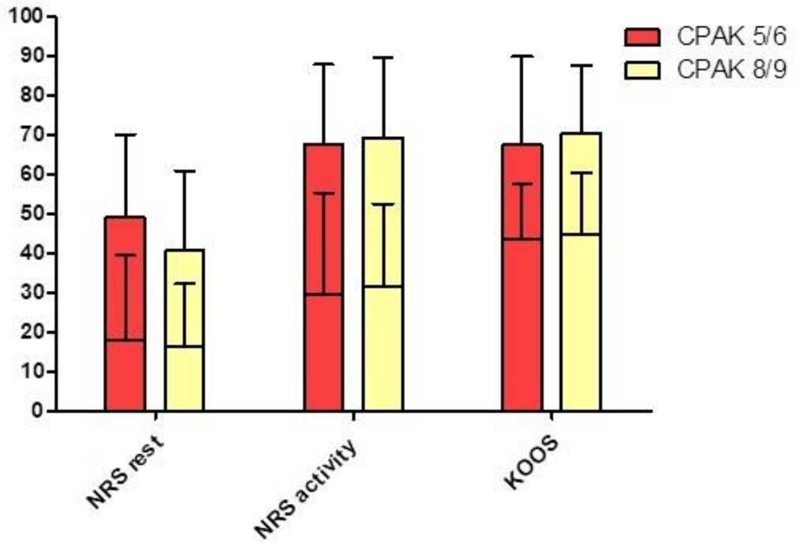


Figure 6. The pre- and postoperative clinical outcomes by postoperative inter-phenotype comparison between CPAK 5/6 and CPAK 8/9. None of the outcomes were significantly different.

DISCUSSION

The most important finding is that no significant clinical or TRR% differences were found between preoperative or postoperative CPAK classifications at 2 year follow-up in accurate MOWHTO corrections (mTFA 180-184°). On the condition of producing an accurate valgus realignment, the 'all on the tibia' principle for medial grade 1-3 OA produced significant clinical improvement even for CPAK 2 (neutral bony alignment with intra-articular wear) and CPAK 4 (femoral-driven varus). The initial hypothesis was that subjects from CPAK 1 have both radiological and clinical favourable outcomes at 2 year follow-up compared to the other CPAK phenotypes. This hypothesis appears to be true for radiological outcomes, but not for short-term clinical follow-up. In contrast to the expectations, the TRR was in favour of CPAK 4 (87%), but was not significantly different from CPAK 1 (67%) or CPAK 2 (69%). Similarly for postoperative clinical comparison of CPAK 6 and CPAK 9, no significant differences in NRS rest/activity or KOOS and in TRR (CPAK 6: 64% and CPAK 9: 80%) were found at 2 year. Equal findings were established by merging CPAK 5 with CPAK 6 and CPAK 8 with CPAK 9. To the authors knowledge, this is the first study describing clinical outcomes after MOWHTO when stratifying for preoperative and postoperative varus phenotypes based on the combination of LDFA° and MPTA° measurements.

The study showed that CPAK 1 (52%) was the most common preoperative varus phenotype while CPAK 6 (49%) was most prevalent after MOWHTO. Regarding radiological outcomes, comparison of CPAK 1 to preoperative CPAK 2 (intra-articular varus) and CPAK 4 (femoral-driven varus) yielded significant differences regarding preoperative LDFA°, MPTA°, JLCA° and mTFA° and postoperative MPTA° and JLCA°. CPAK 1 was featured by tibia-driven varus (84.6° ±1.5 MPTA) and mild intra-articular varus (2.0° ±1,4 JLCA). Postoperative realignment showed an MPTA of 91.9° ±1.9 and an mTFA of 181.9° ±1.2 which can be considered as highly favourable radiological parameters after MOWHTO [8]. In the CPAK 2 phenotype (25%), bony malalignment was absent (MPTA 86.5° ±1.3 and LDFA 87.3° ±1.2) showing mild mechanical varus (175.9° ±0.8) but evident intra-articular wear (JLCA 3.3° ±0.9°). This phenotype was considered 'neutral' according to the CPAK system, since no bony malalignment was present [19]. Postoperative MPTA was 92.1° ±2.2 and JLCA 2.6 ±1.1°. Due to the mild preoperative mechanical varus of CPAK 2, the magnitude of correction was rather small to obtain an accurate correction (180-184° mTFA), hereby preventing the MPTA to be excessively high. On the other hand, CPAK 4 (13%) had a preoperative MPTA of 87.7 ±1.0 (normal), an LDFA of 91.4° ±1.1 (femoral varus), a JLCA of 2.3° ±1.5 (mild IA varus) and mechanical varus of 174.1° ±1.8, which did result in an elevated postoperative MPTA of 94.3° ±2.0. Radiological outcomes of CPAK 4 were therefore considered the least favourable.

Around three quarter of cases was corrected towards CPAK 6 (49%) or CPAK 9 (24%). Similar to CPAK 1, CPAK 6 consisted mainly of tibial-driven varus (preoperative MPTA 85.6° ± 1.6, LDFA 88.0° ±1.1 and JLCA 2.6° ±1.5) as CPAK 9 showed similarities to CPAK 4 featuring femoral-driven varus (MPTA 87.3° ±1.0, LDFA 90.3° ±1.0 and JLCA 2.9° ±1.2) on preoperative status. Of note is the difference in intra-articular wear (preoperative JLCA° difference of 0.6°) which was more profound in CPAK 6/9 than in CPAK 1/4. The postoperative MPTA of CPAK 6 was 92.4° ±1.3 (normal) compared to 94.9° ±1.3° (elevated) in CPAK 9. Kim et al. observed poor clinical outcomes once the postoperative MPTA reached 95.2° or higher [14]. This observation was accompanied by an abrupt elevation in JLO and valgus overcorrection [14]. Sohn et al. found that a preoperative JLCA >5° and JLO >3° are independent risk factors for postoperative MPTA values >95° when correcting with HTO [27]. However no correlation to clinical outcomes was described in their study [27]. Recently, a systematic review by Xie et al. concluded no clear association between the postoperative JLO and clinical outcomes after HTO, which is in line with the observations of our study [30].

Although the short-term clinical outcomes after MOWHTO in our study were remarkably good for femoral varus phenotypes, the indication for a single-level MOWHTO appears debatable from a strict radiological perspective. When post-HTO anatomical angles of the tibia (MPTA<90°, correction to neutral) are desired, Feucht et al. found that HTO was only indicated in less than one third of patients [8]. If an MPTA of <95° should be accepted, single-level HTO is suitable in 57% while a double-level osteotomy should be performed in 33% of patient cases [8]. Again, the study by Feucht et al. investigated no clinical correlations to these cut-off values. Nevertheless, high postoperative MPTA and consequently increased (calculated) JLO angles, as observed in CPAK 4 and CPAK 8/9, raise two concerns: (1) medio-lateral shear stress during gait and (2) future total knee arthroplasty (TKA) conversion difficulties such as tibial bone resection, implant stability (gap balancing) and final alignment [23]. The clinical relevance of high MPTA and JLO after HTO is still unclear [14, 15, 26, 30], but intuitively large deviations from anatomical standards should be avoided when possible. On the other hand, TKA after MOWHTO has previously shown to provide excellent long-term clinical outcomes, which attenuates the obligation for aiming realignment strictly towards 'natural' postoperative angles [4, 7].

The authors are aware of several existing classification systems for the symptomatic varus knee [9, 17, 22, 28], but the CPAK classification appeared to be the most suitable to categorize relevant deformities in both pre- and postoperative status [19]. The advantage of CPAK is that it takes into account both the MPTA and LDFA to calculate the JLO and aHKA while most osteotomy studies only focus on the measured MPTA and JLO. Bartholomeeusen et al. showed that the postoperative measured JLO after MOWHTO is largely determined by an adaptation mechanism of foot positioning and seems therefore difficult to determine on 2D imaging [2]. For this reason, the JLO was calculated as described by MacDessi et al. (MPTA° + LDFA°), and not measured on full-leg radiographs [19]. The disadvantage is that CPAK only refers to bony alignment categorization while ignoring the intra-articular wear pattern determined by the JLCA, which is in fact highly relevant regarding osteotomy planning [21]. The authors tried to address this issue by associating each CPAK phenotype with the respective JLCA° outcome. So ideally, each preoperative CPAK phenotype could be subdivided based on a JLCA >< 2° to include the relevance of the intra-articular wear component on top of the existing bony deformity. However, sample size did not permit to produce reliable data on this matter. Furthermore, the aHKA has been shown to provide an excellent estimation of the constitutional alignment of the lower limb, especially in overall varus malalignment <8° mTFA [3, 18]. Therefore, subjects with mechanical varus alignment primarily due to intra-articular wear (high JLCA) while lacking bony malignment were likely categorized as a ‘neutral’ preoperative phenotype (CPAK 2 or 5). Next to CPAK, another varus classification was recently rendered by Mullaji et al. describing seven varus knee phenotypes (four main categories: ‘normal’, ‘intra-articular varus’, ‘extra-articular’ and ‘valgoïd’) but this seems less applicable for knee osteotomy given the absence of postoperative realignment phenotypes [22].

The retrospective nature of this study is per definition a limitation, mainly regarding selection bias. However, a prospective study design to obtain similar objectives seems inappropriate with the current knowledge about radiological single-level HTO indications [8]. CPAK cohorts with less than 15 subjects were excluded for further analysis. Still, in most cohorts, sample size was relatively low and as such, data should be interpreted as indicative rather than conclusive. Subjects with grade 4 medial OA were excluded for analysis for its known relative contraindication [24]. An internal pre-analysis of this grade 4 cohort showed a conversion rate to arthroplasty of 14% within 36 months. It was decided that these cases could worsen clinical outcomes up to 2 year by allocation in either phenotype of the CPAK classification. Furthermore, a form of selection bias was induced by including only accurate cases (postoperative mTFA of 180-184°). The inclusion was preferred in order to reduce scatter by under- and overcorrections that are known to worsen clinical outcomes after MOWHTO [6, 16]. Finally, cases were selected based on the availability of PROMs at baseline and 2 year follow-up. The response rate on PROMs in our centre is 88% at baseline and 77% at 2 year which seems fairly good compared to other clinical osteotomy studies [10, 29]. Nevertheless, clinical outcome was limited to 2 year after surgery which is considered the minimum for clinical follow-up studies in knee osteotomies. It needs to be emphasised that long-term data from osteotomy registries or survival studies are required to make further definite statements.

Approximately 20% of MOWHTO patients is converted to TKA within 10 years after osteotomy [24]. As many of these MOWHTO patients present with increased MPTA and JLO values after HTO surgery, future research should also focus on the relation between these deviations and postoperative TKA outcomes and alignment. The authors therefore emphasize to grade OA severity and to measure at least the mTFA, MPTA, LDFA, JLCA and JLO during osteotomy planning on a valid full leg bipodal standing radiograph or CT-scan to decide if and at which level a corrective osteotomy is indicated. This should lead to ‘near anatomical’ postoperative knee angles without compromising future total knee arthroplasty as part of continuous long-term care for the orthopedic knee patient.

CONCLUSION

At 2 year follow-up, no clinical significant differences are observed between different CPAK phenotypes. Accurate MOWHTO corrections (0-4° mTFA valgus) provide significant clinical improvement even in the bony femoral-driven varus knee (CPAK 4) and the bony neutral varus knee with intra-articular wear (CPAK 2). Survival studies and osteotomy registries must decide if MOWHTO is truly a contraindication for these radiographically 'less suitable' phenotypes while taking into account the potential angular deformities induced that could compromise future conversion to total knee arthroplasty.

CONFLICT OF INTERST

The authors declare to have no conflict of interest.

FUNDING

No funding was received for this study.

ACKNOWLEDGEMENT

None.

REFERENCES

1. Amis AA (2013) Biomechanics of high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc 21(1):197–205

2. Bartholomeeusen S, Van den Bempt M, van Beek N, Claes T, Claes S (2020) Changes in knee joint line orientation after high tibial osteotomy are the result of adaptation of the lower limb to the new alignment. Knee Elsevier B.V. 27(3):777–786

3. Bellemans J, Colyn W, Vandenneucker H, Victor J (2012) The chitranjan ranawat award: Is Neutral Mechanical Alignment Normal for All Patients? The Concept of Constitutional Varus. Clin Orthop 470(1):45–53

4. Chalmers BP, Limberg AK, Tibbo ME, Perry KI, Pagnano MW, Abdel MP (2019) Total Knee Arthroplasty after High Tibial Osteotomy Results in Excellent Long-Term Survivorship and Clinical Outcomes. J Bone Joint Surg Am 101(11):970–978

5. COVENTRY MB (1965) OSTEOTOMY OF THE UPPER PORTION OF THE TIBIA FOR DEGENERATIVE ARTHRITIS OF THE KNEE. A PRELIMINARY REPORT. J Bone Joint Surg Am 47(47):984–90

6. El-Azab HM, Morgenstern M, Ahrens P, Schuster T, Imhoff AB, Lorenz SGF (2011) Limb Alignment After Open-wedge High Tibial Osteotomy and Its Effect on the Clinical Outcome. Orthopedics 34:622–628

7. El-Galaly A, Nielsen PT, Kappel A, Jensen SL (2020) Reduced survival of total knee arthroplasty after previous unicompartmental knee arthroplasty compared with previous high tibial osteotomy: a propensity-score weighted mid-term cohort study based on 2,133 observations from the Danish Knee Arthroplasty Reg. Acta Orthop 91(2):177–183

8. Feucht MJ, Winkler PW, Mehl J, Bode G, Forkel P, Imhoff AB, Lutz PM (2021) Isolated high tibial osteotomy is appropriate in less than two-thirds of varus knees if excessive overcorrection of the medial proximal tibial angle should be avoided. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(10):3299–3309

9. Hirschmann MT, Moser LB, Amsler F, Behrend H, Leclerq V, Hess S (2019) Functional knee phenotypes: a novel classification for phenotyping the coronal lower limb alignment based on the native alignment in young non-osteoarthritic patients. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 27(5):1394–1402

10. Hoorntje A, Pronk Y, Brinkman JM, van Geenen RCI, van Heerwaarden RJ (2023) High tibial osteotomy versus unicompartmental knee arthroplasty for Kellgren–Lawrence grade 3–4 knee osteoarthritis in younger patients: comparable improvements in patient-reported outcomes, adjusted for osteoarthritis grade and sex. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg (doi 10.1007/s00167-023-07526-5)

11. Jackson JP, Waugh W, Green JP (1969) High tibial osteotomy for osteoarthritis of the knee. The Journal of bone and joint surgery British volume 51(1):88–94

12. Jacquet C, Pioger C, Khakha R, Steltzlen C, Kley K, Pujol N, Ollivier M (2021) Evaluation of the “Minimal Clinically Important Difference” (MCID) of the KOOS, KSS and SF-12 scores after open-wedge high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(3):820–826

13. KELLGREN JH, LAWRENCE JS (1957) Radiological assessment of osteo-arthrosis. Annals of the rheumatic diseases 16(4):494–502

14. Kim JS, Lim JK, Choi HG, Jeong HW, Park SB, Shim SJ, Lee YS (2022) Excessively Increased Joint-Line Obliquity After Medial Opening-Wedge High Tibial Osteotomy Is Associated With Inferior Radiologic and Clinical Outcomes: What Is Permissible Joint-Line Obliquity. Arthroscopy 38(6):1904–1915

15. Kubota M, Kim Y, Sato T, Yamaguchi J, Ohno R, Kaneko K, Ishijima M (2020) The actual knee function was not influenced by joint line obliquity after open-wedge high tibial osteotomy. Sicot-J 6(4):1-6

16. Lee S-S, Kim JH, Kim S, Jung EY, Ryu DJ, Lee DK, Wang JH (2022) Avoiding Overcorrection to Increase Patient Satisfaction After Open Wedge High Tibial Osteotomy. Am J Sports Med 50(9):2453–2461

17. Lin YH, Chang FS, Chen KH, Huang KC, Su KC (2018) Mismatch between femur and tibia coronal alignment in the knee joint: Classification of five lower limb types according to femoral and tibial mechanical alignment. BMC Musculoskeletal Disorders BMC Musculoskeletal Disorders 19(1):1–9

18. Macdessi SJ, Griffiths-Jones W, Harris IA, Bellemans J, Chen DB (2020) The arithmetic HKA (aHKA) predicts the constitutional alignment of the arthritic knee compared to the normal contralateral knee A matched-pairs radiographic study. Bone and Joint Open 1(7):339–345

19. MacDessi SJ, Griffiths-Jones W, Harris IA, Bellemans J, Chen DB (2021) Coronal Plane Alignment of the Knee (CPAK) classification a new system for describing knee phenotypes. Bone Joint J 103 B(2):329–337

20. Micicoi G, Grasso F, Kley K, Favreau H, Khakha R, Ehlinger M, Jacquet C, Ollivier M (2021) Osteotomy around the knee is planned toward an anatomical bone correction in less than half of patients. Orthop Traumatol Surg Res 107(4): 102897

21. Micicoi G, Khakha R, Kley K, Wilson A, Cerciello S, Ollivier M (2020) Managing intra-articular deformity in high Tibial osteotomy: a narrative review. J Exp Orthop Journal of Experimental Orthopaedics 7(1):1–10

22. Mullaji A, Shah R, Bhoskar R, Singh A, Haidermota M, Thakur H (2021) Seven phenotypes of varus osteoarthritic knees can be identified in the coronal plane. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 3 (8): 2793-2805

23. Nakayama H, Schröter S, Yamamoto C, Iseki T, Kanto R, Kurosaka K, Kambara S, Yoshiya S, Higa M (2018) Large correction in opening wedge high tibial osteotomy with resultant joint-line obliquity induces excessive shear stress on the articular cartilage. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 26(6):1873–1878

24. Primeau CA, Birmingham TB, Leitch KM, Willits KR, Litchfield RB, Fowler PJ, Marsh JD, Chesworth BM, Dixon SN, Bryant DM, Robert Giffin J (2021) Total knee replacement after high tibial osteotomy: Time-to-event analysis and predictors. Cmaj 193(5):E158–E166

25. Razak HRBA, Micicoi G, Khakha RS, Ehlinger M, Faizan A, LiArno S, Ollivier M (2021) Patients with varus knee osteoarthritis undergoing high tibial osteotomy exhibit more femoral varus but similar tibial morphology compared to non-arthritic varus knees. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 30(2):680-687

26. Rosso F, Rossi R, Cantivalli A, Pilone C, Bonasia DE (2022) Joint Line Obliquity Does Not Affect the Outcomes of Opening Wedge High Tibial Osteotomy at an Average 10-Year Follow-up. Am J Sports Med 50(2):461–470

27. Sohn S, Koh IJ, Kim MS, In Y (2022) Risk factors and preventive strategy for excessive coronal inclination of tibial plateau following medial opening-wedge high tibial osteotomy. Archives of Orthopaedic and Trauma Surgery Springer Berlin Heidelberg 142(4):561–569

28. Thienpont E, Parvizi J (2016) A New Classification for the Varus Knee. J Arthroplasty 31(10):2156–2160

29. Witjes S, Wanlin S, Litchfield R, van Geenen RCI, Kerkhoffs GMMJ, Getgood A (2018) Realignment osteotomy of the knee allows for return to work and sport activities in the young athletic population. Journal of ISAKOS 3(4):213–219

30. Xie T, Brouwer RW, Akker I Van Den, Hugo S (2023) Clinical relevance of joint line obliquity after high tibial osteotomy for medial knee osteoarthritis remains controversial : a systematic review Hospital for Special Surgery Knee Score. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 31(10):4355-4367

Chapter 2 High tibial osteotomy planning

2.1 The position of the lateral tibial spine and the implications for high tibial osteotomy planning

Published in Acta Orthopaedica Belgica (2023) doi.org/10.52628/89.2.11409

ABSTRACT

The lateral tibial spine (LTS) is frequently proposed as a correction target in high tibial osteotomy (HTO), although little is known about its exact radiographic position. This study primarily aims to define the position and variance of the LTS. Secondly, this study wants to investigate the relevance of the LTS position on the mechanical tibiofemoral angle (mTFA°) while planning and postoperatively landing the weight-bearing line (WBL) on this landmark. First, the LTS position was studied on preoperative full-leg standing radiographs (FLSR) and computed tomography (CT) scans in 70 cases. 3D models of the tibia were created in Mimics 23.0 and measurements were conducted in 3-matic 15.0 (Materialise, Leuven®). Next, 100 HTO cases were retrospectively planned with the WBL through the LTS according to Dugdale's method on FLSR. Finally, 55 postoperative FLSR having the WBL on the LTS (±2%) were assessed for mTFA° outcome. Statistics were conducted in GraphPad 8.0. The LTS was located at 58.3%±1.9 [55-63%] in 2D and 57.3%±2.2 [53-63%] in 3D showing a high correlation (r=0.77 [0.65 to 0.85]). The planned mTFA on the LTS was 181.8°±0.3 (181.3-182.5). On postoperative FLSR, the mTFA was 182.2°±0.6 (180.9-183.1). The lateral tibial spine is located at 57-58% on the tibial plateau with a 10% maximal variation range. Good agreement was found between 2D and 3D imaging modalities while evaluating the position in the coronal plane. When aiming the WBL through the LTS during valgus-producing HTO, a consistent realignment of 181-183° mTFA can be expected when performing accurate surgery.

KEYWORDS: Knee – High tibial osteotomy – Planning – Target – Imaging

INTRODUCTION

High tibial osteotomy (HTO) is an established joint preserving strategy in the varus aligned lower limb to unload the medial arthritic knee compartment [5]. The large majority of HTO procedures is currently planned on full-leg standing radiographs (FLSR) for which the Miniaci or Dugdale planning method is most commonly applied [8, 9]. The target axis on which the final correction should be aimed at, has been a matter of debate until today [3]. Recent osteotomy consensus papers propose an individualized approach based on the indication for knee osteotomy (cartilage procedure, meniscal transplant, isolated medial osteoarthritis (OA)…), size of preoperative malalignment and the severity of cartilage damage [6, 10, 45]. Nevertheless, these correction targets are widely ranging from slight varus over neutral realignment towards the so-called Fujisawa point located at 62% or 62.5% of the tibial plateau width [3, 12]. The absence of literature consensus and proper target guidelines leaves the chosen correction goal in clinical practice often subjected to the individual preference and experience of the surgeon.

Recently, more studies are using the lateral tibial spine (LTS) as an anatomical and radiographical landmark in valgus-producing osteotomy planning. This point is supposed to produce slight overcorrection (valgus) as to the neutral axis [13, 25, 28, 41]. Although the position of the LTS was once estimated to correspond with 55% of the tibial plateau (1.7-1.9° mechanical tibiofemoral angle (mTFA) valgus)[28], thorough investigations about its position, variability and consequences for osteotomy planning were never performed on a large HTO patient population.

This study primarily aims to define the position and variance of the lateral tibial spine on the tibial plateau by in-person 2D (FLSR) and 3D (CT-scan) modality comparison in order to verify imaging projections of the tibial plateau anatomy. Secondly, the study wants to investigate the relevance of the LTS position on mTFA° outcome while planning and postoperatively landing the weight-bearing line (WBL) on this landmark.

METHODS

A retrospective imaging study was performed by merging existing HTO databases (2016-2020) from two independent orthopedic centers. Local ethical committee approval was obtained in both hospitals to use imaging data for study purposes. Study was performed according to the general protection data regulation (GDPR) guidelines.

Lateral tibial spine position

Patients who underwent a unilateral medial opening-wedge HTO were extracted from the database on the condition that a valid preoperative FLSR and a preoperative CT-scan of the index knee, taken within one year before surgery, were available. CT-scans were derived from a past prospective 3D HTO study at both orthopaedic centres, earlier approved by the local and university ethical committees. Measurements in the coronal plane included width of the tibial plateau (mm) and position of the lateral spine (mm). Measurements were performed from medial (0%) towards lateral (100%). Absolute values were converted to ratios and expressed as percentages (%) of the tibial plateau. For 2D measurements, FLSR were first validated based on three criteria: patellar midline alignment, true antero-posterior view of the ankle joint and 1/3 visibility of the proximal fibula. Medial or lateral osteophyte formation at the tibial plateau borders was cautiously excluded from the tibial plateau width determination. Measurements were conducted in IMPAX 6.6 (Agfa Healthcare, Mortsel, Belgium) or Vue PACS 12.1 (Carestream, Rochester NY, USA) medical imaging software (Figure 1).

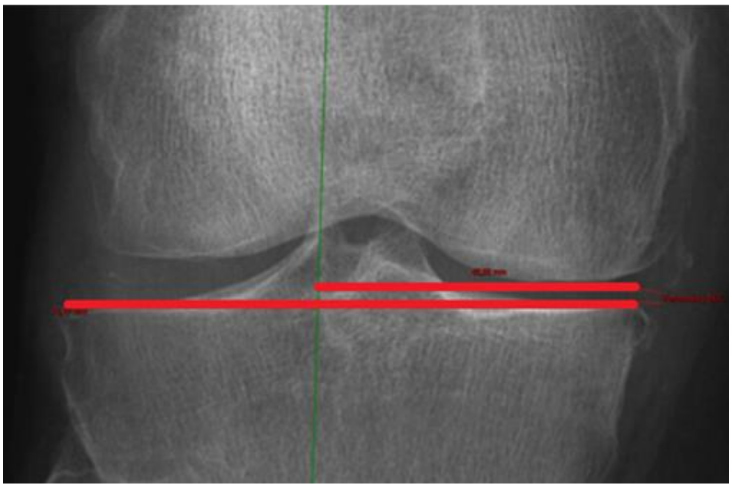


Figure 1. Two-dimensional (2D) lateral tibial spine ratio measurements (red lines) on full-leg standing radiographs (FLSR). Medial corresponds to 0%.

For 3D measurements, Digital Imaging and Communications in Medicine (DICOM) files from knee CT-scan (0.5-0.8mm slice thickness and spacing) were loaded into the segmentation software Mimics® 23.0 (Materialise, Leuven, Belgium) to separate the femur and tibia from surrounding soft tissue. Segmentation threshold was customized and set to a minimum of 130-200 Hounsfield units (HU) to gain adequate shaping of the tibial plateau (Figure 2).

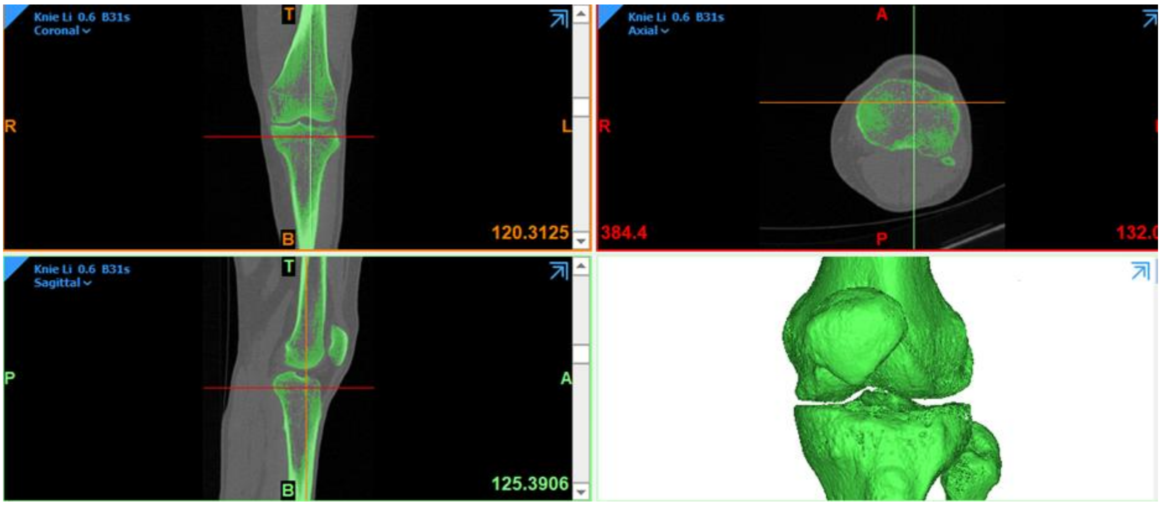


Figure 2. CT-scan segmentation and 3D modelling of the index knee in Mimics 23.0

The anatomical 3D model was then studied in 3-matic® 15.0 (Materialise, Leuven, Belgium). First, a projection plane was created aligned with the medial and lateral posterior condyles of the tibial plateau, starting from the distal tibial centre. Next, the tip of the lateral spine was identified and the longest coronal diameter of the tibial plateau (medial-lateral) was determined with exclusion of osteophytes at the plateau borders. The anatomic tibia model with landmarks was projected using the 'sketch'-tab in which absolute distances were measured (Figure 3a). The square-tool was used to determine the exact position of the lateral spine tip on the tibial plateau width line (Figure 3b).

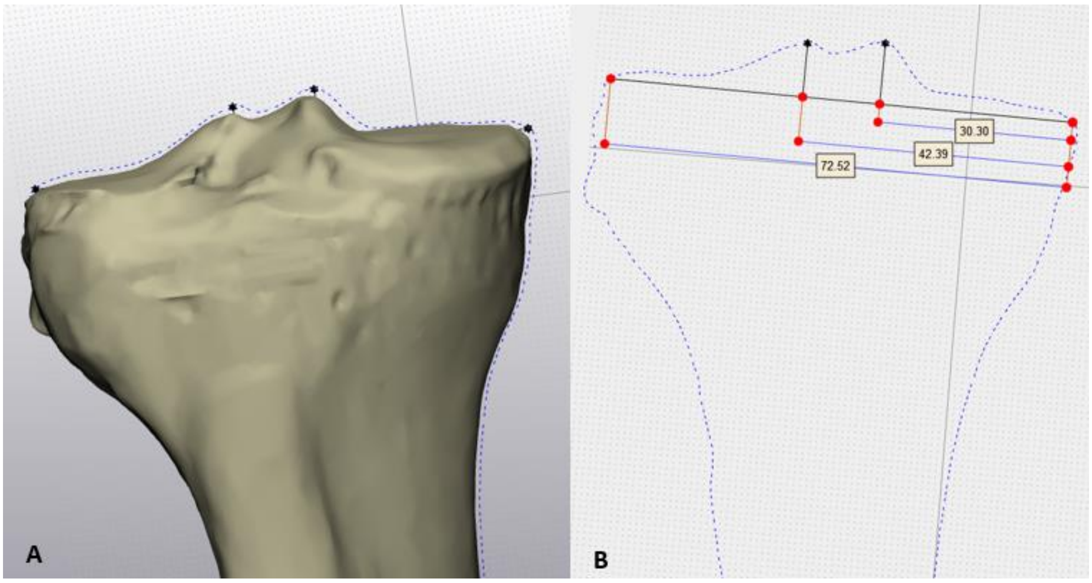


Figure 3. (A) Three-dimensional (3D) measurement of the tibial spines by using the sketch projection tab in 3-matic 15.0. (B) The square-tool was used to determine the exact position of the spine tip on the tibial plateau width line. Medial corresponds to 0%.

WBL planning and landing on the lateral tibial spine

The HTO database was then screened for unilateral medial opening-wedge HTO with valid preoperative FLSR according to the described criteria, but without preoperative 3D imaging. The first 100 cases (database 04/2016 to 04/2017) were included and measurements were performed on FLSR in IMPAX 6.6 (Agfa Healthcare, Mortsel, Belgium). Again, width of the tibial plateau (mm) and position of the LTS (mm) were determined. Next, the WBL was drawn from the hip centre crossing the LTS and ending at the floor. The planned mTFA° was then measured as described by Dugdale et al. [8] (Figure 4a). The correlation between LTS position and mTFA° was determined. Finally, the HTO database was reviewed for cases with a valid 3 month postoperative FLSR and having the WBL crossing the lateral tibial spine (±2%) (Figure 4b). The width of the tibial plateau (mm), the position of the LTS (mm) and the WBL (%) were measured on postoperative FLSR in IMPAX 6.6 and correlated with the postoperative mTFA° to verify the planning outcomes on the LTS.

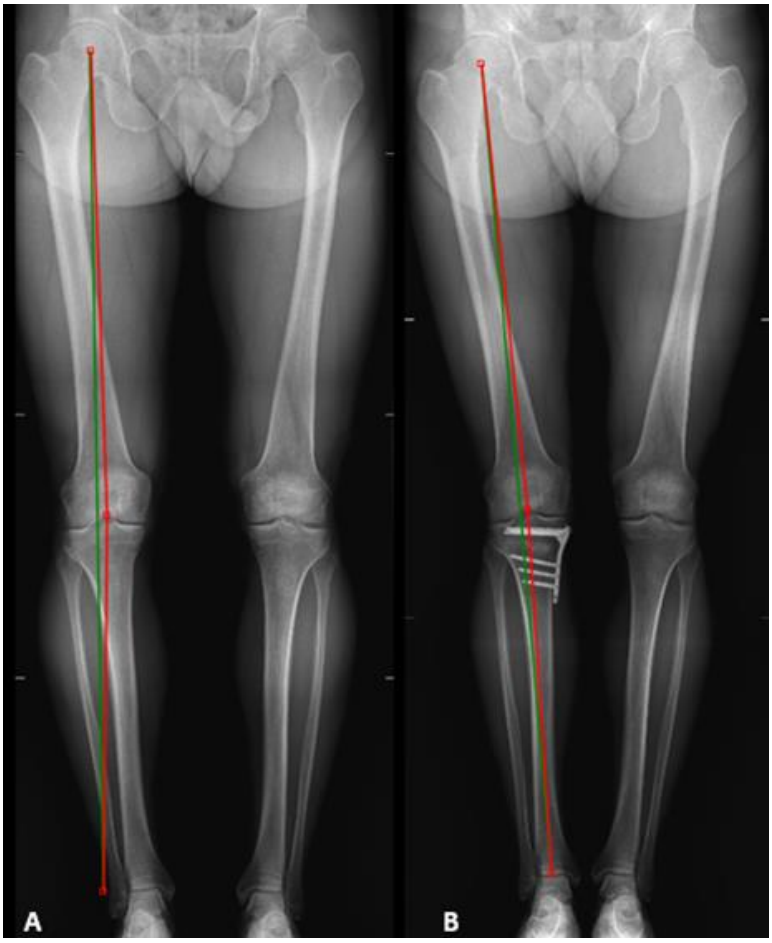


Figure 4. (A) Planning of the WBL (green) on the LTS with mTFA° (red) determination according to Dugdale's planning method. (B) Postoperative FLSR with the WBL (green) running through the lateral tibial spine and mTFA° (red) measurement.

Statistics

All imaging measurements were performed once by two blinded observers (orthopaedic residents). As final outcome, the average of both measuring points was calculated. Descriptive statistics were outlined as mean, standard deviation (SD), minimum and maximum (). Outliers were removed for final analysis according to the extreme studentized deviate method (Grubbs' test). Normalized data distribution was determined by the D'Agostino's and Pearson omnibus normality test. The intraclass correlation coefficient (ICC) 'r' with [95% confidence interval (CI)] and the interobserver reliability were analyzed by the Pearson or Spearman test, depending on presence of normal distribution. Significance level alpha was set at 0.05. All statistical tests were conducted in GraphPad Prism version 8.0.0 for Windows (GraphPad Software, San Diego, California USA, www.graphpad.com)

RESULTS

Lateral tibial spine position

Seventy (70) HTO subjects (45.5y±12.0, 84% male, 100% Caucasian, 51% right side) were found to have both a valid preoperative FLSR and preoperative CT-scan of the index knee. The LTS was located at 58.3%±1.9 (55-63) in 2D and 57.3%±2.2 (53-63) in 3D (Table 1) showing a good correlation between imaging modalities (r=0.77 [0.65-0.85]) (Figure 5a/b).

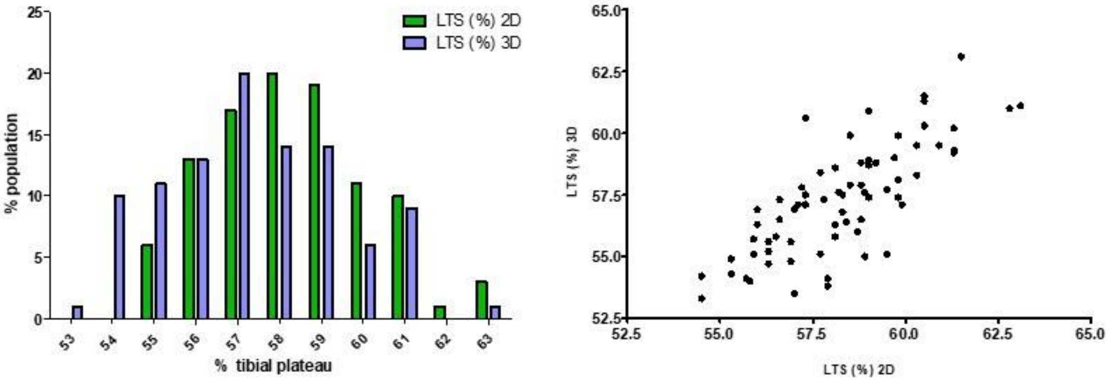


Figure 5. (A) Lateral tibial spine positioning and distribution on the tibial plateau by 2D and 3D comparison. (B) Correlation outcomes of the lateral tibial spine location for 2D and 3D imaging modalities (r=0.77 (0.65 - 0.85) – p<0.001)

Parameter	Imaging modality	Outcome	r [95% CI]
Lateral tibial spine position (n=70)			
LTS (%)	2D (FLSR)	58.3%±1.9 (55-63)	0,84 [0.75-0.89]
	3D (CT-scan)	57.3%±2.2 (53-63)	0,91 [0.85-0.94]
Planning on lateral tibial spine (n=99)			
WBL on LTS (%)	2D (FLSR)	58.4%±1.7 (54-63)	0,90 [0.86-0.94]
mFTA°	2D (FLSR)	181.8°±0.3 (181.3-182.5)	0.67 [0.55-0.77]
Landing on lateral tibial spine (n=55)			
WBL on LTS (%)	2D (FLSR)	58.6%±1.7 (55-63.5)	0.64 [0.42-0.79]
mFTA°	2D (FLSR)	182.2°±0.6 (180.9-183.1)	0.76 [0.60-0.86]

Table 1. Overview of the radiological outcomes (mean±SD (min-max)) with respective interobserver reliability r [95% CI]. LTS, lateral tibial spine; WBL, weight-bearing line; mFTA°, mechanical femorotibial angle (°); FLSR, full-leg standing radiograph.

WBL planning and landing on the lateral tibial spine

Analysis of the first 100 HTO subjects (53.4y±10.6, 70% male, 100% Caucasian, 46% right side) showed a LTS position of 58.4%±1.7 (54%-63%). One case was found to be an outlier (LTS of 64.8%) and consequently excluded. The planned mTFA was 181.8°±0.3 (181.3°-182.5°) (Table 1). A moderate correlation degree existed between the LTS position and the planned mTFA° (r=0.53 [0.37 – 0.66]) – p<0.001) (Figure 6a).

Fifty-five (55) subjects (54.0y±9.4, 80% male, 100% Caucasian, 49% right side) were found to have a valid postoperative FLSR and the WBL crossing the lateral tibial spine (±2%) after HTO surgery. The postoperative WBL was 58.6%±1.7 (55%-63.5%) with a corresponding postoperative mTFA° of 182.2°±0.6 (180.9°-183.1°) (Table 1). The correlation (r=0.36 [0.11-0.57] – p=0.007) between both parameters was considered weak (Figure 6b).

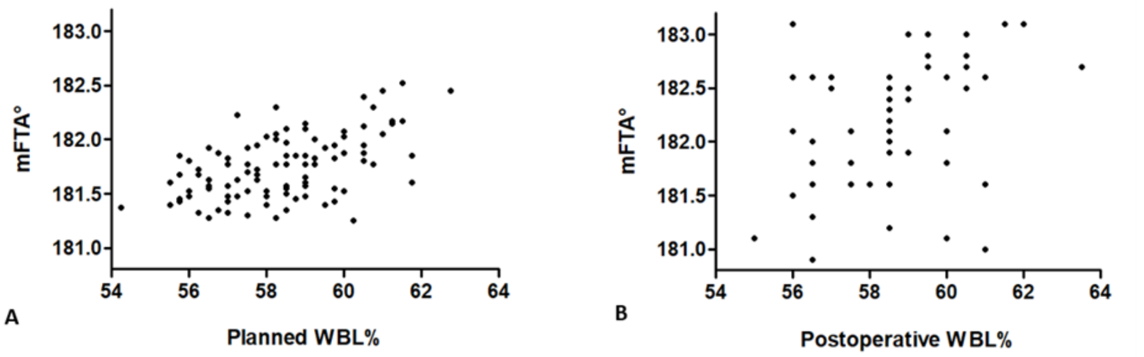


Figure 6. Correlation outcomes respectively of the (A) planned and (B) postoperative WBL% with the mTFA° while aiming for the lateral spine on the tibial plateau. ((A) r=0.53 [0.37 – 0.66]) – p<0.001 and (B) r=0.36 [0.11-0.57] – p=0.007)

DISCUSSION

Nowadays, the lateral tibial spine is frequently proposed as a correction target in HTO, although little is known about the exact radiographic position and variance with respect to preoperative osteotomy planning. This study revealed that the LTS is located at 57-58% on the tibial plateau showing a 10% maximal variation range around its average position (54-63%). The correlation between 2D and 3D LTS location was good (r=0.77), showing a difference of 1% on 2D (58.3%) relative to 3D (57.3%) measurements. Further, planning the WBL on a FLSR through the lateral tibial spine yielded a 181.8°±0.3 (181.3°-182.5°) mTFA valgus correction as was confirmed by the postoperative realignment outcomes (182.2°±0.6 (180.9°-183.1°) mTFA).

The Fujisawa-point at 62,5% has historically been proposed as the benchmark target in valgus-producing osteotomy planning [12]. Lately, some authors and surgeons are advocating the LTS as correction target [13, 28, 41], potentially because of apprehension to overcorrection. This might result in esthetically inferior results and aberrant gait patterns while risking to overload the lateral compartment [28], the onset of patellofemoral symptoms [26] and increased coronal inclination (excessive MPTA and joint line obliquity) [1, 33]. The general tendency of slight under-correction relative to the planning seems therefore 'less worse' than definitive overcorrection [3]. Nevertheless, Sung-Sahn Lee et al. (2020) demonstrated similar short-term clinical outcomes (< 2 year) between aiming for the LTS or for the Fujisawa point (62-62.5%) [25]. After all, the slight difference in obtained correction might be subtle and only become relevant in certain individuals or in long-term outcomes.

An important finding of this study is that the common assumption of the LTS showing a fixed position on the tibial plateau is false. A surprisingly large variation of 10% was observed for the LTS position (54-63%). Moreover, in 4% of 2D cases, the LTS was coinciding with the Fujisawa point at 62-63% of the tibial plateau [12]. Therefore, while planning a (valgus-producing) HTO on FLSR, surgeons should be aware of the average LTS position (57-58%) and its substantial variation present in the described Caucasian HTO population. Noteworthy is the study by Van de Pol et al. which aimed the intraoperative WBL crossing the LTS and correctly estimated its position on 58%, as shown by our data [41]. However, they anticipated a spontaneous postoperative correction increase towards valgus after weightbearing, resulting in a final WBL realignment of 62.5% or 3° mTFA [41]. On the other hand, Martay et al. corresponded the apex of the LTS with 55% (1.7-1.9° mTFA valgus) on the tibial plateau [28]. In line with these results, Tripon et al. recently found an average LTS position of 54% on 3D models from different ethnicities [50]. Although a similar variation of 10% (48.9-57.2%) was found, its average position is contrasting our results that showed the LTS to be located beyond 54% in 90% cases using 3D model projection. Reasons for discrepancy however have not been found. Exactly in line with our results is the study by Xu Jiang et al. which showed a 57.7%±2.1 of the LTS top [16]. Planning realignment surgery with the WBL on the LTS yielded 182.1°±0.5 in a Chinese population compared to 181.8°±0.3 in our study on Caucasians. The similarity of LTS position among ethnicities, as suggested by Tripon et al., seems therefore confirmed [50].

Further, the current study found a good correlation (r=0.77) for the LTS location comparing FLSR with 3D CT-scan reconstruction. Considering 3D measurements as more precise, the average LTS on 2D was found to be located exactly 1% further on the tibial plateau (58.3%). In general, this comparison confirms that the individual 3D anatomy of the tibial plateau is well-projected on a valid FLSR, which makes this imaging modality suitable for knee osteotomy planning. Still, attention should be paid to patient setup during FLSR, as clinically relevant measurement errors occur once exceeding >9° of limb rotation that worsen in combination with >15° of knee flexion [35].

Osteotomy planning with the WBL through the LTS corresponded to 181.8°±0.3 (181.3°-182.5°) mTFA. Postoperative realignment outcomes with the WBL on the LTS (±2%) were confirming the expected 1-3° valgus correction as a reliable interval. A systematic review by Van den Bempt et al. found that the overlapping correction target considered 'acceptable' for all included HTO studies was 2-3° valgus [3]. In addition, Heijens et al. earlier described a 2° valgus threshold (coronal hypomochlion) after which the joint line convergence angle (JLCA) makes a linear decrease (the point after which the medial compartment gets radiographically 'unloaded') [14]. His team proposed an ideal correction between 2-5° valgus based on preoperative JLCA status. However, current evidence about optimal load redistribution between a diseased medial and healthy lateral knee compartment is inconclusive [29, 49, 53]. In a preliminary model, Martay et al. estimated the ideal balance at 55% (1.7°–1.9° mechanical valgus) while Zheng et al. showed balanced loading at 4.3° valgus for the femoral and 2.9° for the tibial cartilage [29, 53]. According to Trad et al., this point should even be located at 4.5° of valgus which seems to interfere with the clinical consequences of overcorrected osteotomies [49].

The authors are aware that observer bias might be a potential concern in radiological studies. Therefore, all measurements were conducted by two blinded observers showing good IOC agreement (Table 1). In brief, this study provides fundamental knowledge about the lateral spine position on the tibial plateau in a Caucasian HTO patient population. The implications for HTO planning are in the 10% variation range of the LTS position, which corresponds to an individual planned and postoperative realignment of 1-3° valgus.

CONCLUSION

The lateral tibial spine is located at 57-58% with a 10% maximal variation range on the tibial plateau in a Caucasian HTO population. Good agreement was found between 2D and 3D imaging modalities while evaluating its position in the coronal plane. When aiming the WBL through the lateral tibial spine during valgus-producing HTO on full-leg standing radiographs, a consistent realignment of 181-183° mTFA can be expected when performing accurate surgery.

CONFLICT OF INTERST

The authors declare to have no conflict of interest.

FUNDING

No funding was received for this study.

ACKNOWLEDGEMENT

None.

2.2 A shift from 2D to 3D planning… or both?

Published as book chapter 24 in ‘Advances in Knee Ligament and Knee Preservation Surgery’ (2022) DOI: 10.1007/978-3-030-84748-7_24

A proper full-leg bipodal standing radiograph has always been the benchmark for determining malalignment of the lower limb and for planning knee osteotomies [44]. The Dugdale and Miniaci method have been popularised to quantify preoperative malalignment and to determine the amount of degrees to correct [8][31]. However, questions have been raised about the reliability and effect of slight knee flexion and limb rotation on 2D imaging modalities [19, 22, 48]. The application of a standardized FLSR seems obvious, given that clinically relevant measurement errors occur beyond leg rotation of 9° alone and 15° of knee flexion [35]. Moreover, the factor weight-bearing might cause an overestimation of the preoperative varus alignment, which will theoretically result in an overcorrected osteotomy [27, 37, 47]. Finally, FLSR are falling short when it comes to intended single or combined tibial slope corrections which altogether stresses the need to integrate 3D imaging in surgical planning.

Despite the imperfections, a conventional FLSR still forms a cornerstone in the planning and postoperative phase, even in the majority of clinical patient-specific instrumentation (PSI) studies [2, 4, 11, 20, 32, 40]. With supine CT-scan, information is lost on knee dynamics during the bipodal stance phase which seems highly relevant to encounter in osteotomy planning. The intra-articular varus component (commonly expressed as joint line converge angle (JLCA)) and its consequent dynamic compensation after realigning the tibia is crucial to understand in order to avoid overcorrections [14, 30]. Before surgery, attention should be paid to correctable varus on clinical examination (lateral soft tissue laxity) and a varus thrust during gait. So, any form of preoperative imaging in weight-bearing condition (bi-or unipedal and with or without stress views) seems obligatory if clinical soft tissue laxity is suspected. A JLCA > 2°, lateral joint space widening and tibiofemoral subluxation on valid FLSR are radiographical indicators for lateral soft tissue stretch [30, 36]. When varus deformity is clinically and/or on valgus stress radiographs correctable, spontaneous postoperative correction of this dynamic component should be anticipated [14]. So, it makes sense that a large preoperative JLCA (>4°) and Kellgren and Lawrence (K-L) grade 3 and 4 OA with tibiofemoral subluxation of 5-10mm have been associated with more overcorrections leading to dissatisfied patients [21, 24, 39]. It is true that large preoperative JLCA values almost never normalize after HTO (JLCA 0-2°), so at least partial correction at the bony level should be factored into planning, but how much should this be?

Several authors have proposed on how to manage the JLCA compensation mechanism; Noyes et al. anticipated on lateral soft tissue laxity by diminishing the planned correction by 1° for each mm of additional preoperative lateral joint space widening [36]. So et al. simply suggested to diminish the planning angle by the difference (Δ) in JLCA on standing radiographs versus supine [46]. In analogue, Ryu et al. performed additional valgus stress radiographs and subtracted 1/3 of the ΔJLCA between weight-bearing and valgus stress views from the intended correction [42]. Micicoi et al. empirically suggested to subtract the planned correction degree by x°= (preoperative JLCA°-2)/2, considering a normal JLCA between 0-2° [30]. However, according to Heijens et al., the dynamic soft-tissue compensation will only manifest when the overall mechanical axis is realigned on or beyond the tipping point of 2° mTFA valgus (coronal hypomochlion) [14]. In their study, a linear correlation was demonstrated for the preoperative standing JLCA and the amount of postoperative JLCA compensation when aiming the mechanical axis at 2° valgus using computer navigation. When dealing with a preoperative JLCA of 3-4°, a 1-2° JLCA decrease should be anticipated (hence, subtracted from the planning) while for a JLCA of 4-6°, this was 2-3°. They concluded that the postoperative JLCA compensation showed a linear correlation with further 'valgisation' up to 5° when aiming surgically on 2° mechanical valgus [14].

Which mathematical method is superior over the other remains to be seen, although in essence, they do not differ much as they all aim to partially correct intra-articular malalignment at the bony level while counting on spontaneous dynamic compensation. The key remains to be aware of the intra-articular varus component, its amount, reducibility with valgus stress and most importantly the risk for overcorrection if not integrated in surgical planning. Of interest and difficult to quantify is the extent of medial collateral ligament (MCL) release performed by the surgeon and final postoperative medial proximal tibial angle (MPTA) (and joint line obliquity (JLO)) that most likely play role as well on how much JLCA will shift postoperatively [1, 38, 46]. This among other factors feed discussion if knee osteotomy planning should be performed on weight-bearing or non-weightbearing imaging modalities or even on both. The value of 3D imaging on this matter however seems low given its unloaded status and poor description of usefulness in benchmark papers.

Now considering the correction and planning of static (i.e. bony) malalignment, emerging 3D imaging has found its way to knee osteotomy since the introduction of computer navigation (CT-scan) at the beginning of this century [43]. Although a full-leg CT-scan was required intraoperatively rather than preoperatively for planning purposes, scanning protocols were elaborated and improved over time. However the use of computer navigation attenuated and never became gold standard to perform knee osteotomies. 3D planning eventually revived with the first PSI guides in 2013 due to major technological advances in planning software (e.g. Materialise®, Leuven, Belgium) [52]. 3D imaging in any form (CT or MRI) of the proximal tibia was minimally required to simulate the bone cut and plan the osteotomy opening in a multiplanar fashion if desired. A full-leg low-dose CT-scan appears to be the better option over MRI, because it is less expensive, the imaging waiting times are shorter and it provides clearer spatial resolution to segment bone [7]. This might be associated with an additional cost and an increased radiation exposure on top of a standard preoperative FLSR. However, the effective radiation dose of a CT-scan is largely dependent on the applied slice thickness, spacing and scanned area. Therefore, very low-dose protocols for scanning the lower limb have been established, only targeting a centred range of the hip, knee and ankle joint resulting in reliable 3D anatomic models for planning realignment and arthroplasty surgery [15]. In this way, the effective radiation dose can be reduced to the equivalent of a FLSR.

After scanning, the obtained imaging DICOM files from the scan are easily loaded into the dedicated segmentation software. The anatomical bone models are exported as STL-files to maintain scale and composition. Finally, the bone models are transferred to 3D medical planning software to virtually pre-plan the correction size and define the bone cut (plane, depth and starting point) which can be followed by PSI design and printing [2, 4, 32, 40]. However, it should be emphasized that alignment of both femur and tibia must be measured at first in order to determine where varus originates from (femur, tibia, intra-articular of a combination). The level and type of osteotomy and the amount of correction should than be planned accordingly [6].

Some authors have recently implemented the MPTA as primary planning angle [4, 32]. The MPTA strictly limits the correction change to the tibial bone in contrast to the mTFA or WBL which might be prone to variation by a patient’s position during preoperative imaging. Moreover, this angle has proven to be the only predictor for alignment errors after opening-wedge HTO and makes its inclusion in modern HTO planning therefore recommendable to improve correction accuracy [23].

In addition, it is supported to conduct MPTA measurements in order to control JLO<5° after HTO without compromising future conversion to arthroplasty. The planned MPTA should not exceed 95° as this might induce excessive joint line obliquity with increased shear stress on the articular cartilage [34]. A double-level osteotomy might therefore be indicated in large varus malalignment which can be planned more precisely in 3D imaging software.

Overall, the main advantages of executing a preoperative 3D osteotomy planning are (1) the reliable angle measurements based on exact identification of unique bony landmarks [18], (2) the multiplanar and multilevel simulation of the surgery [18] and (3) it forms the ideal tool for designing subsequent PSI and tailor-made anatomical models [51]. With the availability of 3D bone models, the intended correction size can be planned precisely in a way that even the thickness of the used sawblade can be taken into account [17]. Nevertheless, 3D planning is restricted to correct bony malalignment. Additional soft tissue corrections due to intra-articular varus (JLCA >2°) should be anticipated and taken into account on weight-bearing or stress imaging [30]. A combination of both imaging modalities seems therefore optimal to strive for precise osteotomy planning and to facilitate conversion to surgery. In future perspectives, technological development might further reduce the radiation exposure and advance required imaging such as EOS weight-bearing full-leg CT-scan and cone-beam. The automation of the segmentation/planning process should be stimulated and the cost of 3D software and printers decreased to enhance the onsite accessibility of medical 3D technology.

2.3 Personal 3D planning methodology for medial opening-wedge high tibial osteotomy

Unpublished (informative)

In our centre, patients receive a low-dose CT-scan of the whole index limb according to the Trumatch protocol by DepuySynthes® [7]. This protocol involves scanning of the hip and ankle joint on a 5mm thickness and spacing, and the knee on a 0.5mm thickness and spacing, captured in 150mm centered range. DICOM-files are loaded in medical image software Mimics 23.0 (Materialise®, Leuven, Belgium) (Figure 2). Threshold of segmentation is set at 130-200 HU and unrequired bone parts such as the acetabular socket and talus are manually removed. The final 3D reconstruction of the lower limb is exported as STL-files and opened in medical 3D planning software 3-matic 14.0 (Materialise®, Leuven, Belgium).

The hip center is determined by marking the femoral head with subsequent fitting of a best fit sphere. The center of the distal tibia (pilon) is defined by measuring the anteroposterior and mediolateral middle of the tibia plafond surface. Correct positioning is visually controlled on an anteroposterior view. Landmarks around the knee joint are manually defined as described by Victor et al. [51]. The anatomic plane of the femur is determined by connecting the medial and lateral epicondyle of the femur and the femoral head center. The mechanical femoral axis is created by connecting the femoral head center and the middle of the trans-epicondylar axis (TEA). The anatomic plane of the tibia is then defined by the tip of the medial and lateral tibial spine and the pilon center. The mechanical tibial axis is created by connecting the center of the tibial pilon to the middle of the medial and lateral spine distance. The lateral distal femoral angle (LDFA), the MPTA, the mTFA and the JLCA are measured in the coronal plane while a best fitting plane for medial and lateral tibial plateau is determined to measure slopes in the sagittal plane (Appendix). The femoral anteversion angle (FAVA) and tibial external version angle (TEVA) are formally added to assess malrotation (Appendix). This 3D analysis report is delivered to the surgeon who decides indication for osteotomy, the bony level, correction in single or multiple planes, and the amount of correction based on clinical and other radiological findings (i.e. weight-bearing imaging).

For osteotomy planning, an individualized target is preferred based on the pre-existing tibial varus (MPTA), overall varus degree (mTFA) and alignment of the contralateral side, but never exceeding a planned MPTA >96°. The target angle can range from slight varus towards crossing the WBL through the lateral tibial spine (slight valgus). For osteotomy simulation, a cutting plane is designed starting from the vertical convex-concave transition of the medial proximal tibia, approximately 35mm below the tibial plateau which is directed towards the tip of the fibular head. The plane offset is set at 0.9mm, corresponding to the actual sawblade thickness and intraoperative bone loss. Next, the hinge axis is determined at 5-10mm from the lateral cortex and perpendicular to the posterior tibial condylar line, if a sole uniplanar correction in the coronal plane is desired. The osteotomy is opened until the desired MPTA and tibial slope are obtained (Figure 7). A second report with the desired planned angles is submitted to the surgeon for feedback. On request, a customized 3D guide can easily be manufactured based on this 3D planning and simulation.

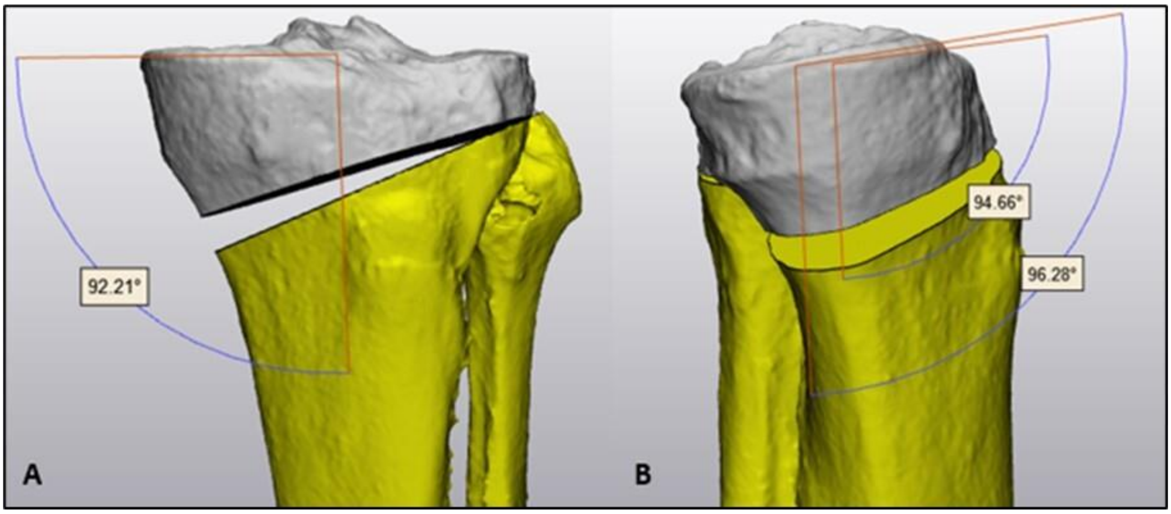


Figure 7. Osteotomy simulation with gradual distraction until the desired (A) MPTA and (B) tibial slope angles are obtained.

REFERENCES

1. Akamatsu Y, Kumagai K, Kobayashi H, Tsuji M, Saito T (2018) Effect of Increased Coronal Inclination of the Tibial Plateau After Opening-Wedge High Tibial Osteotomy. Arthroscopy Arthroscopy Association of North America 34(7):2158-2169.e2

2. Arnal-Burró J, Pérez-Mañanes R, Gallo-del-Valle E, Igualada-Blazquez C, Cuervas-Mons M, Vaquero-Martín J (2017) Three dimensional-printed patient-specific cutting guides for femoral varization osteotomy: Do it yourself. Knee 24(6):1359–1368

3. Van den Bempt M, Van Genechten W, Claes T, Claes S (2016) How accurately does high tibial osteotomy correct the mechanical axis of an arthritic varus knee? A systematic review. Knee Elsevier B.V. 23(6):925–935

4. Chaouche S, Jacquet C, Fabre-Aubrespy M, Sharma A, Argenson JN, Parratte S, Ollivier M (2019) Patient-specific cutting guides for open-wedge high tibial osteotomy: safety and accuracy analysis of a hundred patients continuous cohort. Int Orthop International Orthopaedics 43(12):2757–2765

5. COVENTRY MB (1965) OSTEOTOMY OF THE UPPER PORTION OF THE TIBIA FOR DEGENERATIVE ARTHRITIS OF THE KNEE. A PRELIMINARY REPORT. J Bone Joint Surg Am 47(47):984–90

6. Dawson MJ, Ollivier M, Menetrey J, Beaufils P (2022) Osteotomy around the painful degenerative varus knee: a 2022 ESSKA formal consensus. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 31(8):3041-3043

7. DePuy Orthopaedics Inc (2010) Radiation Exposure Considerations with the use of TruMatch Personalized solutions.

8. Dugdale T, Noyes F, Styer D (1992) Preoperative planning for high tibial osteotomy. The effect of lateral tibiofemoral separation and tibiofemoral length. Clin Orthop (274):248–64

9. Elson DW, Petheram TG, Dawson MJ (2015) High reliability in digital planning of medial

opening wedge high tibial osteotomy, using Miniaci’s method. Knee Surg Sports Traumatol Arthrosc 23(7):2041–2048

10. Feucht MJ, Minzlaff P, Saier T, Cotic M, S??dkamp NP, Niemeyer P, Imhoff AB, Hinterwimmer S (2014) Degree of axis correction in valgus high tibial osteotomy: proposal of an individualised approach. Int Orthop 38(11):2273–2280

11. Fucentese SF, Meier P, Jud L, Köchli GL, Aichmair A, Vlachopoulos L, Fürnstahl P (2020) Accuracy of 3D-planned patient specific instrumentation in high tibial open wedge valgisation osteotomy. J Exp Orthop Journal of Experimental Orthopaedics 7(1):1–7

12. Fujisawa Y, Masuhara K, Shiomi S (1979) The effect of high tibial osteotomy on osteoarthritis of the knee. An arthroscopic study of 54 knee joints. Orthop Clin North Am 10(3):585–608

13. Van Genechten W, Van den Bempt M, Van Tilborg W, Bartholomeeusen S, Van Den Bogaert G, Claes T, Claes S (2020) Structural allograft impaction enables fast rehabilitation in opening-wedge high tibial osteotomy: a consecutive case series with one year follow-up. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 28(12):3747–3757

14. Heijens E, Kornherr P, Meister C (2016) The coronal hypomochlion: A tipping point of clinical relevance when planning valgus producing high tibial osteotomies. Bone Joint J 98(5):628–633

15. Henckel J, Richards R, Lozhkin K, Harris S, Baena FMR y, Barrett ARW, Cobb JP (2006) Very low-dose computed tomography for planning and outcome measurement in knee replacement: THE IMPERIAL KNEE PROTOCOL. J Bone Joint Surg Br 88-B(11):1513–1518

16. Jiang X, Li B, Xie K, Ai S, Hu X, Gao L, Wang L, Yan M (2021) Lateral tibial intercondylar eminence is a reliable reference for alignment correction in high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc 31(4):1515-1523

17. Jones GG, Jaere M, Clarke S, Cobb J (2018) 3D printing and high tibial osteotomy. EFORT Open Reviews 3(5):254–259

18. Jörgens M, Keppler AM, Degen N, Bachmeier AT, Bergstraesser M, Sass J, Prall WC, Böcker W, Fürmetz J (2022) Reliability of 3D planning and simulations of medial open wedge high tibial osteotomies. Journal of Orthopaedic Surgery 30(2):1–9

19. Kawakami H, Sugano N, Yonenobu K, Yoshikawa H, Ochi T, Hattori A, Suzuki N (2004) Effects of rotation on measurement of lower limb alignment for knee osteotomy. Journal of Orthopaedic Research 22(6):1248–1253

20. Kim H-J, Park J, Shin J-Y, Park I-H, Park K-H, Kyung H-S (2018) More accurate correction can be obtained using a three-dimensional printed model in open-wedge high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 26(11):3452-3458

21. Kim YT, Choi JY, Lee JK, Lee YM, Kim J Il (2019) Coronal tibiofemoral subluxation is a risk factor for postoperative overcorrection in high tibial osteotomy. Knee Elsevier B.V. 26(4):832–837

22. Koshino T, Takeyama M, Jiang LS, Yoshida T, Saito T (2002) Underestimation of varus angulation in knees with flexion deformity. Knee 9(4):275–279

23. Kubota M, Ohno R, Sato T, Yamaguchi J, Kaneko H, Kaneko K (2018) The medial proximal tibial angle accurately corrects the limb alignment in open-wedge high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 27(8):2410-2416

24. Lee S-S, Kim JH, Kim S, Jung EY, Ryu DJ, Lee DK, Wang JH (2022) Avoiding Overcorrection to Increase Patient Satisfaction After Open Wedge High Tibial Osteotomy. Am J Sports Med 50(9):2453–2461

25. Lee SS, Lee H Il, Cho ST, Cho JH (2020) Comparison of the outcomes between two different target points after open wedge high tibial osteotomy: The Fujisawa point versus the lateral tibial spine. Knee Elsevier B.V. 27(3):915–922

26. Lee SS, So SY, Jung EY, Kim HJ, Lee BH, Wang JH (2019) Predictive Factors for Patellofemoral Degenerative Progression After Opening-Wedge High Tibial Osteotomy. Arthroscopy Elsevier Inc. 35(6):1703–1710

27. Lee YS eu., Kim MG y., Byun HW o., Kim SB u., Kim JG o. (2015) Reliability of the imaging software in the preoperative planning of the open-wedge high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc 23(3):846–851

28. Martay JL, Palmer AJ, Bangerter NK, Clare S, Monk AP, Brown CP, Price AJ (2018) A preliminary modeling investigation into the safe correction zone for high tibial osteotomy. Knee 25(2):286–295

29. Martay JL, Palmer AJ, Bangerter NK, Clare S, Monk AP, Brown CP, Price AJ (2018) A preliminary modeling investigation into the safe correction zone for high tibial osteotomy. Knee Elsevier B.V. 25(2):286–295

30. Micicoi G, Khakha R, Kley K, Wilson A, Cerciello S, Ollivier M (2020) Managing intra-articular deformity in high Tibial osteotomy: a narrative review. J Exp Orthop Journal of Experimental Orthopaedics 7(1):1–10

31. Miniaci a., Ballmer FT, Ballmer PM, Jakob RP (1988) Proximal tibial osteotomy. A new fixation device. Clin Orthop 17(5):456-458

32. Munier M, Donnez M, Ollivier M, Flecher X, Chabrand P, Argenson JN, Parratte S (2017) Can three-dimensional patient-specific cutting guides be used to achieve optimal correction for high tibial osteotomy? Pilot study. Orthop Traumatol Surg Res Elsevier Masson SAS 103(2):245–250

33. Nakayama H, Schröter S, Yamamoto C, Iseki T, Kanto R, Kurosaka K, Kambara S, Yoshiya S, Higa M (2018) Large correction in opening wedge high tibial osteotomy with resultant joint-line obliquity induces excessive shear stress on the articular cartilage. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 26(6):1873–1878

34. Nakayama H, Schröter S, Yamamoto C, Iseki T, Kanto R, Kurosaka K, Kambara S, Yoshiya S, Higa M (2018) Large correction in opening wedge high tibial osteotomy with resultant joint-line obliquity induces excessive shear stress on the articular cartilage. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 26(6):1873–1878

35. Nguyen HC, Gielis WP, van Egmond N, Weinans H, Slump CH, Sakkers RJB, Custers RJH (2021) The need for a standardized whole leg radiograph guideline: The effects of knee flexion, leg rotation, and X-ray beam height. J Cartil Jt Preserv Elsevier B.V. 1(3):100022

36. Noyes FR (2020) Editorial Commentary: Measurements for Successful High Tibial Osteotomy: Understanding Supine Versus Standing and Intraoperative Fluoroscopic Alignment Is Required. Arthroscopy Arthroscopy Association of North America 36(6):1665–1669

37. Ogawa H, Matsumoto K, Ogawa T, Takeuchi K, Akiyama H (2016) Preoperative varus laxity correlates with overcorrection in medial opening wedge high tibial osteotomy. Archives of Orthopaedic and Trauma Surgery Springer Berlin Heidelberg 136(10):1337–1342

38. Pape D, Duchow J, Rupp S, Seil R, Kohn D (2006) Partial release of the superficial medial collateral ligament for open-wedge high tibial osteotomy: A human cadaver study evaluating medial joint opening by stress radiography. Knee Surg Sports Traumatol Arthrosc 14(2):141–148

39. Park CH, Bae DK, Kim K Il, Lee JW, Song SJ (2017) Serial Changes in the Joint Space Width and Joint Line Convergence Angle After Closed-Wedge High Tibial Osteotomy. Am J Sports Med 45(14):3254–3261

40. Pérez-Mañanes R, Burró JA, Manaute JR, Rodriguez FC, Martín JV (2016) 3D Surgical Printing Cutting Guides for Open-Wedge High Tibial Osteotomy: Do It Yourself. J Knee Surg 29(8):690–695

41. van de Pol GJ, Verdonschot N, van Kampen A (2012) The value of the intra-operative clinical mechanical axis measurement in open-wedge valgus high tibial osteotomies. Knee 19(6):933–938

42. Ryu DJ, Lee SS, Jung EY, Kim JH, Shin TS, Wang JH (2021) Reliability of Preoperative Planning Method That Considers Latent Medial Joint Laxity in Medial Open-Wedge Proximal Tibial Osteotomy. Orthop J Sports Med 9(10):1–9

43. Saragaglia D, Roberts J (2005) Navigated osteotomies around the knee in 170 patients with osteoarthritis secondary to genu varum. Orthopedics 28(10 Suppl):s1269–s1274

44. Schröter S, Ihle C, Mueller J, Lobenhoffer P, Stöckle U, van Heerwaarden R (2013) Digital planning of high tibial osteotomy. Interrater reliability by using two different software. Knee Surg Sports Traumatol Arthrosc 21(1):189–196

45. Snow M, Jermain P, Mandalia V, Murray J, Khakha R, McNicholas M, Dawson M (2021) A 2021 consensus statement on osteotomies around the knee by the UK Knee Osteotomy consensus Group (KOG). Knee Elsevier B.V. 33(December):73–83

46. So SY, Lee SS, Jung EY, Kim JH, Wang JH (2020) Difference in joint line convergence angle between the supine and standing positions is the most important predictive factor of coronal correction error after medial opening wedge high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 28(5):1516–1525

47. Specogna A V., Birmingham TB, Hunt MA, Jones IC, Jenkyn TR, Fowler PJ, Giffin JR (2007) Radiographic measures of knee alignment in patients with varus gonarthrosis: Effect of weightbearing status and associations with dynamic joint load. Am J Sports Med 35(1):65–70

48. Swanson KE, Stocks GW, Warren PD, Hazel MR, Janssen HF (2000) Does axial limb rotation affect the alignment measurements in deformed limbs? Clin Orthop 371(Feb):246–252

49. Trad Z, Barkaoui A, Chafra M, Tavares JMR (2018) Finite element analysis of the effect of high tibial osteotomy correction angle on articular cartilage loading. J Eng Med 232(6):553–564

50. Tripon M, Sautet P, Argenson J, Jacquet C, Martz P, Ollivier M (2022) Is the lateral tibial spine a reliable landmark for planning tibial or femoral valgus osteotomies ? Orthop Traumatol Surg Res 108(3):103253

51. Victor J, Van Doninck D, Labey L, Innocenti B, Parizel PM, Bellemans J (2009) How precise can bony landmarks be determined on a CT scan of the knee? Knee Elsevier B.V. 16(5):358–

365

52. Victor J, Premanathan A (2013) Virtual 3D planning and patient specific surgical guides for osteotomies around the knee: a feasibility and proof-of-concept study. Bone Joint J 95 B(11 Suppl A):153–158

53. Zheng K, Scholes CJ, Chen J, Parker D, Li Q (2017) Multiobjective optimization of cartilage stress for non-invasive, patient-specific recommendations of high tibial osteotomy correction angle – a novel method to investigate alignment correction. Med Eng Phys Elsevier Ltd 42(Apr):26–34

Chapter 3 High tibial osteotomy simulation

3.1 The effect of osteotomy depth and hinge axis alignment on biplanar accuracy – a deeper understanding by 3D simulations

ABSTRACT

OBJECTIVE Not all surgical steps of the osteotomy procedure itself have been investigated for their potential impact on surgical accuracy. The main study objective was to investigate the osteotomy parameters that have respectively major and minor impact on coronal and sagittal bony accuracy in medial opening-wedge high tibial osteotomy (MOWHTO).

METHODS Three tibias from an existing 3D MOWHTO database were chronologically selected based on segmentation quality, tibial plateau size and the presence of tibial varus (medial proximal tibial angle (MPTA) < 86°). The study consisted of three parts; (1) translating the hinge axis in the coronal plane and switching osteotomy starting point (30-40mm), eight simulations were performed with varying osteotomy depths. (2) the starting point (35mm) and hinge axis (15mm x 7.5mm) were fixed in the coronal plane, but in the sagittal plane, the hinge axis was rotated stepwise by 10° to perform five simulations (-20°, -10°, 0°, +10°, +20°). (3) the starting point and hinge axis were similarly fixed in the coronal plane but the hinge axis was rotated towards stepwise by 10° anterolateral to perform four simulations (0°, +10°, +20°, +30°) and the anterior and posterior cortical distances were measured. The MPTA and lateral tibial slope were the primary outcomes. Simulations were performed with 5, 10 and 15mm gap distraction.

RESULTS In the coronal plane, maximum difference in osteotomy depth was 10mm which represented an MPTA difference of 0.8°-1.1° in 10mm gap distraction and 1.2°-2.0° in 15mm gap distraction. Tibial slope remained unchanged. Rotating the hinge axis in the sagittal plane delivered minor changes on both MPTA (<0.5°) and tibial slope (<1.5°) at 10mm gap distraction. Per 10° of axial rotation of the hinge axis towards anterolateral, the tibial slope increased by 1.0°-1.3° in 10mm gap distraction while the MPTA remained nearly unchanged. This difference is 1.6°-2.2° in 15mm gap distraction. The difference in anteroposterior osteotomy length is 7-8mm when the hinge axis is 10° axially rotated and doubles with every 10° stepwise rotation.

CONCLUSION The study showed that (1) the osteotomy depth is the main parameter for obtaining bony accuracy in the coronal plane (MPTA°) and (2) controlling the axial hinge axis position is crucial in maintaining the native tibial slope. Correct axial alignment of the hinge axis can be obtained by creating an equal osteotomy depth of the anterior and posterior tibial cortices. A difference of approximately 7mm (longer anterior cortex) results in 10° of anterolateral hinge axis rotation corresponding to a tibial slope increase of 1.0-1.3° when performing 10mm gap distraction in MOWHTO.

KEYWORDS: High tibial osteotomy – 3D – simulation – accuracy – hinge axis – posterior tibial slope

INTRODUCTION

Medial opening-wedge high tibial osteotomy (MOWHTO) is considered to be a technically demanding procedure with excellent long-term outcomes when performed accurately [8]. Despite good survival rates, conventional MOWHTO techniques (and planning methods) appear to have a surprisingly low accuracy in the coronal plane [2]. This can be attributed to imprecise planning methods, difficult translation of the planned correction into surgery, and unpredicted soft-tissue correction after postoperative weight-bearing [9, 10]. Regarding the intraoperative bony correction, the ‘1° planned correction = 1mm wedge opening’ rule has been outperformed by the Hernigou table and commonly used if not applying 3D technology [5, 12]. The Hernigou table includes osteotomy depth in order to reliably determine the required wedge opening (mm) at the medial cortex, but neglects for example thickness of the sawblade, hinge axis position and the oblique orientation of the proximal anteromedial tibial cortex. So, a 3-planar accurate correction cannot be guaranteed when blindly following this conversion table. Besides coronal inaccuracy, unintended tibial slope increase in the sagittal plane is often described after MOWHTO, ranging from 2° to 5° [14]. The amount of tibial slope increase that can be accepted with regards to anterior cruciate ligament (ACL) strain and knee biomechanics is still debated, however, excessive increase should be strictly avoided [7]. Technical reasons for slope increase are the 45° anteromedial approach to the tibia, difficulties in controlling unequal anteroposterior gap distraction and an anterolateral shift of the hinge axis [13].

Despite progressive research on virtual osteotomy simulations and 3D cutting guides, not all surgical steps of an MOWHTO and consequent gap distraction are fully understood in a 3-planar fashion[1, 6, 14]. A deeper understanding seems therefore necessary when performing MOWHTO in daily practice to comprehend the key steps of an osteotomy to obtain accurate biplanar outcomes. The main study objective was to illustrate 3-planar osteotomy parameters that have respectively major and minor impact on coronal and sagittal bony accuracy in MOWHTO. These factors include the 3D osteotomy plane orientation, the anteroposterior osteotomy depth differences, the hinge axis location, the proximal tibial size and the amount of intended correction.

METHODS

From an existing 3D HTO database, three full leg CT scans were chronologically selected based on segmentation quality, tibial plateau size and the presence of tibial varus (medial proximal tibial angle (MPTA) < 86°). A small, moderate and large tibial plateau were intentionally obtained to assess relevant difference regarding proximal tibia size. The CT-scan protocol (Trumatch), segmentation threshold in Mimics 23.0 (Materialise®, Leuven, Belgium) and 3D reconstruction are outlined in Chapter 2 (section 2.3). All measurements, axes and plane definitions were conducted in 3-matic 14.0 (Materialise®, Leuven, Belgium). Case details of the three selected 3D models are outlined in table 1. Tibial plateaus were intentionally selected by size (70mm, 77.5mm and 85mm).

	Case 1	**Case 2**	**Case 3**
Age	48y	39y	60y
Sex	Female	Male	Male
Tibial plateau width	70 mm	77.5 mm	85 mm
MPTA°	85.8°	84.0°	85.5°
Medial tibial slope°	91.73°	101.8°	94.8°
Lateral tibial slope°	92.5°	98.9°	95.4°

Table 1. Patient demographics and bony features of the three selected tibias. MPTA, medial proximal tibial angle; mm, millimetre

Axes and plane definition

Anatomical tibial axis (ATA)

The center of the tibial plateau was determined by bisecting the line between the tip of the medial and lateral tibial spine. This point was connected to the center of the tibial dome which was determined by the middle of the medial and lateral malleolus. During osteotomy simulation, the new tibial axis was redefined by the new center of the tibial dome after translation of the distal tibia.

Tibial joint line (TJL)

The deepest points on the medial and lateral tibial plateau were determined and connected to define the tibial joint line.

Posterior condylar line (PCL)

The most posterior point on the medial and lateral tibial condyle were determined and connected to define the posterior condylar line. In case of medial posterior osteophytes, the point was redefined as to the original bony anatomy of the patient.

Posterior tibial plane (PTP)

The posterior condylar line (2 points) was connected to the center of the tibial dome to create the posterior tibial plane. The MPTA (coronal alignment) was measured in this plane.

Medial and lateral slope plane (MSP/LSP)

The medial and lateral tibial plateau were separately marked 'free hand' in an anteroposterior way with the lasso tool. A 'best fitting plane' was created which represented the tibial slope.

Tibia slope plane (TSP)

This plane was created by using the anatomical tibial axis (2 points) as baseline and was set perpendicular to the posterior tibial plane. The medial and lateral tibial slope angles were measured in this tibial slope plane. The baseline axial position of the hinge axis was created parallel to the tibial slope plane and in neutral position in the sagittal plane according to the world coordinate system.

<u>Hinge axis translations and rotations</u>

The hinge axis was sequentially translated in the (A) coronal and rotated in (B) the sagittal and (C) the axial plane in order to assess the effect on coronal (MPTA) and sagittal (lateral tibial slope) alignment. Osteotomy plane thickness was set at 1.35mm in all simulations. Medial opening-wedge osteotomies were simulated with respectively 5mm, 10mm and 15mm gap distraction measured at the posteromedial cortex of the 3D model. Corrections were obtained by rotating the distal tibial including the tibial dome center point over the desired hinge axis. After each simulation, a new anatomical tibial axis was created which was used to measure the new MPTA and the lateral tibial slope.

A. *Coronal plane hinge translations (Figure 1)*

The osteotomy starting point was set 30mm or 40mm (2) inferior to the medial tibial plateau at the posteromedial cortex. The hinge axis was translated at 10mm or 20mm (2) inferior to the lateral tibial plateau and at 5mm or 10mm (2) from the lateral cortex. In total, eight osteotomy cuts were simulated (2x2x2). In all simulations, the hinge axis was kept perpendicular to the posterior tibial plane and parallel to the TSP (=neutral hinge axis). The osteotomy depth from starting point to hinge axis was also determined.

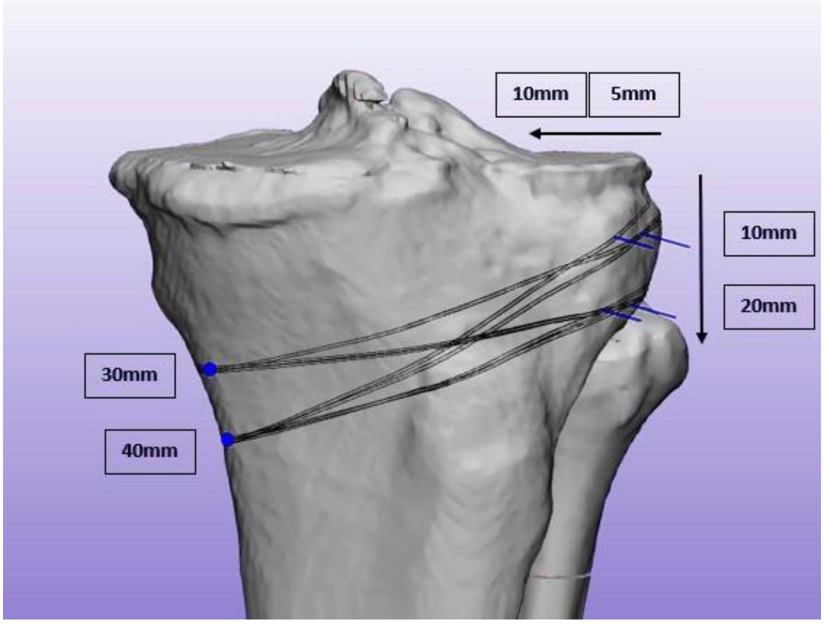


Figure 1. Eight osteotomy were simulated by translating the starting point and hinge axis (blue) in the coronal plane (2x2x2).

B. Sagittal plane hinge rotations (Figure 2)

A fixed osteotomy starting point (35mm inferior to the medial tibial plateau) and fixed hinge axis location (15mm inferior to the lateral tibial plateau and 7.5mm from the lateral cortex) were maintained during sagittal osteotomy plane simulations. The neutral osteotomy plane (0°), defined as the plane formed by the starting point and neutral hinge axis, was rotated stepwise by 10° from the center to perform five simulations (+20°, +10°, 0°, -10°, -20°) (Figure 2A). The hinge axes were kept parallel to the TSP (Figure 2B).

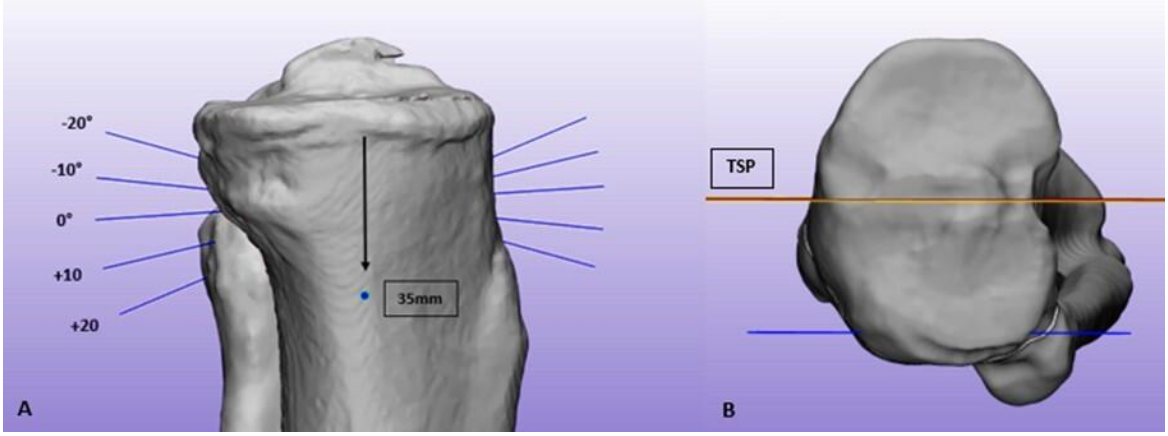


Figure 2. (A) Five osteotomies were simulated by rotating the hinge axis (blue) in the sagittal plane. The starting point (35mm) and coronal hinge axis position (15mm x 7.5mm) were fixed. (B) Superior view of the hinge axis rotations that were kept parallel to the tibial slope plane (TSP).

C. Axial plane hinge rotations (Figure 3 and 4)

Similar to the sagittal simulations, the osteotomy starting point (35mm inferior to the medial tibial plateau) and hinge axis location (15mm inferior to the lateral tibial plateau and 7.5mm from the lateral cortex) were fixed in the coronal plane during axial hinge axis rotations. The neutral osteotomy plane (0°) was maintained during all simulations, only the hinge axis was rotated stepwise by 10° from the center towards anterolateral. Four simulations were conducted (hinge axis at 0°, 10°, 20° and 30°). In addition, the anterior and posterior osteotomy distances to the respective hinge axis were measured to outline any relevant differences (Figure 4).

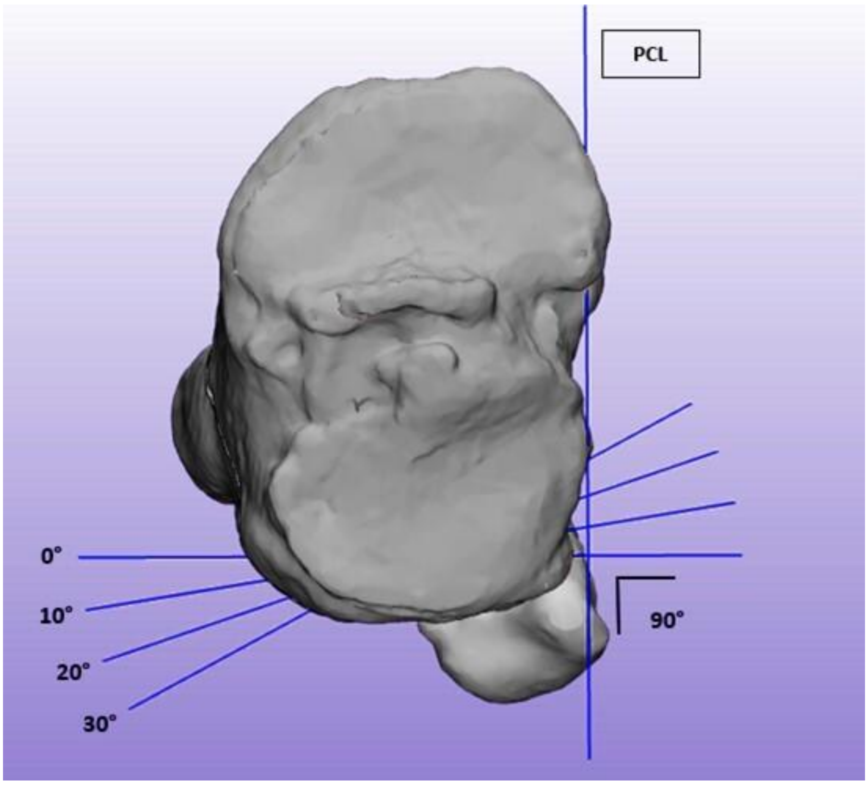


Figure 3. Superior view of the stepwise anterolateral hinge axis rotations (blue) in the axial plane. Rotations were performed in line with the neutral osteotomy plane that was used for every simulation (starting point 35mm, hinge axis 15mm x 7.5mm lateral). The initial hinge axis (0°) was perpendicular to the posterior condylar line (PCL).

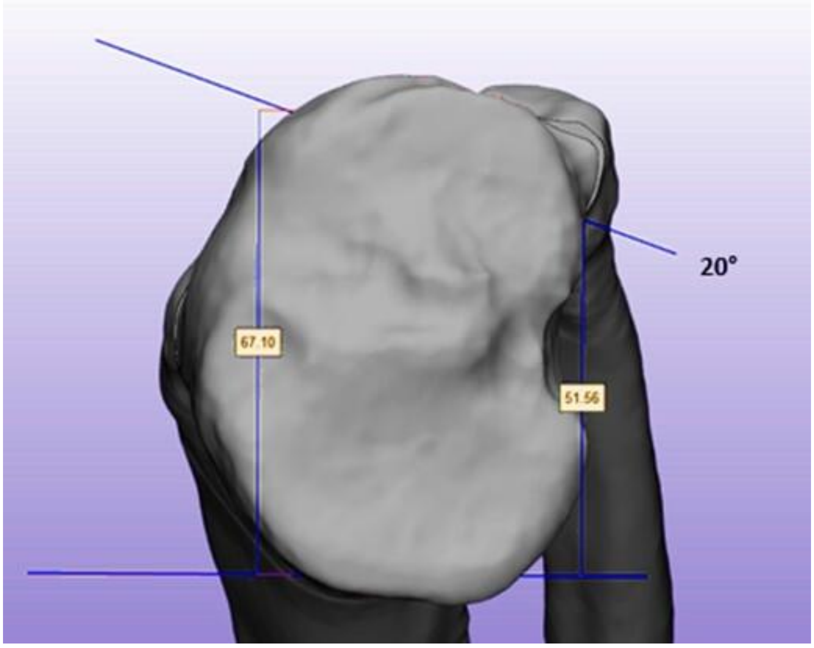


Figure 4. Superior view of the anterior and posterior cortex distances measured from the starting point to the rotating hinge axis in the axial plane.

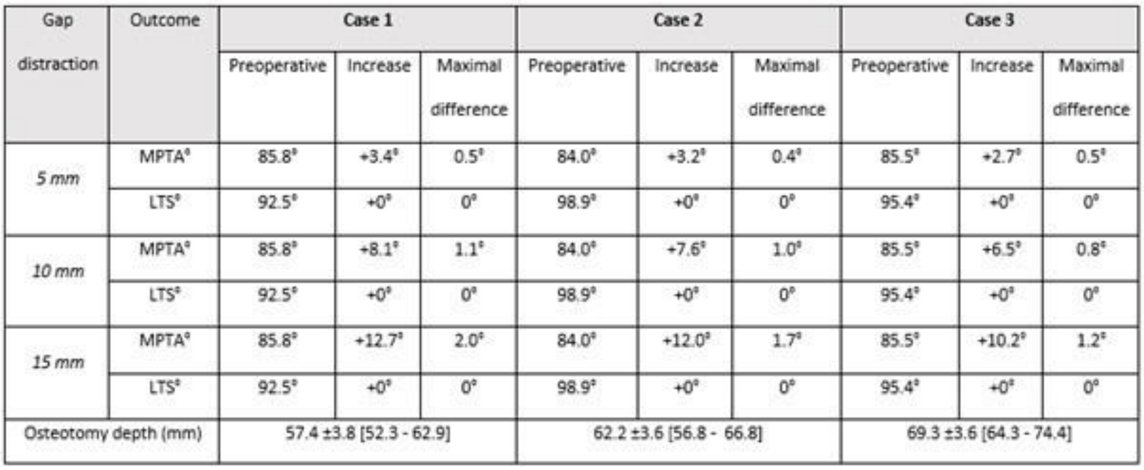
Statistics

Case outcomes in the coronal and sagittal plane were described separately. Descriptive statistics were expressed as mean, standard deviation (SD), minimum and maximum values [min;max]. A single observer performed all the simulations. Statistical tests were not performed due to the illustrative nature of the study.

RESULTS

A. Coronal plane hinge translations

Outcomes of coronal plane hinge translations are shown in table 2. The maximum difference after eight simulations for MPTA was 0.5° in 5mm distraction, 1.1° in 10mm distraction and 2.0° in 15mm distraction. The largest differences were observed in the smallest tibial plateau (case 1). The osteotomy depth varied by the starting point and position of the hinge axis. In all three cases, the shortest osteotomy was simulated by starting at 40mm inferior to the tibial plateau and the hinge axis at 20mm x 10mm laterally. The deepest osteotomy was found by starting at 40mm inferior to the tibial plateau and the hinge axis at 10mm x 5mm laterally. The LTS remained unchanged regardless of gap distraction.

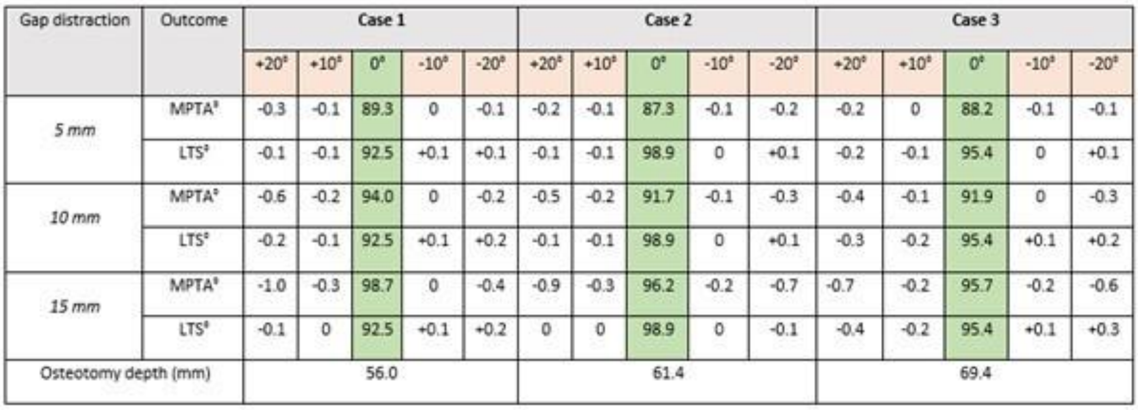


Gap distraction	Outcome	Case 1			Case 2			Case 3		
		Preoperative	Increase	Maximal difference	Preoperative	Increase	Maximal difference	Preoperative	Increase	Maximal difference
5 mm	MPTA°	85.8°	+3.4°	0.5°	84.0°	+3.2°	0.4°	85.5°	+2.7°	0.5°
	LTS°	92.5°	+0°	0°	98.9°	+0°	0°	95.4°	+0°	0°
10 mm	MPTA°	85.8°	+8.1°	1.1°	84.0°	+7.6°	1.0°	85.5°	+6.5°	0.8°
	LTS°	92.5°	+0°	0°	98.9°	+0°	0°	95.4°	+0°	0°
15 mm	MPTA°	85.8°	+12.7°	2.0°	84.0°	+12.0°	1.7°	85.5°	+10.2°	1.2°
	LTS°	92.5°	+0°	0°	98.9°	+0°	0°	95.4°	+0°	0°
Osteotomy depth (mm)		57.4 ±3.8 [52.3 - 62.9]			62.2 ±3.6 [56.8 - 66.8]			69.3 ±3.6 [64.3 - 74.4]		

Table 2. Case by case outcomes (average increase and maximal difference between osteotomies) of the eight 3D simulations in the coronal plane. MPTA, medial proximal tibial angle; LTS, lateral tibial slope; mm, millimetre.

B. *Sagittal plane hinge rotations*

Outcomes of sagittal plane rotations are shown in table 3. The maximum difference after five simulations for MPTA per 10° hinge axis tilt was -0.2° in 5mm distraction (-0.1° general), -0.4° in 10mm distraction (-0.3° general) and -0.7° in 15mm distraction (-0.4° general). This maximum was observed in the smallest tibia (case 1) between +10° and +20° hinge axis tilting. The LTS changed by 0.1° or did not change in gap distractions 5 and 10mm. By opening 15mm, the LTS did maximally change 0.2° per 10° hinge axis tilt.

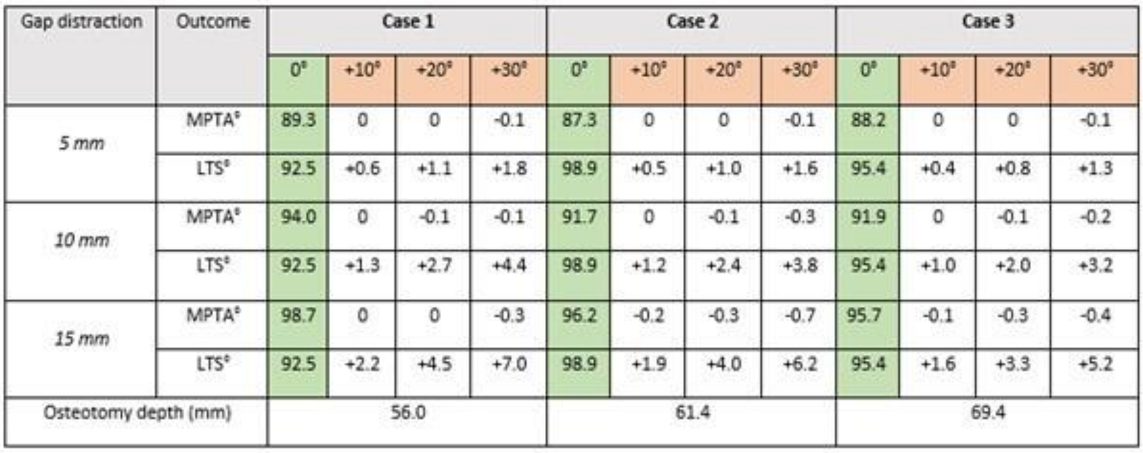


Gap distraction	Outcome	Case 1					Case 2					Case 3				
		+20°	+10°	0°	-10°	-20°	+20°	+10°	0°	-10°	-20°	+20°	+10°	0°	-10°	-20°
5 mm	MPTA°	-0.3	-0.1	89.3	0	-0.1	-0.2	-0.1	87.3	-0.1	-0.2	-0.2	0	88.2	-0.1	-0.1
	LTS°	-0.1	-0.1	92.5	+0.1	+0.1	-0.1	-0.1	98.9	0	+0.1	-0.2	-0.1	95.4	0	+0.1
10 mm	MPTA°	-0.6	-0.2	94.0	0	-0.2	-0.5	-0.2	91.7	-0.1	-0.3	-0.4	-0.1	91.9	0	-0.3
	LTS°	-0.2	-0.1	92.5	+0.1	+0.2	-0.1	-0.1	98.9	0	+0.1	-0.3	-0.2	95.4	+0.1	+0.2
15 mm	MPTA°	-1.0	-0.3	98.7	0	-0.4	-0.9	-0.3	96.2	-0.2	-0.7	-0.7	-0.2	95.7	-0.2	-0.6
	LTS°	-0.1	0	92.5	+0.1	+0.2	0	0	98.9	0	-0.1	-0.4	-0.2	95.4	+0.1	+0.3
Osteotomy depth (mm)		56.0					61.4					69.4				

Table 3. Case by case outcome of 3D simulations in the sagittal plane. MPTA, medial proximal tibial angle; LTS, lateral tibial slope; mm, millimetre.

C. *Axial plane hinge rotations*

Outcomes of axial plane rotations are shown in table 4. For 5 and 10mm gap distractions, the MPTA decreased by 0.1° or remained unchanged per shift of 10° hinge axis rotation. The MPTA decreased by 0.1-0.4° per 10° shift when gap distraction was performed up to 15mm. In the sagittal plane, the LTS increased by 0.4-0.6° in 5mm gap distraction, by 1.0-1.3° in 10mm gap distraction and by 1.6-2.5° in 15mm gap distraction per 10° of hinge axis rotation. The largest increase in LTS was observed in the smallest tibial model (case 1). This determination was further investigated by measuring the anterior and posterior cortical distance from starting point to the respective hinge axis (table 5). When rotating the hinge axis in the axial plane towards anterolateral, the breached anterior cortex becomes larger than posterior. At 10° of hinge axis rotation, the anteroposterior cortical difference was 7-8mm. At 20°, the differences was 13-16mm while at 30°, the difference was 18-21mm.



Gap distraction	Outcome	Case 1				Case 2				Case 3			
		0°	+10°	+20°	+30°	0°	+10°	+20°	+30°	0°	+10°	+20°	+30°
5 mm	MPTA°	89.3	0	0	-0.1	87.3	0	0	-0.1	88.2	0	0	-0.1
	LTS°	92.5	+0.6	+1.1	+1.8	98.9	+0.5	+1.0	+1.6	95.4	+0.4	+0.8	+1.3
10 mm	MPTA°	94.0	0	-0.1	-0.1	91.7	0	-0.1	-0.3	91.9	0	-0.1	-0.2
	LTS°	92.5	+1.3	+2.7	+4.4	98.9	+1.2	+2.4	+3.8	95.4	+1.0	+2.0	+3.2
15 mm	MPTA°	98.7	0	0	-0.3	96.2	-0.2	-0.3	-0.7	95.7	-0.1	-0.3	-0.4
	LTS°	92.5	+2.2	+4.5	+7.0	98.9	+1.9	+4.0	+6.2	95.4	+1.6	+3.3	+5.2
Osteotomy depth (mm)		56.0				61.4				69.4			

Table 4. Case by case outcome of 3D simulations in the sagittal plane. Hinge axes rotation was performed in the anterolateral direction. MPTA, medial proximal tibial angle; LTS, lateral tibial slope; mm, millimetre.

Outcome	Case 1				Case 2				Case 3			
	0°	+10°	+20°	+30°	0°	+10°	+20°	+30°	0°	+10°	+20°	+30°
Anterior cortex (mm)	56.7	59.9	62.6	64.2	61.7	64.8	67.1	68.6	73.2	75.4	77.5	78.5
Posterior cortex (mm)	56.3	53.0	49.5	46.4	61.8	57.0	51.6	47.4	73.0	68.2	63.9	59.1
Difference (mm)	0.4	6.9	13.0	17.9	0.1	7.8	15.5	21.2	0.2	7.2	13.6	19.4

Table 5. Case by case outcome of the anterior and posterior cortical distance from osteotomy starting point to the hinge axis with stepwise rotating of the hinge axis in the axial plane. Mm, millimetre.

DISCUSSION

The most important findings of this study are that (1) the osteotomy depth is the main parameter for obtaining bony accuracy in the coronal plane (MPTA°) and (2) controlling the hinge axis position in the axial plane is crucial in maintaining the native tibial slope. Correct alignment of the hinge axis can be obtained by creating an equal osteotomy depth of the anterior and posterior tibial cortices. A difference of approximately 7mm (longer anterior cortex) results in 10° of anterolateral hinge axis rotation corresponding to a tibial slope increase of 1.0-1.4° when performing a common 10mm gap distraction.

Given a fixed gap distraction, the MPTA increase was largely depend on the depth of the osteotomy (distance from starting point to hinge axis) in coronal hinge axis translations. After the eight performed simulations, the maximum difference in osteotomy length was 10mm for all cases with MPTA differences up to 2° at 15mm gap distraction. This was true between the osteotomies starting at 40mm to 20mm x 10mm hinge axis (shortest) and starting at 40mm to 10mm x 5mm hinge axis (longest) in the smallest tibia (case 1). In general, outcomes of the coronal simulations are in line with the published converting tables by Hernigou et al. (2001) and Noyes et al. (2005) [5, 13]. Of note, the osteotomy plane thickness (i.e. sawblade thickness) was 1.35mm in our study which should be added to the total gap distraction in order to become the desired correction degree according to these tables. The tibial slope did not change during these simulations because the hinge axis was maintained perpendicular to the posterior condylar line.

Regarding hinge rotations in the sagittal plane, tilting away in either direction from 0° yielded in a minor change in MPTA (-0.2° at 10mm opening). The tibial slope was also mildly affected by hinge rotations in the sagittal plane given that clinically relevant slope changes only start at >2-5° [4, 7, 11]. Our results are in line with the study by Teng et al. (2021) which equally suggests no tibial slope alternations by hinge axis rotations in the sagittal plane [14].

Surprisingly, anterolateral hinge axis rotations in the axial plane revealed no relevant differences on the MPTA outcome. Only at 10 and 15mm wedge opening, the MPTA decreased by 0.1-0.4° per 10° hinge rotation. On the other hand, the posterior slope was strongly affected by the axial hinge axis position. A tibial slope increase of 1.0-1.4° per 10° hinge rotation at 10mm wedge opening was found. Slope changes were higher for the small tibia (case 1) and for increasing gap distractions. Gap distraction of 15mm in case 3 yielded 10° of MPTA correction and a gradual tibial slope increase of 1.6° per 10° of hinge rotation. This finding is similar to the conclusion by Teng et al. who performed a large simulation study on 93 knees [14]. As illustrated by our simulations, the axial rotation of the hinge axis is a consequence of unequal anteroposterior cortical breaching/ gap distraction during osteotomy [13]. The anteromedial tibial approach for MOWHTO, the posterior neurovascular bundle and incomplete transection of the superficial medial collateral ligament (MCL) might compromise thorough posterior cortical osteotomy during surgery. In this study, approximately 7mm difference between the anterior and posterior cortical osteotomy was corresponding to 10° of axial hinge rotation. To the authors knowledge, this difference was not previously investigated. Now, when a slope increase is intended, the 7mm stepwise difference might be a useful tool to obtain the desired tibial slope. However, the individualized anteroposterior width of the proximal tibia and the cortical curvature at the lateral tibial plateau might produces variation on this 7mm system. Although this study results support thorough osteotomy of the posterior cortex by chisel or saw, attention should be paid to maintain 7.5-10mm of lateral bone stock and to avoid violation of the proximal tibiofibular joint [6].

Furthermore, two general findings need to be derived from this study. First, larger corrections were associated with more profound differences in MPTA and LTS by hinge axis repositioning. Realistic gap distractions of 5, 10 and 15mm were tested and measured at the posteromedial tibial cortex. So when planning on large MOWHTO surgery, a higher risk for correction error in both planes should be anticipated. Secondly, the size of the proximal tibia determines the absolute depth of the osteotomy and so the risk for error. A small tibia (case 1) with a relatively shallow osteotomy bears higher risk for surgical error in both sagittal and coronal plane compared to a large tibia (case 3). This was reflected by higher standard deviations for the coronal plane simulations (table 2) in case 1 relative to case 3. The clinical relevance of these differences among proximal tibia size however are unclear.

Some limitations need to be addressed to this study. A mathematical model could not be delivered because of three included cases. However, this study aimed to illustrate relevant key steps for the orthopaedic surgeon to consider during MOWHTO. The outcome in the sagittal plane was limited to the lateral tibial slope. Since no rotational changes were simulated (proximal tibia with respect to distal tibia), medial and lateral tibial slope changes should always be similar as outlined in the study by Teng et al. [14].

Recently, several authors have investigated the use of 3D cutting guides to improve surgical accuracy in MOWHTO [3]. Superiority of these systems has not yet been clarified, although less outliers are generally observed [3]. However, with regards to correction accuracy, the use of a 3D cutting guide as such appears to be questionable despite its upcoming popularity. Our study shows that properly determining the osteotomy depth and controlling equal anteroposterior cortical osteotomy seems more relevant towards bony accuracy compared to the exact reproduction of a planned osteotomy plane through a guide. Moreover, within a certain planned 'accurate' osteotomy plane, axial hinge rotation and osteotomy depth can still pervert biplanar accuracy when distracting the osteotomy up to a given wedge opening.

CONCLUSION

The study showed that (1) the osteotomy depth is the main parameter for obtaining bony accuracy in the coronal plane (MPTA°) and (2) controlling the axial hinge axis position is crucial in maintaining the native tibial slope. Although challenging during MOWHTO surgery, correct axial alignment of the hinge axis can be obtained by creating an equal osteotomy depth of the anterior and posterior tibial cortices. A difference of approximately 7mm (longer anterior cortex) results in 10° of anterolateral hinge axis rotation corresponding to a tibial slope increase of 1.0-1.4° when performing 10mm gap distraction in MOWHTO.

CONFLICT OF INTERST

The authors declare to have no conflict of interest.

FUNDING

No funding was received for this study.

ACKNOWLEDGEMENT

None.

REERENCES

1. Akamatsu Y, Kobayashi H, Tsuji M, Nejima S, Kumagai K, Saito T (2018) Should sagittal osteotomy line be parallel to tibial posterior slope in high tibial osteotomy? BMC Musculoskeletal Disorders BMC Musculoskeletal Disorders 19(1):3–9

2. Van den Bempt M, Van Genechten W, Claes T, Claes S (2016) How accurately does high tibial osteotomy correct the mechanical axis of an arthritic varus knee? A systematic review. Knee Elsevier B.V. 23(6):925–935

3. Cerciello S, Ollivier M, Corona K, Kaocoglu B, Seil R (2022) CAS and PSI increase coronal alignment accuracy and reduce outliers when compared to traditional technique of medial open wedge high tibial osteotomy: a meta-analysis. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 30(2):555-566

4. Giffin JR, Vogrin TM, Zantop T, Woo SLY, Harner CD (2004) Effects of Increasing Tibial Slope on the Biomechanics of the Knee. Am J Sports Med 32(2):376–382

5. Hernigou P, Ma W (2001) Open wedge tibial osteotomy with acrylic bone cement as bone substitute. Knee 8(2):103–110

6. Jung GH, Lee KH, Wang L (2020) Three-dimensional analysis of lateral cortical hinge in medial open-wedge high tibial osteotomy: A computational simulation study of adult cadavers. Journal of Orthopaedic Surgery 28(3):1–7

7. Kim GB, Kim K Il, Song SJ, Lee SH (2019) Increased Posterior Tibial Slope After Medial Open-Wedge High Tibial Osteotomy May Result in Degenerative Changes in Anterior Cruciate Ligament. J Arthroplasty Elsevier Inc. 34(9):1922–1928

8. Kim JH, Kim HJ, Lee DH (2017) Survival of opening versus closing wedge high tibial osteotomy: A meta-Analysis. Sci Rep Springer US 7(1):1–7

9. Micicoi G, Khakha R, Kley K, Wilson A, Cerciello S, Ollivier M (2020) Managing intra-articular deformity in high Tibial osteotomy: a narrative review. J Exp Orthop Journal of Experimental Orthopaedics 7(1):1–10

10. Nguyen HC, Gielis WP, van Egmond N, Weinans H, Slump CH, Sakkers RJB, Custers RJH (2021) The need for a standardized whole leg radiograph guideline: The effects of knee flexion, leg rotation, and X-ray beam height. J Cartil Jt Preserv Elsevier B.V. 1(3):100022

11. Nha KW, Kim HJ, Ahn HS, Lee DH (2016) Change in Posterior Tibial Slope after Open-Wedge and Closed-Wedge High Tibial Osteotomy. Am J Sports Med 44(11):3006–3013

12. Nicolau X, Bonnomet F, Micicoi G, Eichler D, Ollivier M, Favreau H, Ehlinger M (2020) Accuracy of the correction obtained after tibial valgus osteotomy. Comparison of the use of the Hernigou table and the so-called classical method. Int Orthop International Orthopaedics 44(12):2613–2619

13. Noyes FR, Goebel SX, West J (2005) Opening wedge tibial osteotomy: The 3-triangle method to correct axial alignment and tibial slope. Am J Sports Med 33(3):378–387

14. Teng Y, Mizu-uchi H, Xia Y, Akasaki Y, Akiyama T, Kawahara S, Nakashima Y (2021) Axial But Not Sagittal Hinge Axis Affects Posterior Tibial Slope in Medial Open-Wedge High Tibial Osteotomy: A 3-Dimensional Surgical Simulation Study. Arthroscopy Arthroscopy Association of North America 37(7):2191–2201

Chapter 4 High tibial osteotomy and patient-specific instrumentation

4.1 A narrative review on existing patient-specific instrumentation (PSI) techniques

Published as book chapter 24 in ‘Advances in Knee Ligament and Knee Preservation Surgery’ (2022) DOI: 10.1007/978-3-030-84748-7_24

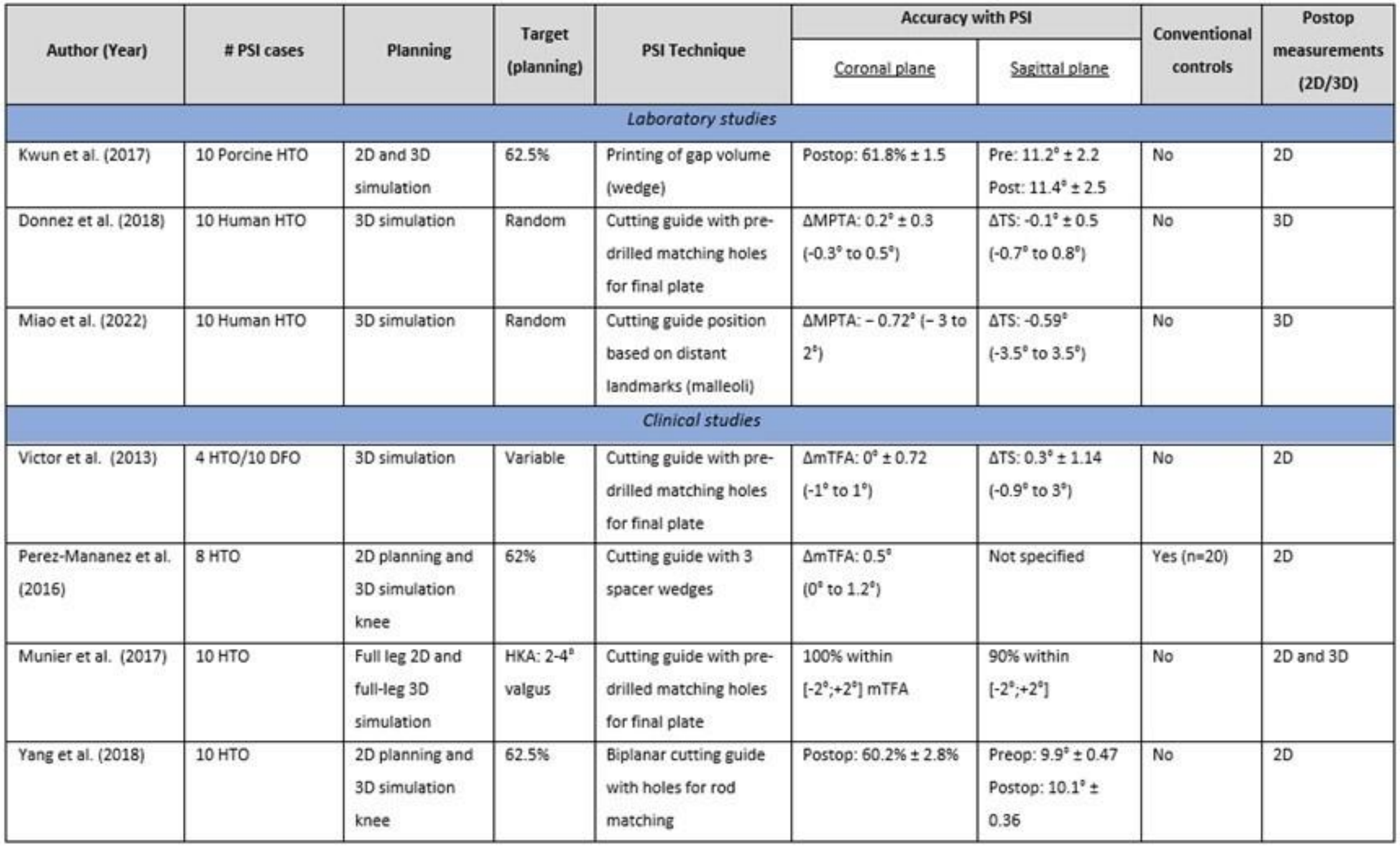
Since modern volumetric imaging modalities such as very low-dose computer tomography (CT) scans and magnetic resonance imaging (MRI) became available on large-scale, several attempts have been made to virtually simulate surgeries and print 3D anatomical models [21]. Shortly afterwards, the intraoperative use of 3D printed patient-specific instrumentation (PSI) was introduced, first in maxillofacial surgery which was later successfully translated to surgical corrections of the spine and mal-union fractures of the forearm [7, 33, 44]. The implementation of PSI in realignment surgery of the lower limb has started about ten years ago [53]. The thought of having customized surgical tools available during surgery, which instantly determine the intended correction size in both the coronal and sagittal plane, sounded very appealing. This led to the development of a handful innovative PSI approaches with promising accuracy outcomes, predominantly for MOWHTO [25, 29, 36, 41, 55]. This chapter provides an overview about the clinical use of PSI developed for MOWHTO with accuracy outcomes. Our personal experience in developing a novel PSI approach will be discussed with results, general considerations and concerns about the topic.

Measurement precision of preoperative malalignment and the possibility for osteotomy simulation has been optimized by 3D technology. The remaining difficulty can often be found in converting the planned correction into actual operating room (OR) performance, certainly without proper tools, experience and knowledge. The general rule of thumb ‘1° planned correction = 1 mm wedge opening’ has long been used as a gold standard but meanwhile refuted [39, 54]. This rule does not correct for depth of the osteotomy and thickness of the sawblade (± 1 mm) which generally leads to static and overall undercorrection [5, 39]. In 2005, Noyes et al. published on a mathematical method which consisted of three triangles that need to be monitored during osteotomy distraction [39]. Ideally, if a sole correction in the coronal plane was desired (as is in most HTO surgeries for degenerative reasons), the hinge axis must be perpendicular to the posterior tibial axis in the axial plane [26, 51]. However in practice, bone cuts during MOWHTO are difficult to perform strictly in the coronal plane given the anteromedial surgical approach to the tibia and its triangular shape. While opening an anteromedial osteotomy, the correction will be biplanar instead of uniplanar resulting in an undesired tibial slope increase [26, 51]. Overall, if planning on performing conventional MOWHTO, understanding Noyes' mathematical principle of anteroposterior gap measurement and his practical conversion table are key to obtain accurate outcomes while maintaining tibia slope [39]. The introduction of computer navigation in the early 2000s has certainly been a step towards improved control of the planned correction and realignment, due to real-time intraoperative visualization of the limb [5, 43]. However, expensive equipment, a long learning-curve with prolonged surgical duration and unpredicted technology failure has constrained this approach from becoming widespread among orthopaedic knee surgeons [5, 22]. The pendulum of intraoperative technology in knee osteotomy might nevertheless swing back, given the rising popularity of robot-assisted knee arthroplasty and its precision on alignment and soft tissue balancing [35].

Recently, Chernchujit et al. reported on a full-leg supine 3D model modulated under 'weight-bearing circumstances' and simulated the intended osteotomy without using PSI intraoperatively. Despite precise 3D planning, only 79% of cases (n=19) fell into a wide ± 3° range around target, which suggests an additional value of customized surgical tools on the OR table besides preoperative 3D simulations [10]. The relevance of PSI cutting guides was further highlighted in a controlled laboratory study for improving general osteotomy accuracy [48]. Customized slot guides (closed) were compared to open guides and free-hand sawing on a mid-shaft femur model. The closed guides had favorable outcomes in both precision of the osteotomy cut and translation of the preoperative 3D planning. The authors concluded that the use of PSI guides (open and closed) leads to more predictable outcomes in osteotomy surgery and bony resections, and can especially be recommended in multiplanar and rotational corrections [48]. In the context of osteotomies around the knee joint, PSI guides are suggested to be beneficial in two ways; first by defining the starting point, inclination and plane for the actual bone cut(s) and secondly by determining the planned gap opening at the anterior and posterior medial cortex. Victor et al. clinically tested the first PSI prototype for knee osteotomies (MOWHTO and distal femoral osteotomy (DFO)) which included a robust frame for fitting patient's bony landmarks to assure proper positioning (Table 1) [53]. This guide was equipped with a cutting slot and drill holes which would later match with the screw holes of the fixation plate as under optimal gap distraction. After 14 cases, an accuracy outcome of 0° ±0.72 ΔmTFA relative to the planning was found in the coronal plane with all cases falling within [-1°; +1°] around the target. Overall, minor changes were observed in the sagittal plane. Despite these highly accurate results, a large incision (13 cm femur and 12 cm tibia) and soft tissue dissection was required to properly fit the guide, inducing higher risk for wound infections and delayed or non-union of the gap [25]. Nevertheless, this technique was later adopted by several research groups developing their own PSI technique for MOWHTO [9, 12, 15, 36]. The largest case series with PSI was recently published by Chaouche et al., who included 100 MOWHTO cases [9]. In the coronal plane, an accuracy of 1.0° ±0.9 ΔmTFA and 0.5° ±0.6 ΔMPTA was established while the planned and postoperative tibial slope differed with 0.4° ±0.8. The authors concluded that by applying this PSI technique, predictable correction outcomes can be delivered, most importantly in the sagittal plane, without increasing (non-)specific HTO complications [9].

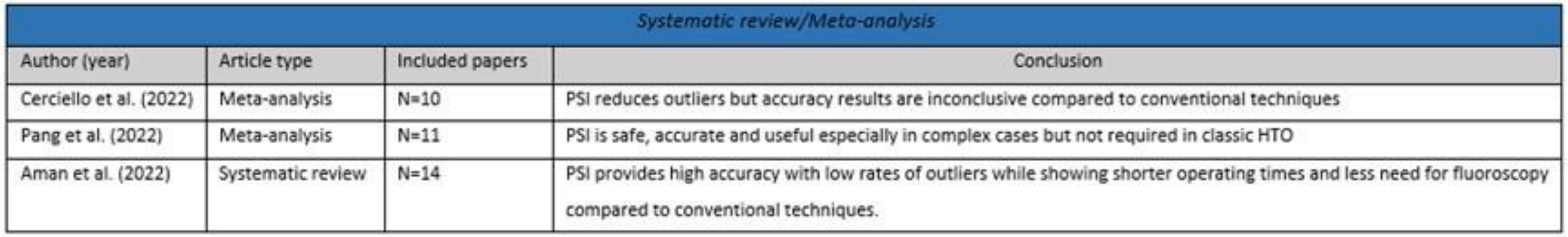
To avoid large skin incisions for robust PSI guides, Jones et al. developed an external device to align the osteotomy cutting guide based on distant superficial bony landmarks including the fibular head and malleoli [25]. His group suggested to use a customized ‘correction block’ fixed with three Kirschner-wires to determine and maintain the intended gap opening during surgery. Preliminary results with this technique ensure an accuracy within 3° around the target after 18 HTO cases [25]. In this way, an HTO can be performed minimally-invasive while maintaining freedom for the surgeon to choose the fixation device and plate positioning. However, the authors admit to a longer multi-step procedure which is in conflict with a principal advantage of PSI, namely reducing the time and complexity of the operation [23, 41].

Another way to obtain the planned limb realignment is simply to print the complementary wedge spacers needed to fill the osteotomy gap [29, 31, 41]. Perez-Mananez et al. described this approach by exchanging the spacers for structural bone autograft derived from the iliac crest in eight HTO cases [41]. In combination with a customized positioning guide, an average accuracy of 0.5° ΔmTFA (ranging 0° to 1.2°) was demonstrated. Twenty conventional control HTOs were performed and although showing lower accuracy (average 1.1° ΔmTFA (ranging 0° to 2.8°)), both groups were not significantly different. Interestingly, an additional 3D anatomical model of the proximal tibia was always available intraoperatively to confirm fitting of the cutting guide. Similarly, but without the inclusion of an osteotomy cutting guide and the implementation of bone autograft, Kim et al. demonstrated a lower absolute difference from the correction target of 62.5% in 20 PSI HTO cases (2.3% ±2.5 ΔWBL) compared to 20 conventional controls (6.2% ±5.1 ΔWBL) [29]. The tibial slope remained almost unchanged in the PSI cases while for the conventional approach, a statistically significant increase was observed. Yang et al. found an alternative way to obtain the desired wedge opening by designing a biplanar cutting guide consisting of a proximal and distal part, each equipped with an aligning hole [55]. While distracting the osteotomy, a metal rod was placed in the proximal hole and only fitted in the second distal hole of the guide when the planned osteotomy gap was obtained. A pilot study of 10 HTOs yielded a postoperative alignment of 60.2% ± 2.8 while aiming for 62.5% and a tibial slope that barely increased relative to the preoperative status. The same technique appeared to be superior in coronal accuracy relative to conventional HTO planning and surgery, although postoperative assessment was performed on full leg standing radiograph (FLSR) with low number of patients and absence on reporting tibial slope changes [34].



Author (Year)	# PSI cases	Planning	Target (planning)	PSI Technique	Accuracy with PSI		Conventional controls	Postop measurements (2D/3D)
					Coronal plane	Sagittal plane		
Laboratory studies								
Kwun et al. (2017)	10 Porcine HTO	2D and 3D simulation	62.5%	Printing of gap volume (wedge)	Postop: 61.8% ± 1.5	Pre: 11.2° ± 2.2 Post: 11.4° ± 2.5	No	2D
Donnez et al. (2018)	10 Human HTO	3D simulation	Random	Cutting guide with pre-drilled matching holes for final plate	ΔMPTA: 0.2° ± 0.3 (-0.3° to 0.5°)	ΔTS: -0.1° ± 0.5 (-0.7° to 0.8°)	No	3D
Miao et al. (2022)	10 Human HTO	3D simulation	Random	Cutting guide position based on distant landmarks (malleoli)	ΔMPTA: – 0.72° (– 3 to 2°)	ΔTS: -0.59° (-3.5° to 3.5°)	No	3D
Clinical studies								
Victor et al. (2013)	4 HTO/10 DFO	3D simulation	Variable	Cutting guide with pre-drilled matching holes for final plate	ΔmTFA: 0° ± 0.72 (-1° to 1°)	ΔTS: 0.3° ± 1.14 (-0.9° to 3°)	No	2D
Perez-Mananez et al. (2016)	8 HTO	2D planning and 3D simulation knee	62%	Cutting guide with 3 spacer wedges	ΔmTFA: 0.5° (0° to 1.2°)	Not specified	Yes (n=20)	2D
Munier et al. (2017)	10 HTO	Full leg 2D and full-leg 3D simulation	HKA: 2-4° valgus	Cutting guide with pre-drilled matching holes for final plate	100% within [-2°;+2°] mTFA	90% within [-2°;+2°]	No	2D and 3D
Yang et al. (2018)	10 HTO	2D planning and 3D simulation knee	62.5%	Biplanar cutting guide with holes for rod matching	Postop: 60.2% ± 2.8%	Preop: 9.9° ± 0.47 Postop: 10.1° ± 0.36	No	2D

Kim et al. (2018)	20 HTO	2D planning and 3D simulation knee	62.5%	Printing of gap volume (wedge),	ΔWBL: 3.9% ± 4.5	Preop: 9.6° ± 3.3 Postop: 9.8° ± 3.2	No	2D
Kim et al. (2018)	20 HTO	2D planning and 3D simulation knee	62.5%	Printing of gap volume (wedge), no slot for bone cut	ΔWBL: 2.3% ± 2.5	Preop: 8.6° ± 3.3 Postop: 8.9° ± 3.1	Yes (n=20)	2D
Jones et al. (2018)	18 HTO	3D simulation	Not specified	Cutting guide position based on distant landmarks and 'correction block'	100% within [-3°;+3°] mTFA	100% within [-3°;+3°] TS	No	3D
Chaouche et al. (2019)	100 HTO	Full leg 2D and full-leg 3D simulation	Not specified	Cutting guide with pre-drilled matching holes for final plate	ΔmTFA: 1.0° ± 0.9 ΔMPTA: 0.5° ± 0.6	ΔTS: 0.4° ± 0.8	No	3D
Fucentese et al. (2020)	23 HTO	Full leg 2D and full-leg 3D simulation	Majority on 62.5%	Cutting guide with pre-drilled matching holes for final plate	ΔmTFA: 0.8° ± 1.5 74% within [-2°;+2°] mTFA	ΔTS: 1.7° ± 2.2 61% within [-2°;+2°] TS	No	2D and 3D
Van Genechten et al. (2020)	10 HTO	3D simulation (full-leg)	Lateral spine	Customized wedge and cast for structural bone allograft	ΔmTFA: -0.4° ± 1.0 100% within [-2°;+2°] mTFA	ΔTS: 2.1° ± 2.6	No	2D and 3D
Mao et al. (2020)	18 HTO	2D planning and 3D simulation knee	62.5%	Biplanar cutting guide with holes for rod matching	ΔmTFA: 0.2° ± 0.6	Not specified	Yes (n=19)	2D
Predescu et al. (2021)	25 HTO	Full leg 2D and full-leg 3D simulation	Not specified	Cutting guide with pre-drilled matching holes for final plate	100% within [-2°;+2°] mTFA	100% within [-2°;+2°] TS	No	2D and 3D



Systematic review/Meta-analysis			
Author (year)	Article type	Included papers	Conclusion
Cerciello et al. (2022)	Meta-analysis	N=10	PSI reduces outliers but accuracy results are inconclusive compared to conventional techniques
Pang et al. (2022)	Meta-analysis	N=11	PSI is safe, accurate and useful especially in complex cases but not required in classic HTO
Aman et al. (2022)	Systematic review	N=14	PSI provides high accuracy with low rates of outliers while showing shorter operating times and less need for fluoroscopy compared to conventional techniques.

Table 1. Overview of laboratory and clinical studies and systematic reviews/meta-analysis about using patient-specific instrumentation (PSI) in HTO. (HTO, high tibial osteotomy; DFO, distal femur osteotomy; Δ, difference; MPTA, medial proximal tibial angle; mTFA, mechanical tibiofemoral angle; WBL, weight-bearing line; TS, tibial slope)

4.2 The Antwerp PSI technique

Published preceding PhD in the journal of knee surgery (2020) DOI 10.1055/s-0040-1710379

Our originally developed PSI technique consisted of a wedge and cast system designed to prepare structural bone allograft in MOWHTO. Based on the planned osteotomy opening (Figure 1), a structural bone allograft is prepared during surgery matching the exact size of the planned gap in 3D. By introducing the customized graft, the planned correction should instantly be determined and maintained after plate fixation. Ten patients were initially operated in a primary pilot study determining accuracy in the coronal and sagittal plane [17]. Accuracy results showed that 90% (9/10) was within an accuracy range of [-1.5°;+1.5°] mTFA around the target while all cases were within [-2°;+2°] (Table 2). In the sagittal plane, an absolute tibial slope increase of 2.7° ±1.8 was observed with an effective average slope increase of 2.1° (Table 2). In comparison to other PSI osteotomy studies (Table 1), this pilot study showed highly accurate and therefore similar results in the coronal plane while performing postoperative accuracy assessment on reliable 3D imaging. Consolidation was reached without occurrence of major adverse events. However in the sagittal plane, an unintended increase of the posterior slope was observed. We hypothesized that this might have been due to the limited width of the printed wedge and structural graft (10 mm) which allowed for tibial plateau tilting in the sagittal plane and poor control of the anteroposterior difference in opening wedge height. Therefore, a larger pilot study was designed to investigate a resized model of this PSI methodology on accuracy and early clinical outcomes. The decision for not including a cutting slot to guide the osteotomy was a conscious choice. Coronal accuracy was certainly acceptable in the first pilot study and before advancing the next study, a 3D osteotomy simulation project was conducted to assess different MOWHTO scenarios and the effect on coronal and sagittal realignment (Chapter 3). According to our data and supported by available literature, the osteotomy starting point (30-40 mm), inclination angle, hinge point height and sagittal sawblade tilt did not induce clinically relevant correction errors related to MPTA or tibial slope within a range of realistic free-hand osteotomy cuts and gap distractions [2, 26, 51]. On the other hand, osteotomy depth is crucial for the MPTA change [39] and hinge axis position in the axial plane is the most relevant factor to control in order to avoid tibial slope changes [26, 51]. Therefore, equally breaching the anterior and posterior cortices during osteotomy seems highly important for correct hinge axis alignment, independent from the chosen osteotomy plane. For these reasons, we decided to maintain the same PSI strategy with structural bone graft impaction and did not add a cutting slot to guide the osteotomy since doubtful added value was expected.

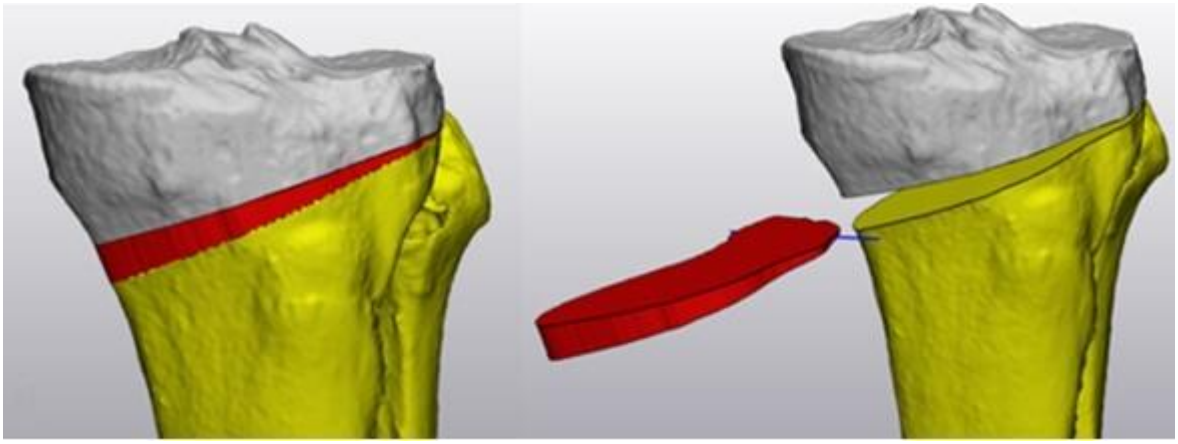


Figure 1. The negative of the planned osteotomy gap (red) is embodied and exported with the hinge axis (blue) to design the 3D printed customization kit for bone graft preparation.

Angle	Outcome	3D imaging (mean ± SD)	2D imaging (mean ± SD)
mTFA (°)	Relative Δ	-0.4 ± 1.0	-0.5 ± 1.3
	Absolute Δ	0.9 ± 0.6	1.2 ± 0.7
MPTA (°)	Relative Δ	-1.0 ± 1.4	0.3 ± 2.2
	Absolute Δ	1.3 ± 1.1	1.7 ± 1.3
TS (°)	Relative Δ	2.1 ± 2.6	0.0 ± 3.2
	Absolute Δ	2.7 ± 1.8	2.2 ± 2.2

Table 2. Accuracy outcomes of the first PSI pilot study for opening-wedge HTO. (Δ, difference; MPTA, mechanical medial proximal tibial angle; mTFA, mechanical femorotibial angle; WBL, weight-bearing line; TS, tibial slope; SD, standard deviation)

4.3 Impacted bone allograft personalized by a novel 3D printed customization kit produces high surgical accuracy in MOWHTO – a pilot study

Published in the journal of experimental orthopaedics (2023) DOI: 10.1186/s40634-023-00593-0

ABSTRACT

PURPOSE Contemporary medial opening wedge high tibial osteotomy (MOWHTO) still seems to struggle with inconsistent accuracy outcomes. Our objective was to assess surgical accuracy and short-term clinical outcomes when using 3D planning and a patient-specific instrumentation (PSI) kit to prepare customized bone allografts.

METHODS Thirty subjects (age 48y±13) were included in a double-center prospective case series. A low-dose CT-scan was performed to generate 3D bone models, a MOWHTO was simulated, and PSI was designed and 3D printed based on the complementary negative of the planned osteotomy gap. Clinical outcome was assessed at 2, 4 , 12 weeks and 1 year using NRS, KOOS, UCLA activity score, EQ-5D and anchor questions. A linear-mixed model approach was implemented for data analysis.

RESULTS Preoperative 3D values were 175.0°±2.2 mechanical tibiofemoral angle (mTFA), 85.0°±3.0 medial proximal tibial angle (MPTA), and 94.1°±3.4 medial posterior tibial slope (MPTS). Target planning ranged from slight varus to the lateral tibial spine (slight valgus). Postoperative 3D analysis showed an accuracy of 1.1°±0.7 ΔMPTA ($p=0.04$) and 1.2°±1.2 ΔMPTS ($p=0.11$). NRS decreased from baseline 6.1±1.9 to 2.7±1.9 at 4 weeks ($p<0.001$) and 1.7±1.9 at 1 year ($p<0.001$). KOOS increased from 31.4±17.6 to 50.6±20.6 at 12 weeks ($p<0.001$) and to 71.8±15.6 at 1 year ($p<0.001$).

CONCLUSION The study suggests that 3D printed instrumentation to personalize structural bone allograft is a viable alternative method in MOWHTO that has the benefit of optimizing surgical accuracy while providing early and consistent pain relief after surgery.

KEYWORDS: High tibial osteotomy – 3D planning – Patient-specific instrumentation – Accuracy – Joint preservation

INTRODUCTION

Medial opening wedge high tibial osteotomy (MOWHTO) is an established procedure to correct varus malalignment of the lower limb, primarily indicated for isolated osteoarthritis and focal cartilage lesions in medial compartment of the knee or ligamentous instability [5]. Over the past decades, there has been a general decline in MOWHTO performance in Europe and North America, even though excellent survival rates are reported with favorable clinical and radiological outcomes in the young and active patient [30].

Contemporary MOWHTO still seems to struggle with inconsistent accuracy outcomes [5]. A systematic review from 2016 uncovered a fairly low surgical accuracy relative to the proposed planning by conventional MOWHTO techniques; eight out of 14 cohorts (57%) reported an accuracy rate below 75% within a self-defined accuracy interval [5]. The majority of inaccurate cases appeared to be under-corrected [5]. Reasons for low accuracy outcomes may lie in unprecise 2D planning of the osteotomy, the challenging translation of the planned correction, postoperative soft tissue rebalancing and loss of correction due to unstable hinge fractures [20, 42, 49]. Measuring errors might not be surprising, given that the majority of MOWHTO planning is solely based on a single full-leg bipedal standing radiograph (FLSR) [37].

Besides under-correction in the coronal plane, an unintended tibial slope increase in the sagittal plane often cannot be avoided after conventional MOWHTO [13, 38]. Although the actual slope change might be of minor clinical relevance in the majority of patients, Kim et al. found degenerative changes of the ACL on second-look arthroscopy in a subgroup of patients with higher BMI and an excessive tibial slope increase [28]. Ultimately, obtaining the planned correction in MOWHTO is considered a highly important factor as long-term clinical results depend on the accuracy of the lower limb realignment [19]. Recently, a bone allograft impaction technique revealed promising results on early pain scores, weight-bearing and initial construct stability after MOWHTO, which justifies further research on this topic [4, 16]. The study aims to assess surgical accuracy and short-term clinical outcomes when using 3D planning and a patient-specific instrumentation (PSI) kit to prepare customized impacted bone allografts.

METHODS

A two center prospective case series was conducted involving the orthopedic departments of AZ Herentals and AZ Monica. From September 2020 to October 2021, patients for whom an MOWHTO was indicated, were screened for study inclusion according to the following criteria: symptomatic isolated medial knee osteoarthritis evidenced by radiographs (Kellgren-Lawrence grade 1-4), varus alignment on full-leg standing radiograph (mechanical tibiofemoral angle (mTFA) <178°) and age > 18 years. Concomitant procedures such as knee arthroscopy, anterior cruciate ligament (ACL)/anterolateral ligament (ALL) reconstruction and cartilage restoration were allowed per protocol. Exclusion criteria were extreme varus malalignment (mTFA < 165°), preoperative range of motion (ROM) <100°, significant collateral ligament laxity, bilateral simultaneous HTO, any systemic inflammatory condition (e.g. rheumatic disorders, Sjörgens disease…) and any of the following medical disorders or factor: active psychiatric or neurologic diseases, active alcohol or drug abuse, unwilling to stop smoking for 8 weeks.

Study was approved by the university and local ethical committees on 06/10/2020 (#B3002020000026). Written informed consent was obtained from all subjects preceding participation. The study was conducted in accordance with the Helsinki Declaration, the European Union Directive on Medical Devices (93/42 / EEC art.15), the guidelines related to clinical studies as outlined in EN ISO 14155 and in agreement with the rules of good clinical practice.

Preoperative imaging, 3D planning and customized kit

A preoperative standardized FLSR (2D) was part of the pre-study diagnostic work-up and so available in every patient. After study enrollment, subjects received a low-dose CT-scan of the whole index limb according to the Trumatch protocol by DepuySynthes®[11]. The applied preoperative planning and osteotomy simulation is described in Chapter 2 (‘Personal 3D planning methodology for MOWHTO’). An individualized target was desired based on the pre-existing tibial varus (MPTA), overall varus degree (mTFA) and alignment of the contralateral side, while keeping the planned MPTA <96°. Accordingly, the target angle was ranging from slight varus towards crossing the weight-bearing line (WBL) through the lateral tibial spine (slight valgus). During simulation, the osteotomy was gradually opened until the desired MPTA and tibial slope were obtained. Subsequently, the negative of the created osteotomy gap was embodied and together with the hinge axis exported for design of the customization bone graft preparation kit (Figure 2). Each kit consists of five parts: (a) a winged nut, (b) an adjustable upper fixation part, (c) a cutting block, (d) a backed platform and (e) a sliding cast of the required gap opening (Figure 2). Cutting blocks (c) were marked with patients' initials, side of surgery, correction size and anteroposterior graft orientation. Kits were all 3D printed (OCEANZ®, Ede, Netherlands) in medical-grade biocompatible polyamide 12 (ISO-13485) and sterilized in an autoclave with saturated steam at 134°C for 3.5 hours.

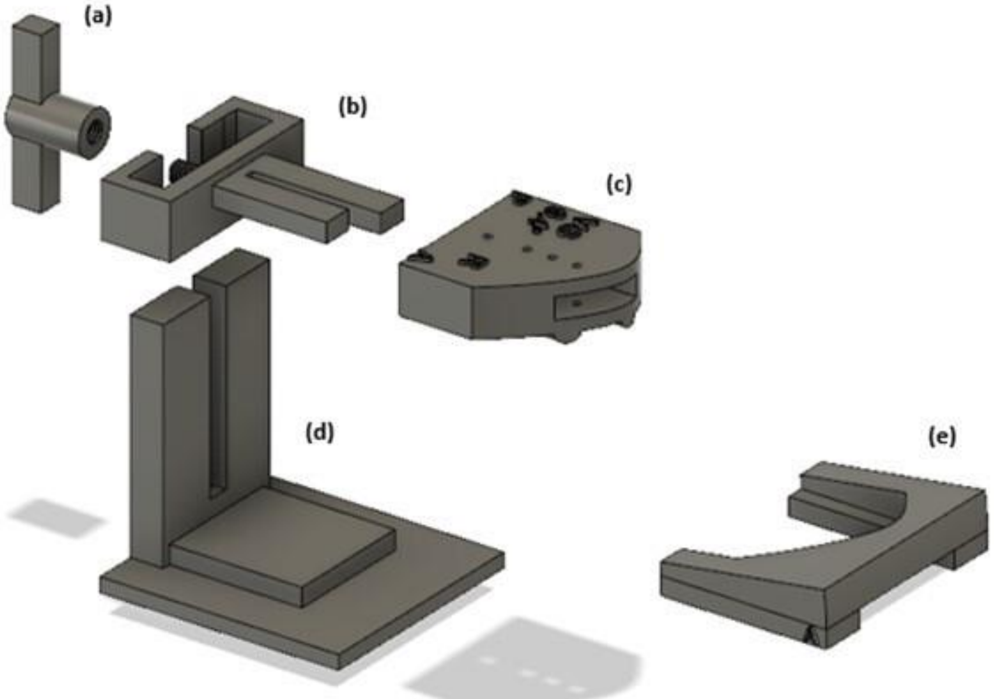


Figure 2. Design of the customized bone graft preparation kit: (a) a winged nut, (b) an adjustable upper fixation part, (c) a cutting block, (d) a backed platform and (e) a sliding cast of the required gap opening. Cutting block (c) is marked with patients' initials, side of surgery, correction size and anteroposterior graft orientation.

Surgical technique

Four senior knee surgeons contributed to the study. A conventional uniplanar (33%) or biplanar (66%) medial opening wedge HTO procedure was performed as previously described [16, 32]. As preplanned, the osteotomy was started at the vertical convex-concave transition of the medial proximal tibia, approximately 35mm below the tibial plateau and was directed towards the tip of the fibular head. . The superficial medial collateral ligament was first released while the pes anserinus remained untouched. The osteotomy was then performed and gradually opened by inserting multiple chisels (DepuySynthes®) or by use of a screwed spreader device (Arthrex®). While allowing the lateral cortical hinge to accommodate in this position, attention was directed to the customized bone graft preparation kit (Figure 3). A fresh-frozen femoral head from the tissue bank was used to manufacture the customized impacted bone graft. The allograft was fixed with two 1.8mm Kirschner pins through the cutting block. The anterior and posterior edges of the graft were first cut perpendicular to the platform followed by the medial cortical contour of the graft. Next all debris was discarded and the designated cast was shifted over the platform encasing the graft at the anterior, posterior and medial side. The upper surface of the cast was used as guiding plane to make the final horizontal cut at the proximal side of the graft in order to obtain the desired bone wedge dimensions. The customized bone graft was then introduced using a horseshoe-like instrument (Gaplocker®) or lamina spreader that maintained the osteotomy opening. Attention was paid for matching the medial contours of both tibial cortex and allograft which ultimately indicated proper press-fit graft orientation. Correct graft positioning was checked under fluoroscopy. A locking plate (depending on the surgeons preference) was finally applied to stabilize the osteotomy construct.

Postoperative weight-bearing was allowed as tolerated (but not mandatory) from the first day. All subjects had a physiotherapy session on the orthopaedic ward before discharge the day after surgery. Acetaminophen (PO, max 4 g/day) and tramadol 50 mg (PO, max 200 mg/day) were prescribed for ambulatory pain control. After 4 weeks, physiotherapy sessions were initiated if deemed required by the treating physician.

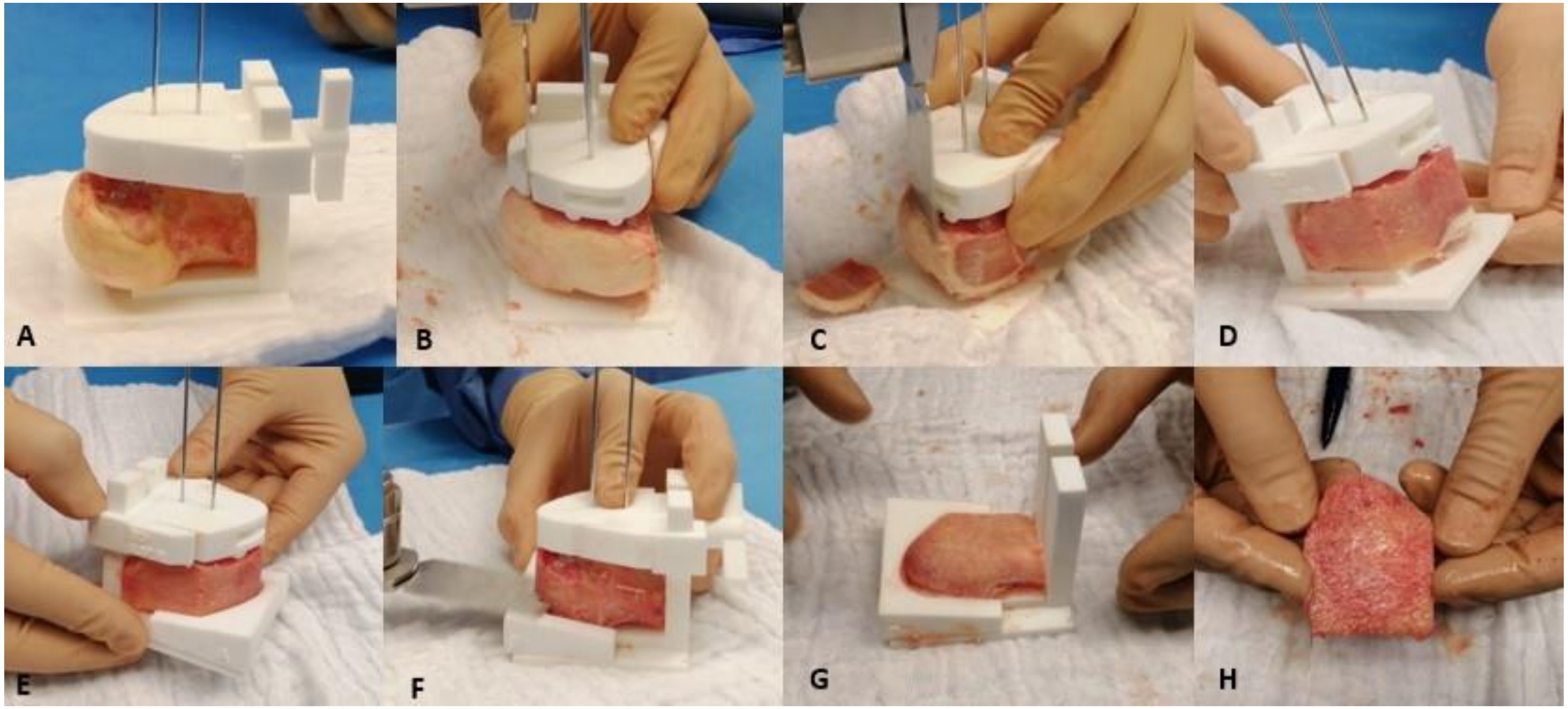


Figure 3. Intraoperative preparation of structural impacted bone allograft with the customized 3D printed kit. (A) The femoral head is placed on the platform and fixed with two 1.8mm Kirschner pins through the cutting block, without full engagement to the bottom. (B) The anterior and posterior borders of the graft are cut perpendicular to the platform. (C) The medial contour of the graft is trimmed, which identically matches the curvature of the medial cortex of the patient. Correct graft positioning can hereby later controlled. (D) The desired result after graft shape contouring with an oscillating saw. (E) Next, the designated cast is pushed to the graft, again matching the prepared medial curvature of the graft. (F) The upper surface of the cast is used as guiding plane to obtain (G) the desired bone wedge. (H) Finally, the intended structural bone allograft can safely be removed from the guide and is ready for introduction in the osteotomy gap.

Patient-reported outcome measures (PROMs)

Short-term clinical outcomes were assessed by the Numeric rating scale (NRS) for pain, the knee injury and osteoarthritis outcome score (KOOS), the UCLA activity score and the EQ-5D global assessment score at baseline and 2, 4, 12 weeks and 1 year after surgery. At 4 weeks, specific anchor questions were asked about the use of walking aids and the ability of car driving.

Postoperative imaging and accuracy

A CT-scan of the knee and ankle, with the same parameters as the preoperative CT-scan, was repeated at 3 months postoperative to assess biplanar accuracy, bone union and lateral hinge fractures [50]. Standard knee radiographs and a full-leg standing radiograph were also provided at 3 months and knee radiographs repeated at 1 year after surgery. Equal thresholds were applied during 3D bone segmentation (130-200 HU). To allow precise accuracy measurements, the proximal tibial plateau (above the osteotomy) was matched with the preoperative 'planned' model using the global registration-tool (Figure 4). Only the pilon point had to be redefined on the postoperative 3D model. All other preoperative planning landmarks, axes and planes were re-used to rule out measurement errors (Figure 5). The preferred accuracy method was the ΔMPTA (postoperative – planned MPTA) in the coronal plane and the medial posterior tibial slope (ΔMPTS; postoperative – planned MPTS) in the sagittal plane. Accuracy outcomes were expressed both as relative (x) and absolute values (|x|).

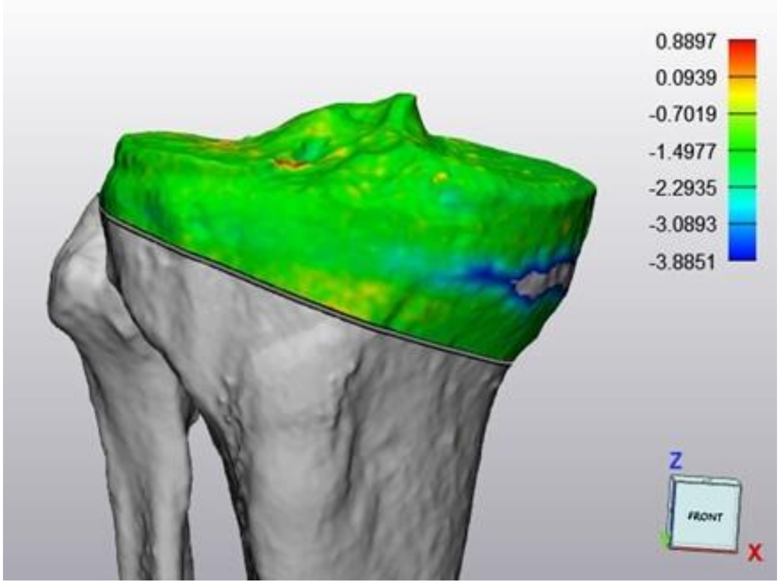


Figure 4. 3D matching of the pre- and postoperative proximal tibial plateaus, above the osteotomy level. Average distance error between bone models was 0.0716±0.0019 mm.

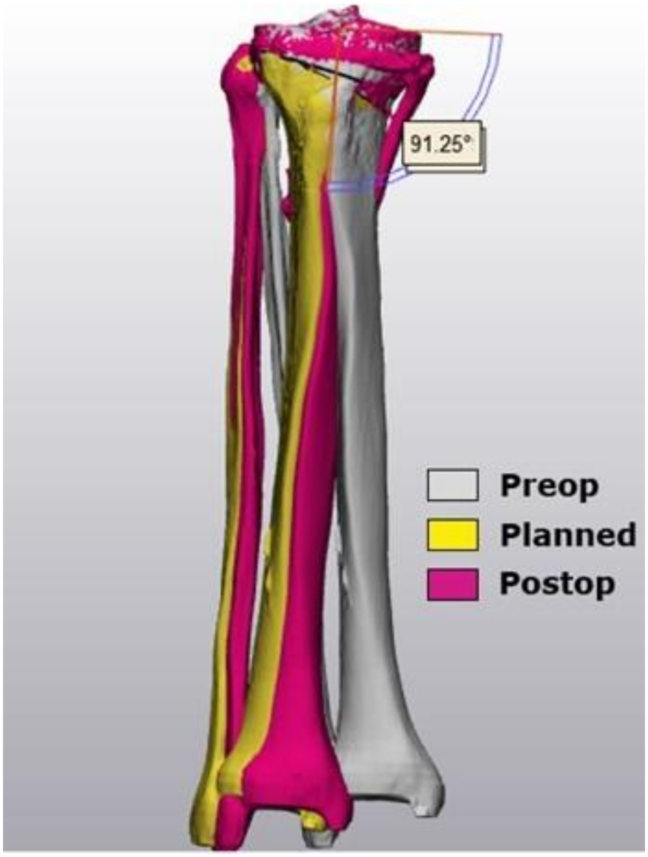


Figure 5. Postoperative 3D accuracy analysis by matching the pre-and postoperative proximal tibial plateaus.

Statistics

Descriptive statistical analysis were conducted to provide an overview of the patients' characteristics and radiological measurements in mean, standard deviation (SD), and minimum/maximum range []. First, normal distribution was assessed by Shapiro-Wilk test without exclusion of outliers. Outcomes for normal distribution guided further statistics into parametric or non-parametric tests. In case where data were normally distributed, paired student t-test were performed to compare planned with postoperative angles. Based on this analysis, surgical accuracy in both the coronal and the sagittal plane could be determined. When data was not normally distributed, the non-parametric Mann-Whitney test was used. For each clinical parameter of interest, a linear-mixed model repeated measures approach (LMM) was implemented. Alpha was set at 0.05 to define statistical significance. Statistical tests were conducted in Graphpad 8.0. (IBM Co., Armonk, NY, USA) and R Core Team (2013. Vienna, Austria: R Foundation for Statistical Computing).

RESULTS

Thirty (30) subjects (31 surgeries) were enrolled and received an MOWHTO with customized impacted bone allograft (Table 3). The indication for MOWHTO was isolated medial OA (90%), focal medal cartilage defect (3%) and ligamentous instability (6%). One subject had a consecutive bilateral HTO within a 3.5 month interval, with both knees included in the study. A single subject was excluded for analysis because of immediate correction loss due to plate mal-positioning (surgical error). Study demographics and preoperative angles of the remaining 30 analyzed HTO surgeries are outlined in table 1. Six subjects (20%) had a concomitant index knee procedure in the form of a knee arthroscopy (n=3, 10%), implantation of a metal resurfacing button on the medial femoral condyle for a focal cartilage lesion (n=1, 3%), an ACL reconstruction (n=1, 3%) or a mono-loop ALL reconstruction (n=1, 3%).

	Analysed group (n=30)		*mean±SD [range]*
Age, mean±SD [range]	48±13 [18-70]	*MPTA (°)*	3D| 85.0°±3.0 [76.6-88.9]
Male, n(%)	27 (90)		2D| 85.2°±2.5 [78.0-89.3]
Right, n(%)	16 (53)	*mTFA (°)*	3D| 175.0°±2.2 [169.3-177.9]
BMI, mean±SD [range]	27.9±5.1 [16.9-37.0]		2D| 174.2°±2.4 [167.5-177.2]
OA grade 1, n(%)	8 (27%)	*LDFA (°)*	3D| 87.6°±1.4 [84.8-90.7]
OA grade 2, n(%)	8 (27%)		2D| 88.2°±1.6 [85.1-92.7]
OA grade 3, n(%)	11 (36%)	*MPTS (°)*	3D| 94.1°±3.4 [87.9-102.3]
OA grade 4, n(%)	3 (10%)		2D| -

Table 3. Baseline patient characteristics. Severity of OA was scored according to the Kellgren- Lawrence classification. Preoperative angles were measured on full leg standing radiographs (2D) or in 3D software on non-weightbearing CT-scan (BMI, body mass index; OA, osteoarthritis; MPTA, medial proximal tibial angle mTFA, mechanical tibiofemoral angle; LDFA, lateral distal femoral angle; MPTS, medial posterior tibial slope)

Accuracy outcomes, complications and bone healing

The planned MPTA was 91.9°±2.6 [84.1-95.7] and mTFA was 181.9°±2.0 [178.3-184.8]. The average planned correction size was 6.9°±1.1 [4.8-9.4]. In the sagittal plane, no major corrections were desired, leaving the MPTS at 94.1°±3.0 [88.6-102.4] after planning. By matching the preoperative with the postoperative proximal tibia for accuracy analysis, the average distance error between bone models was 0.0716±0.0019 mm. 3D accuracy outcomes (table 4) in the coronal plane were -0.8°±1 [-3.0 to 1.9] relative ΔMPTA and 1.1°±0.7 [0.1-3.0°] absolute ΔMPTA (p=0.04). The absolute MPTS deviation was 1.2°±1.2 [0.1-5.1°] (n.s.). In 63%, the obtained correction (MPTA) was falling within 1° around the planned target, while 90% fell into the <2° range. All osteotomies fell within <3° around the target. In the sagittal plane, the MPTS did not alter more than 2° in 87%. Five (16%) lateral hinge fractures were observed on postoperative CT-scan (3 type I, 1 type II and 1 type III Takeuchi), while none were noticeable on conventional fluoroscopy. Fractures were undisplaced without the need for additional fixation. Beginning to advanced bone graft incorporation was observed 3 months after surgery on CT-scan while all osteotomies were consolidated at one year on plain radiographs. One minor postoperative bleeding the day after surgery was observed which was conservatively managed by compression therapy. One patient presented with a deep infection distally at the plate 2 months after surgery which was treated with open debridement and both local and IV antibiotics. Knee radiograph at 6 months showed progressive consolidation which was completed at 1 year. Another subject had a delayed union (no consolidation at 6 months) of unknown origin which was conservatively managed. CT-scan at 1 year revealed complete consolidation. Previous MOWHTO surgery on the contralateral side however showed a similar delayed healing pattern. Finally, five patients had their implant removed within the first year (7.8 months ±3.6) for local irritation.

Angle mean±SD [range]	Planned	Postoperative	P-value	Relative accuracy (x)	Absolute accuracy (|x|)
MPTA (°)	3D| 91.9°±2.6 [84.1-95.7]	3D| 91.1°±2.3 [85.1-95.9]	0.04	-0.8°±1.0 [-3.0 to 1.9]	1.1°±0.7 [0.1-3.0°]
	2D| -	2D| 91.5°±1.7 [86.6-95.13]	-	-	-
mTFA (°)	3D| 181.9°±2.0 [178.3-184.8]	3D| 181.1°±1.8 [176.1-183.2]	n.s.	-0.8°±1.0 [-3.0 to 1.9]	1.0°±0.8 [0.1-3.0°]
	2D| -	2D| 181.0°±1.8 [176.6-183.3]	-	-	-
MPTS (°)	3D| 94.1°±3.0 [88.6-102.4]	3D| 94.6°±3.6 [88.2-104.3]	n.s.	0.5°±1.6 [-3.2-5.1°]	1.2°±1.2 [0.1-5.1°]

Table 4. The planned, postoperative and accuracy outcomes in 3D and 2D. (MPTA, medial proximal tibial angle mTFA, mechanical tibiofemoral angle; MPTS, medial posterior tibial slope; n.s., not significant)

Clinical outcomes

The NRS pain score decreased from 6.1±1.9 at baseline to 4.5±2.1 at 2 weeks (p=0.010), to 2.7±1.9 at 4 weeks (p<0.001) and to 2.9±2.3 at 12 weeks (p<0.001) after surgery (Figure 5). After 4 weeks up to 1 year postoperatively (NRS 1.7±1.9), no significant decrease in NRS was observed. KOOS outcome was 31.4±17.6 preoperatively and increased to 50.6±20.6 at 12 weeks (p<0.001) and to 70.2±15.0 at 1 year (p<0.001) (Figure 5). Baseline UCLA activity score was 5.7±2.3, which increased to 6.1±1.9 at 12 weeks (n.s) and to 7.6±2.2 at 1 year (p=0.002) (Figure 6). The preoperative EQ-5D score was 71.8±15.6 and increased to 76.6±15.1 at 12 weeks (n.s.) and to 83.2±11.4 at 1 year after surgery (p=0.008) (Figure 5). Anchor questions at 4 weeks revealed that 60% was able to drive a car and 80% was able to walk with 1 crutch or without any.

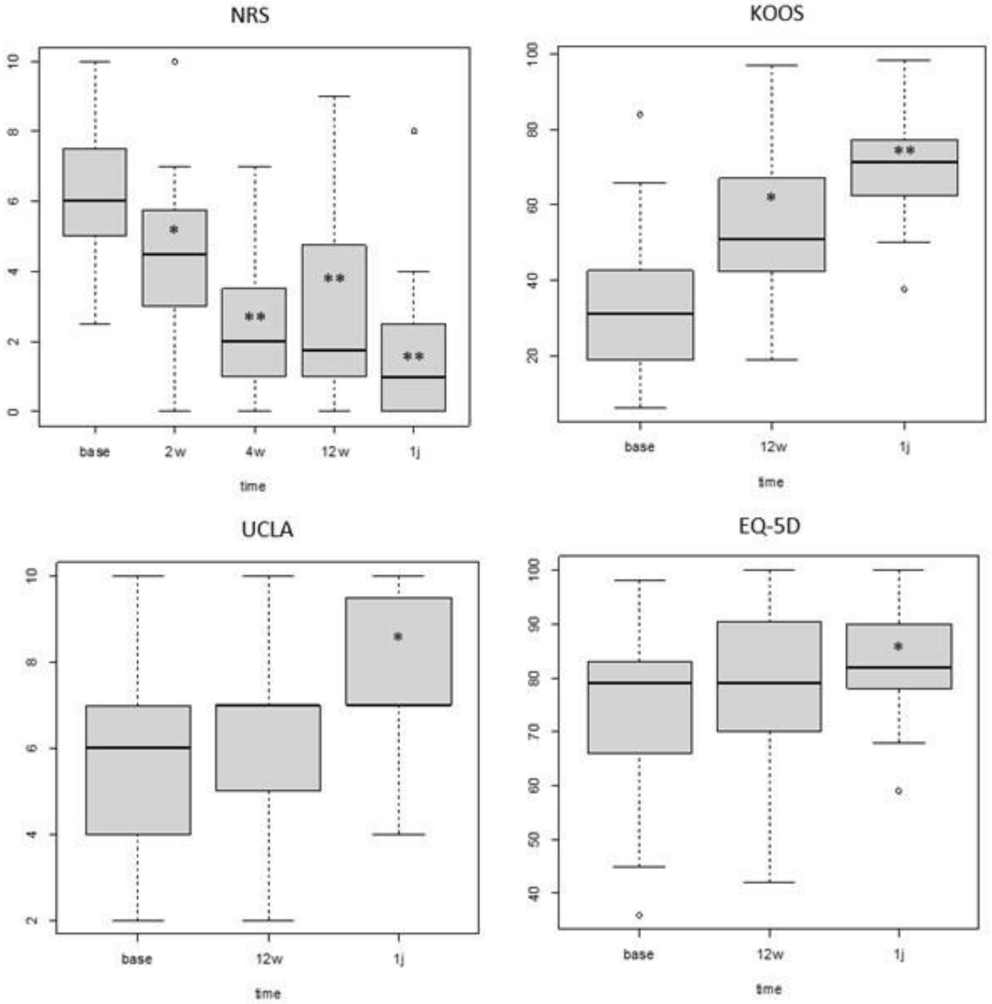


Figure 6. The Numeric Rating Scale (NRS), KOOS, UCLA and EQ-5D outcomes up to 1 year after surgery. (*significant difference compared to baseline; **significant difference compared to baseline and first postoperative timepoint)

DISCUSSION

The main study findings are that by using the 3D printed customization kit for bone allograft preparation in MOWHTO, accuracy outcomes are 1.1°±0.7 absolute ΔMPTA (p=0.04) with 63% of cases falling within [-1°;+1°] and 90% within [-2°;+2°] around the target. In the sagittal plane, a minor tibial slope increase of 1.2°±1.2 ΔMPTS was found relative to the planning (n.s.). Pain levels rapidly decreased in the first 4 weeks after surgery while 'weight-bearing as tolerated' was allowed from the first postoperative day.

The concept of customizing structural bone allograft to enhance surgical accuracy in MOWHTO originates from a pilot study published in 2020 [17]. The preoperative 3D planning remained unchanged in the current study, however modifications to guide design have facilitated graft preparation intraoperatively with special attention to maximize filling of the osteotomy gap (antero-posterior) and to assure correct posterior slope. The latter is reflected by the absolute accuracy outcomes in the sagittal plane being 1.2°±1.2 compared to 2.7°±1.8 in the initial PSI study [17]. One case of the current study had an unintended slope increase of 5.1°. It was hypothesized that this bone graft was correctly prepared but conversely introduced (antero-posterior flip) by the surgeon.

Since the first publication on the use of PSI for knee osteotomies [53], several surgeons have focused on the implementation of CT-based 3D planning and personalized guides in order to advance accuracy outcomes [8, 9, 15, 36, 41]. The systematic review by Van den Bempt et al., uncovered a critical problem concerning accuracy outcomes with conventional MOWHTO techniques, mainly featured by undercorrected cases [5]. Computer navigation has long been considered a potential solution for inaccurate osteotomy outcomes [43], nevertheless, due to time-consuming setup of equipment, additional cost and long learning curve, it never became the gold standard for MOWHTO. Moreover, in a level-1 randomized control trial (RCT), Schröter et al. found no difference in absolute accuracy between computer navigation and the gap measurement method [46]. Since no conventional control group was included in our study, the absolute accuracy outcome in our series (1.1°±0.7) appears to be at least numerically in favor compared to the navigation (2.1°±1.4) and gap measurement group (1.7°±1.2) as described in the RCT [46].

Regarding other PSI techniques, the 3D accuracy outcomes in both coronal and sagittal plane are comparable with the pilot study by Munier et al. [36]. They found 100% MPTA accuracy within 2° around the planning while showing 90% accuracy in the sagittal plane (MPTS) [36]. This PSI technique was later investigated on a large population and showed relative accuracy outcomes of 0.5°±0.6 ΔMPTA and 1.0°±0.9 ΔmTFA [9]. Although the ΔMPTA was significantly different in our series (p=0.04), it is unlikely to be clinically relevant. Moreover, our accuracy outcomes appear comparable with previous HTO PSI series [15, 17, 36].

The accuracy evaluation (ΔMPTA, ΔmTFA and ΔMPTS) was conducted in 3D by merging the preoperative and postoperative proximal tibia model with retainment of preoperative and planned bony landmarks and axes. The methodology for accuracy measurement can hereby be considered more precise and reliable compared to other studies describing ΔMPTA accuracy results in 2D [46] or 2D versus 3D [53]. Nevertheless, a CT-scan of the knee and ankle was required in order to apply this accuracy methodology.

In the study, pain levels rapidly decreased after surgery evidenced by a significant reduction of 1.6 points at 2 weeks (p=0.010) and 3.4 points at 4 weeks (p<0.001). The relative immobilization period and use of pain medication immediately after surgery can partially be held responsible for low pain levels, however at 4 weeks, 80% was able to walk with only one crunch or none while 60% felt comfortable driving a car. After 4 weeks (NRS 2.7±1.9), pain levels did not significantly decrease further up to 1 year (NRS 1.7±1.9). The observation of early pain relief within the first 4 weeks supports previous research regarding the use of structural bone graft impaction allowing 'weight-bearing as tolerated' from day 1 [6, 16, 45]. At 3 months, the general KOOS outcome increased by 19.2 points which is at least comparable to most prospective HTO series publishing on short-term clinical outcomes [6, 14, 16]. The activity level improved slowly and was significantly better at 1 year after surgery (UCLA 7.6±2.2) (p=0.002).

Although this planning method and kit preparation logistics looked seemingly time-consuming, a minimal time-interval of 14 days was required before surgery could proceed. For medical-grade 3D printing of the kit, study hospitals collaborated with an external company (OCEANZ®, Ede, Netherlands) which occupied the majority of the preoperative timeframe. Onsite availability of the required software, resin and 3D printing equipment could streamline this process within 48h, although knee osteotomy surgery seems never to be that urgent. In two cases, guide transport to the hospital was compromised due to Covid-19 border restrictions but none of the surgeries had to be postponed. Total cost for guide manufacturing and transport included 180 euro/case. The 3D kit was used in combination with three different locking plate systems based on surgeons' preference (Powerpeek (Arthrex®), Tomofix (Synthes®) and Königsee (Königsee Implantate®). This supports the accessibility of using this 3D kit in combination with multiple off-the-shelf locking plate systems contrasting other 'plate-inclusive' PSI techniques [9, 24] All benefits and drawbacks of this PSI technique are outlined in table 5. Complication rate was compliant with the reported adverse events after MOWHTO within the first year.[18, 47] Five stable lateral hinge fractures (17%), one postoperative hematoma (3%), one deep infection (3%) and one delayed union (3%) was observed. Only local implant irritation for which removal was performed appeared to be more frequent (17%) than generally reported (4.8%).[18]

Benefits
• Soft-tissue sparing PSI technique • OR time reduction • Instant obtainment of desired correction • Less fluoroscopic exposure • Compatible with several off-the-shelf plating systems • Freedom for plate positioning • Excellent bony accuracy • Convenient use of guide
Drawbacks
• Availability of bone allograft and additional cost • Cost for 3D print and software • Fixed target angle (not adjustable during surgery) • No guidance for the osteotomy

Table 5. Overview of the benefits and drawbacks of the described PSI technique in MOWHTO.

The authors acknowledge certain limitations to the study. A rather small sample size (n=30) was described with no conventional control group, which moderately tempers the impact of study outcomes. However, considering the first-time use of this 3D bone graft customization kit, low sample size can be defended under the heading of 'pilot study'. Compared to the authors' previous impaction graft study in which an accuracy outcome of 52% was reached within [-2°;+2°], the current study showed accuracy outcomes as high as 90% [16]. 3D and 2D measurements and analysis were performed by a single observer which could have made data prone to repetitive measuring errors. Nevertheless, Victor et al. showed high reproducibility of positioning knee landmarks in the same 3D software used for this study [52]. Moreover, accuracy outcomes were evaluated as the difference in planned and postoperative alignment by merging both proximal tibia 3D models and reusing bony landmarks and axes, which makes concerns about potential preoperative bony landmark mal-positioning insignificant. Response rate to clinical questionnaires was > 90%, except at 1 year (73%). Missing data were processed by the linear-mixed model repeated measures approach (LMM). Finally, six subjects (20%) had a concomitant index knee procedure which could only have prolonged rehabilitation.

CONCLUSION

The study suggests that 3D printed instrumentation to personalize structural bone allograft is a viable alternative method in MOWHTO that has the benefit of optimizing surgical accuracy (1.1°±0.7 absolute ΔMPTA) while providing early and consistent pain relief after surgery.

ETHICAL APPROVAL

Study was approved by the university and local ethical committees on 06/10/2020 (#B3002020000026). Written informed consent was obtained from all subjects preceding participation. The study was conducted in accordance with the Helsinki Declaration, the European Union Directive on Medical Devices (93/42 / EEC art.15), the guidelines related to clinical studies as outlined in EN ISO 14155 and in agreement with the rules of good clinical practice.

CONFLICT OF INTERST

The authors declare to have no conflict of interest.

FUNDING

The authors would like to thank the MoRe Foundation (Antwerp, Belgium) for funding the manufacturing and transport cost of all 3D printed customization kits.

ACKNOWLEDGEMENT

We would like to acknowledge the work of Kristien Vuylsteke and Lauranne Dierckxsens for helping in patient inclusion, informed consenting and in- hospital logistics of the 3D customization kits.

4.4 General considerations and concerns on PSI

Unpublished (informative)

Surgical experience should be taken into account when the accuracy and potential advantages of PSI and conventional HTO studies are investigated. Recently, Abdelhameed et al. stated that PSI has no clinical or accuracy benefits for knee osteotomy when performed by an experienced surgeon [1]. However, the question is how many dedicated knee surgeons can truly call themselves experienced in knee osteotomies? A meta-analysis of the currently available PSI studies concluded that PSI use is accurate however not required in classical (uniplanar) HTO surgery [40]. Cerciello et al. equally performed a systematic review and meta-analysis for computer assisted surgery (CAS) and PSI in HTO [8]. Significantly reduced outliers were observed for both techniques compared to conventional, however, accuracy outcomes did not appear statistically better. Overall, factors as radiation exposure, costs for equipment, time-intensive preoperative planning and experience of the surgeon need to be outbalanced with the relative benefits associated with surgical accuracy. We assume that the implementation of PSI might indeed be most beneficial for young or unexperienced orthopaedic surgeons performing standard knee osteotomies, since a short learning-curve can be expected with most PSI guides. However, for the experienced senior surgeon with already satisfying accuracy levels obtained with conventional HTO techniques, PSI might still be of high value in more complex surgeries such as large or rotational corrections, multiplanar deformities and double-level osteotomies.

In one PSI strategy, final plate type and positioning are already included in the 3D planning by determining the predrilled screw holes in the PSI guide [9, 15, 36, 53]. This facilitates immediate and correct implant positioning intraoperatively, but leaves small margin for unexpected alternations during surgery. A legitimate concern however, is the effect of PSI guide mal-positioning as this might potentially increase the risk of tibial plateau fractures, intra-articular screw positioning, inaccurate translation of the planning and poor clinical outcomes [27]. To assess the potential consequences, Jud et al. simulated mal-positioning of the guide (cutting slot with predrilled screw holes for matching plate fixation) by stepwise translation (5 mm) and rotation (2.5°) of the guide on the proximal tibia [27]. Although a proximal 5 mm translation of the guide resulted in surgical failure, the authors concluded that PSI mal-positioning was safe within the possible ‘degrees of freedom’ and had low impact on coronal accuracy. Tibial slope errors due to guide mal-positioning however were not assessed in this study.

Finally, practical burdens are certainly present for the surgeon when advancing in PSI application. The availability of 3D planning software, medical grade resin, a 3D printer and most importantly, trained personnel are mandatory factors for streamlining an in-hospital preoperative planning and printing process. If one of these requirements is missing onsite, external companies can be involved, however this may result in an increased cost per case, a longer manufacturing process and more complex logistics. Therefore, it can be recommended for certain hospitals/orthopaedic departments to invest in a 3D core facility, especially in case of high surgical turnovers and short waiting lists. The application of 3D planning and PSI is far from only reserved for knee osteotomies. PSI has proven its value in multiple disciplines and operations such as maxillofacial/craniofacial surgery, bone tumour resections, osteotomies for mal- or non-union fractures and corrections of forearm deformities [3]. So theoretically, a 3D core facility can supply several departments of interest, hereby sharing the costs of its own establishment and maintenance.

REFEERENCES

1. Abdelhameed MA, Yang CZ, AlMaeen BN, Jacquet C, Ollivier M (2022) No benefits of knee osteotomy patient’s specific instrumentation in experienced surgeon hands. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 31(8):3133-3140
2. Akamatsu Y, Kobayashi H, Tsuji M, Nejima S, Kumagai K, Saito T (2018) Should sagittal osteotomy line be parallel to tibial posterior slope in high tibial osteotomy ? BMC Musculoskeletal Disorders 19(1):3–9
3. Auricchio F (2016) Instructional Lecture : General Orthopaedics 3D printing : clinical applications in orthopaedics and traumatology. EFORT Open Reviews 1(May):121–127
4. Belsey J, Diffo Kaze A, Jobson S, Faulkner J, Maas S, Khakha R, Wilson AJ, Pape D (2019) Graft materials provide greater static strength to medial opening wedge high tibial osteotomy than when no graft is included. J Exp Orthop Journal of Experimental Orthopaedics 6(1):13
5. Van den Bempt M, Van Genechten W, Claes T, Claes S (2016) How accurately does high tibial osteotomy correct the mechanical axis of an arthritic varus knee? A systematic review. Knee Elsevier B.V. 23(6):925–935
6. Brinkman JM, Luites JWH, Wymenga AB, Van Heerwaarden RJ (2010) Early full weight bearing is safe in open-wedge high tibial osteotomy: RSA analysis of postoperative stability compared to delayed weight bearing. Acta Orthop 81(2):193–198
7. Byrne A-M, Impelmans B, Bertrand V, Van Haver A, Verstreken F (2017) Corrective Osteotomy for Malunited Diaphyseal Forearm Fractures Using Preoperative 3-Dimensional Planning and Patient-Specific Surgical Guides and Implants. The Journal of hand surgery 42(10):836.e1-836.e12
8. Cerciello S, Ollivier M, Corona K, Kaocoglu B, Seil R (2022) CAS and PSI increase coronal alignment accuracy and reduce outliers when compared to traditional technique of medial open wedge high tibial osteotomy: a meta-analysis. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 30(2):555-566
9. Chaouche S, Jacquet C, Fabre-Aubrespy M, Sharma A, Argenson JN, Parratte S, Ollivier M (2019) Patient-specific cutting guides for open-wedge high tibial osteotomy: safety and accuracy analysis of a hundred patients continuous cohort. Int Orthop International Orthopaedics 43(12):2757–2765
10. Chernchujit B, Tharakulphan S, Prasetia R, Chantarapanich N, Jirawison C, Sitthiseripratip K

(2019) Preoperative planning of medial opening wedge high tibial osteotomy using 3D computer-aided design weight-bearing simulated guidance: Technique and preliminary result. Journal of Orthopaedic Surgery 27(1):1–8

11. DePuy Orthopaedics Inc (2010) Radiation Exposure Considerations with the use of TruMatch Personalized solutions.
12. Donnez M, Ollivier M, Munier M, Berton P, Podgorski JP, Chabrand P, Parratte S (2018) Are three-dimensional patient-specific cutting guides for open wedge high tibial osteotomy accurate? An in vitro study. Journal of Orthopaedic Surgery and Research Journal of Orthopaedic Surgery and Research 13(1):1–8
13. Ducat A, Sariali E, Lebel B, Mertl P, Hernigou P, Flecher X, Zayni R, Bonnin M, Jalil R, Amzallag J, Rosset P, Servien E, Gaudot F, Judet T, Catonné Y (2012) Posterior tibial slope changes after opening- and closing-wedge high tibial osteotomy: A comparative prospective multicenter study. Orthop Traumatol Surg Res 98(1):68–74
14. Ekeland A, Nerhus TK, Dimmen S, Thornes E, Heir S (2017) Good functional results following high tibial opening-wedge osteotomy of knees with medial osteoarthritis: A prospective study with a mean of 8.3 years of follow-up. Knee Elsevier B.V. 24(2):380–389
15. Fucentese SF, Meier P, Jud L, Köchli GL, Aichmair A, Vlachopoulos L, Fürnstahl P (2020) Accuracy of 3D-planned patient specific instrumentation in high tibial open wedge valgisation osteotomy. J Exp Orthop Journal of Experimental Orthopaedics 7(1):1–7
16. Van Genechten W, Van den Bempt M, Van Tilborg W, Bartholomeeusen S, Van Den Bogaert G, Claes T, Claes S (2020) Structural allograft impaction enables fast rehabilitation in opening-wedge high tibial osteotomy: a consecutive case series with one year follow-up. Knee Surg Sports Traumatol Arthrosc 28(12):3747–3757
17. Van Genechten W, Van Tilborg W, Van Den Bempt M, Van Haver A, Verdonk P (2020) Feasibility and 3D Planning of a Novel Patient-Specific Instrumentation Technique in Medial Opening-Wedge High Tibial Osteotomy. J Knee Surg 34(14):1560–1569
18. Han SB, In Y, Oh KJ, Song KY, Yun ST, Jang KM (2019) Complications Associated With Medial Opening-Wedge High Tibial Osteotomy Using a Locking Plate: A Multicenter Study. J Arthroplasty Elsevier Inc. 34(3):439–445
19. Hankemeier S, Mommsen P, Krettek C, Jagodzinski M, Brand J, Meyer C, Meller R (2010) Accuracy of high tibial osteotomy: comparison between open- and closed-wedge technique. Knee Surg Sports Traumatol Arthrosc 18(10):1328–1333

20. Heijens E, Kornherr P, Meister C (2016) The coronal hypomochlion: A tipping point of clinical relevance when planning valgus producing high tibial osteotomies. Bone Joint J 98(5):628–633
21. Henckel J, Richards R, Lozhkin K, Harris S, Baena FMR y, Barrett ARW, Cobb JP (2006) Very low-dose computed tomography for planning and outcome measurement in knee replacement: THE IMPERIAL KNEE PROTOCOL. J Bone Joint Surg Br 88-B(11):1513–1518
22. Iorio R, Pagnottelli M, Vadalà a., Giannetti S, Di Sette P, Papandrea P, Conteduca F, Ferretti a. (2013) Open-wedge high tibial osteotomy: Comparison between manual and computer-assisted techniques. Knee Surg Sports Traumatol Arthrosc 21(1):113–119
23. Jacquet C, Sharma A, Fabre M, Ehlinger M, Argenson JN, Parratte S, Ollivier M (2020) Patient-specific high-tibial osteotomy's 'cutting-guides' decrease operating time and the number of fluoroscopic images taken after a Brief Learning Curve. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 28(9):2854–2862
24. Jeong SH, Samuel LT, Acuña AJ, Kamath AF (2022) Patient-specific high tibial osteotomy for varus malalignment: 3D-printed plating technique and review of the literature. European Journal of Orthopaedic Surgery and Traumatology Springer Paris 32(5):845–855
25. Jones GG, Jaere M, Clarke S, Cobb J (2018) 3D printing and high tibial osteotomy. EFORT Open Reviews 3(5):254–259
26. Jörgens M, Keppler AM, Degen N, Bachmeier AT, Bergstraesser M, Sass J, Prall WC, Böcker W, Fürmetz J (2022) Reliability of 3D planning and simulations of medial open wedge high tibial osteotomies. Journal of Orthopaedic Surgery 30(2):1–9
27. Jud L, Fürnstahl P, Vlachopoulos L, Götschi T, Leoty LC, Fucentese SF (2019) Malpositioning of patient-specific instruments within the possible degrees of freedom in high-tibial osteotomy has no considerable influence on mechanical leg axis correction. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 28(5):1356-1364
28. Kim GB, Kim K Il, Song SJ, Lee SH (2019) Increased Posterior Tibial Slope After Medial Open-Wedge High Tibial Osteotomy May Result in Degenerative Changes in Anterior Cruciate Ligament. J Arthroplasty Elsevier Inc. 34(9):1922–1928
29. Kim H-J, Park J, Shin J-Y, Park I-H, Park K-H, Kyung H-S (2018) More accurate correction can be obtained using a three-dimensional printed model in open-wedge high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 26(11):3452-3458
30. Kim JH, Kim HJ, Lee DH (2017) Survival of opening versus closing wedge high tibial

osteotomy: A meta-Analysis. Sci Rep Springer US 7(1):1–7

31. Kwun JD, Kim HJ, Park J, Park IH, Kyung HS (2017) Open wedge high tibial osteotomy using three-dimensional printed models: Experimental analysis using porcine bone. Knee Elsevier B.V. 24(1):16–22
32. Lobenhoffer P, Agneskirchner JD (2003) Improvements in surgical technique of valgus high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc 11(3):132–138
33. Lu S, Zhang YZ, Wang Z, Shi JH, Chen YB, Xu XM, Xu YQ (2012) Accuracy and efficacy of thoracic pedicle screws in scoliosis with patient-specific drill template. Medical & biological engineering & computing 50(7):751–8
34. Mao Y, Xiong Y, Li Q, Chen G, Fu W, Tang X, Yang L, Li J (2020) 3D-Printed Patient-Specific Instrumentation Technique Vs. Conventional Technique in Medial Open Wedge High Tibial Osteotomy: A Prospective Comparative Study. BioMed Research International 2020
35. Mart JPS, Goh EL (2021) The current state of robotics in total knee arthroplasty. EFORT Open Reviews 64(4):270–279
36. Munier M, Donnez M, Ollivier M, Flecher X, Chabrand P, Argenson JN, Parratte S (2017) Can three-dimensional patient-specific cutting guides be used to achieve optimal correction for high tibial osteotomy? Pilot study. Orthop Traumatol Surg Res Elsevier Masson SAS 103(2):245–250
37. Nguyen HC, Gielis WP, van Egmond N, Weinans H, Slump CH, Sakkers RJB, Custers RJH (2021) The need for a standardized whole leg radiograph guideline: The effects of knee flexion, leg rotation, and X-ray beam height. J Cartil Jt Preserv Elsevier B.V. 1(3):100022
38. Nha KW, Kim HJ, Ahn HS, Lee DH (2016) Change in Posterior Tibial Slope after Open-Wedge and Closed-Wedge High Tibial Osteotomy. Am J Sports Med 44(11):3006–3013
39. Noyes FR, Goebel SX, West J (2005) Opening wedge tibial osteotomy: The 3-triangle method to correct axial alignment and tibial slope. Am J Sports Med 33(3):378–387
40. Pang R, Jiang Z, Xu C, Shi W, Zhang X, Wan X, Bahat D, Li H, Senatov F, Bulygina I, Wang H, Zhang H, Li Z (2022) Is Patient-Specific Instrumentation Accurate and Necessary for Open-Wedge High Tibial Osteotomy? A Meta-Analysis. Orthopaedic Surgery (December 2021):1–10
41. Pérez-Mañanes R, Burró JA, Manaute JR, Rodriguez FC, Martín JV (2016) 3D Surgical Printing Cutting Guides for Open-Wedge High Tibial Osteotomy: Do It Yourself. J Knee Surg 29(8):690–695

42. van de Pol GJ, Verdonschot N, van Kampen A (2012) The value of the intra-operative clinical mechanical axis measurement in open-wedge valgus high tibial osteotomies. Knee 19(6):933–938
43. Saragaglia D, Roberts J (2005) Navigated osteotomies around the knee in 170 patients with osteoarthritis secondary to genu varum. Orthopedics 28(10 Suppl):s1269–s1274
44. Sarment DP, Al-Shammari K, Kazor CE (2003) Stereolithographic surgical templates for placement of dental implants in complex cases. The International journal of periodontics & restorative dentistry 23(3):287–95
45. Schröter S, Ateschrang A, Löwe W, Nakayama H, Stöckle U, Ihle C (2017) Early full weight-bearing versus 6-week partial weight-bearing after open wedge high tibial osteotomy leads to earlier improvement of the clinical results: a prospective, randomised evaluation. Knee Surg Sports Traumatol Arthrosc 25(1):325–332
46. Schröter S, Ihle C, Elson DW, Döbele S, Stöckle U, Ateschrang A (2016) Surgical accuracy in high tibial osteotomy: coronal equivalence of computer navigation and gap measurement. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 24(11):3410–3417
47. Seo S-S, Kim O-G, Seo J-H, Kim D-H, Kim Y-G, Lee I-S (2016) Complications and Short-Term Outcomes of Medial Opening Wedge High Tibial Osteotomy Using a Locking Plate for Medial Osteoarthritis of the Knee. Knee Surgery & Related Research 28(4):289–296
48. Sys G, Eykens H, Lenaerts G, Shumelinsky F, Robbrecht C, Poffyn B (2017) Accuracy assessment of surgical planning and three-dimensional-printed patient-specific guides for orthopaedic osteotomies. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine 231(6):499–508
49. Takagawa S, Kobayashi N, Yukizawa Y, Oishi T, Tsuji M, Inaba Y (2020) Preoperative soft tissue laxity around knee was associated with less accurate alignment correction after hybrid closed-wedge high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 28(9):3022–3030
50. Takeuchi R, Ishikawa H, Kumagai K, Yamaguchi Y, Chiba N, Akamatsu Y, Saito T (2012) Fractures around the lateral cortical hinge after a medial opening-wedge high tibial osteotomy: A new classification of lateral hinge fracture. Arthroscopy Elsevier Inc. 28(1):85–94
51. Teng Y, Mizu-uchi H, Xia Y, Akasaki Y, Akiyama T, Kawahara S, Nakashima Y (2021) Axial But Not Sagittal Hinge Axis Affects Posterior Tibial Slope in Medial Open-Wedge High Tibial

Osteotomy: A 3-Dimensional Surgical Simulation Study. Arthroscopy Arthroscopy Association of North America 37(7):2191–2201

52. Victor J, Van Doninck D, Labey L, Innocenti B, Parizel PM, Bellemans J (2009) How precise can bony landmarks be determined on a CT scan of the knee? Knee Elsevier B.V. 16(5):358–365
53. Victor J, Premanathan A (2013) Virtual 3D planning and patient specific surgical guides for osteotomies around the knee: a feasibility and proof-of-concept study. Bone Joint J 95 B(11 Suppl A):153–158
54. Yang CZ, Abdelhameed MA, AlMaeen BN, De Villeneuve FB, Fernandes LR, Jacquet C, Ollivier M (2022) In slope-changing osteotomy one millimeter is not one degree: results of an artificial intelligence-automated software analysis. Int Ortho 47(4):915-920
55. Yang JCS, Chen CF, Luo CA, Chang MC, Lee OK, Huang Y, Lin SC (2018) Clinical Experience Using a 3D-Printed Patient-Specific Instrument for Medial Opening Wedge High Tibial Osteotomy. BioMed Research International Hindawi (May):9246529

Chapter 5 High tibial osteotomy and rehabilitation

5.1 Structural allograft impaction enables fast rehabilitation in medial opening-wedge high tibial osteotomy – a consecutive case series with one year follow-up

Published in KSSTA (2020) DOI: 10.1007/s00167-019-05765-z

ABSTRACT

PURPOSE Painful and slow recovery are presumed disadvantages after opening-wedge high tibial osteotomy (HTO) and play a role in favouring arthroplasty as treatment for moderate isolated medial knee arthritis. The primary study objective was to investigate the effect of press-fit structural impacted bone allograft with locking plate fixation on early ambulation, postoperative pain levels and resumption of daily-life activities in opening-wedge HTO.

METHODS A prospective consecutive opening-wedge HTO case series was conducted, including 103 patients with final follow-up at one year. Weightbearing was allowed from the day after surgery "as tolerated" by the patient. Clinical assessment included the Numeric Rating Scale (NRS), Knee injury and Osteoarthritis Outcome Score (KOOS) and Lysholm score. Additionally, the Knee Society Score (KSS) was assessed during consultation at one, three and 12 months postoperatively with special attention for clinical anchor questions. Required sample size was calculated and a linear mixed-effect model was used for repeated measures over time of the clinical scores.

RESULTS The NRS decreased by 1.5 at one month ($p<0.01$) and 2.1 at three months ($p<0.01$) while KOOS pain significantly improved with 19.2 ($p<0.01$) by this time compared to baseline. Under reduced pain levels, 98% were able to walk > 500m without support while all patients were able to climb up and down the stairs three months postoperatively.

CONCLUSION The study strongly supports the initial hypothesis that applying structural triangular bone allograft in HTO leads to low postoperative pain levels, early ambulation and excellent short-term clinical outcomes. Study results have the potential to alter the general perception about HTO being a painful procedure with painstakingly slow recovery and consequently encourage the consideration of HTO as a highly valuable joint-preserving option while treating unicompartmental knee arthritis.

KEYWORDS: knee - high tibial osteotomy – osteoarthritis – rehabilitation - joint preservation – outcome – allograft

INTRODUCTION

High tibial osteotomy (HTO) is an established surgical procedure for active patients suffering from isolated medial compartment osteoarthritis (OA) of the knee associated with varus deformity of the lower limb. Following this procedure significant functional and clinical improvements have been reported together with excellent long-term survival rates of ≥90% after 10 years [6, 16]. High tibial osteotomy is a joint preserving procedure and has been shown to restore normal biomechanics in gait analysis and facilitates high rates of return to sport (90-100%) and return to work (81-96%) [8, 22]. In case of progressive osteoarthritis, HTO can be converted in total knee arthroplasty (TKA) without compromising outcomes and these procedures have been shown to demonstrate a lesser need for the use of revision TKA components compared to revision of UKA [20]. Despite these advantages, the amount of HTO procedures performed is low and largely outnumbered by UKA as indicated by comparing the United Kingdom Knee Osteotomy Registry (UKKOR) with the UK National Joint Registry (NJR) [39, 40] and a recent meta-analysis of both treatments [4].

Despite the fact that surgeons tend to opt more often for UKA instead of TKA nowadays, these numbers reflect a certain reluctance to perform HTO procedures and at least a part of this reluctance potentially originates from concerns associated with the early recovery after HTO e.g. pain, ambulation and complications [32]. Surely, osteotomies need time to achieve solid bony healing, generally considered to occur only after 12 weeks [3]. The burden of these restrictions probably is the most important factor determining attractiveness of HTO surgery in both patients' and surgeons' minds. The introduction of angular stable locking plates has improved early osteotomy stability theoretically enabling faster weightbearing without increased risk of associated complications, but despite these newer implants, the allowance of full weight-bearing is mostly deliberately postponed to up to 9 weeks [2, 3, 23, 33, 34]. Moreover, osteotomies are believed to be painful in the early postoperative stage and this argument is often used to prefer UKA over HTO for the overlapping indication of moderate isolated knee OA [4]. Strikingly, there is a lack of scientific data to confirm or explain these presumed post-operative pain levels, but in general it is believed that bleeding and leakage of bone marrow from the osteotomy site is one of the primary causes. Possibly industry driven research may also favour the popularity of joint replacement procedures instead of the less invasive joint preserving procedures. The presumed disadvantages of painful and slow recovery after HTO might explain a tendency to devaluate osteotomy surgery in favour of arthroplasty despite its proven benefits.

In an attempt to eliminate these two major drawbacks of HTO surgery, the present clinical study hypothesized that a specific surgical technique involving the impaction of a structural gap-filling bone allograft allows early ambulation with low pain levels after HTO.

METHODS

A single-centre, prospective consecutive case series study was conducted. All patients undergoing an opening-wedge HTO between April 15, 2016 to April 15, 2017 were screened for eligibility. Inclusion criteria were predominant medial knee pain with radiological evidence of isolated medial OA. A significant varus malalignment (≥ 2.0° mechanical tibiofemoral angle (mTFA)), failure of conservative therapy and significant pain relief under application of an unloading knee brace. Exclusion criteria consisted of extreme varus malalignment > 15° mTFA, preoperative range of motion (ROM) < 100°, significant collateral ligament laxity (≥10°), symptomatic lateral OA, rheumatoid arthritis, lateral closing-wedge HTO, double level (tibial + femoral) osteotomy, simultaneous bilateral HTO and osteotomy procedures with a postoperative correction target other than the lateral tibial spine (more lateral target for severe OA and more medial target for low OA severity and large varus deformity). No age restrictions were applied. Thirteen patients declined to participate in the study. At the expiry date of patient recruitment (April 15, 2017), 109 cases were enrolled in this prospective clinical trial of which six patients were lost to follow-up in the post-surgical year (Figure 1). Final quantitative data analysis was applied on 103 patients (Table 1). The study was approved by the academic and local ethical committee and included in the national register for clinical trials (B300201629156). The clinical study was conducted according to the Helsinki declaration of 1964 and its later amendments. Informed consent was obtained from each patient before study inclusion.

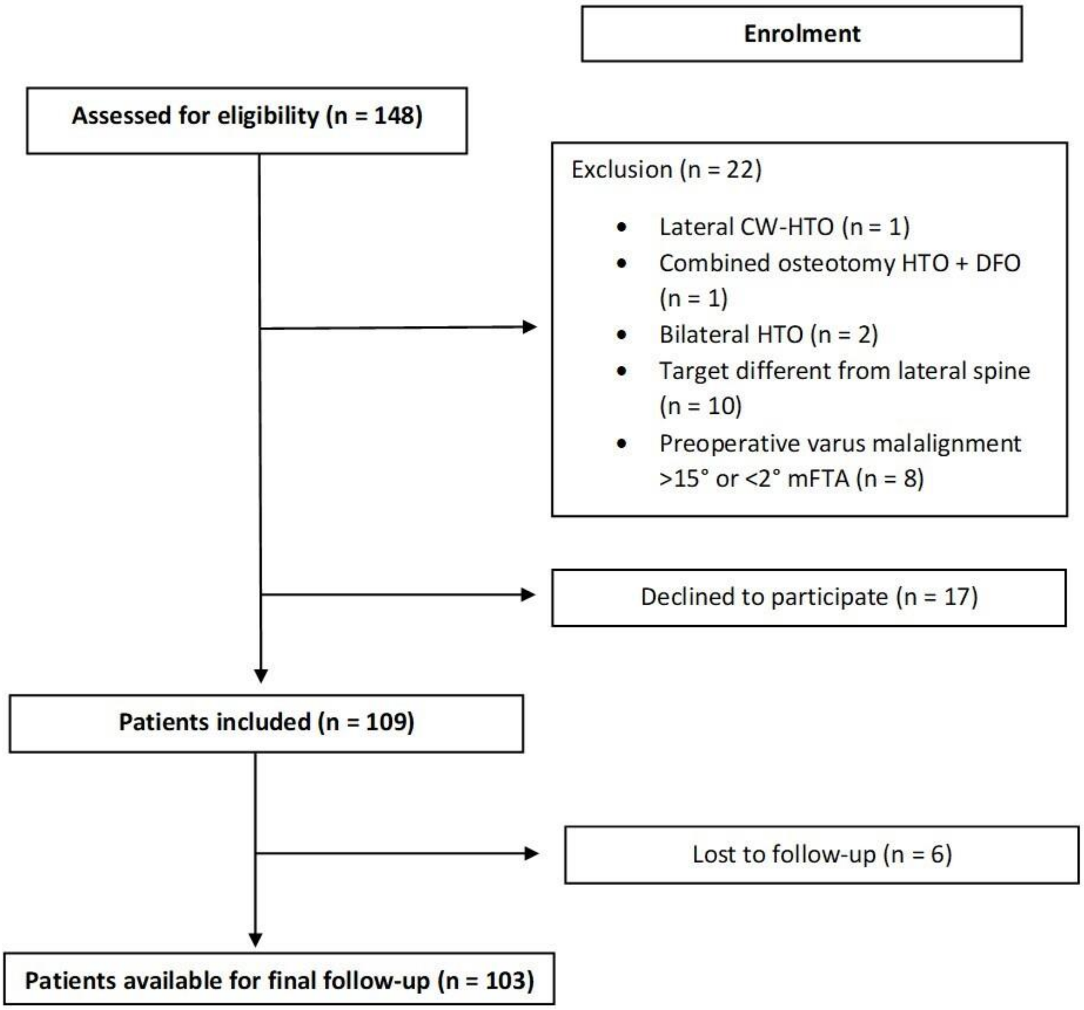


Figure 1. Flowchart of patient enrolment according to the standards of reporting trials statement with numbers of excluded and analysed patients (CW, closing-wedge; OW, opening-wedge; DFO, distal femoral osteotomy; HTO, high tibial osteotomy).

	Analysed group (n = 103)	**Lost to follow-up (n = 6)**
Age (years), mean (range)	54 (19 to 77)	48 (34 to 66)
Female, n (%)	34 (33)	2 (29)
Right, n (%)	47 (46)	2 (33)
Smoking, n (%)	8 (8)	1 (17)
BMI (kg/m2), mean (range)	28.4 (19.3 to 40.4)	29.0 (24.2 to 36.4)
WBL (%), mean (range)	22.9 (-9.0 to 38.0)	14.0 (3.0 to 37.0)
Alignment (mTFA°), mean (range)	-6.0 (-14.0 to -2.0)	-7.9 (-10.6 to -2.7)
MPTA (°), mean (range)	85.9 (79.5 to 90.7)	85.6 (81.7 to 87.9)
Severity OA, n (%)		
Grade 0	5 (5)	0 (0)
Grade 1	20 (19)	2 (33)
Grade 2	11 (11)	0 (0)
Grade 3	47 (46)	3 (50)
Grade 4	20 (19)	1 (17)

Table 1. Baseline patient characteristics. Severity of OA was scored according to the Kellgren- Lawrence classification (BMI, body mass index; OA, osteoarthritis; mTFA, mechanical tibiofemoral angle; WBL, weight-bearing line; MPTA, medial proximal tibial angle)

Clinical data

Data collection of included patients was performed by three investigators at fixed time intervals; preoperatively, one month, three months, six months and 12 months postoperatively. Before surgery, personal (age, sex, BMI and smoking habit), radiological (severity of OA, malalignment and tibial slope) and clinical data were collected for each patient to establish the baseline parameters. Patient-reported clinical outcomes consisted of the numeric rating scale (NRS) for pain, Knee injury and Osteoarthritis Outcome Score (KOOS) and the Lysholm score [35]. In addition, a physical examination was performed by the respective surgeon preoperatively, at one month, three months and 12 months postoperatively to assess the Knee Society Score (KSS) [14]. For clinical analysis, the KSS score was subdivided in KSS knee and KSS functional. Specific "anchor" questions about walking, climbing stairs, walking aids and housekeeping were posed at one and three months after surgery. The data collection process is summarized in table 2. Direct complications from surgery in which conservative or surgical management was indicated together with hardware removal were monitored until one year follow-up.

Outcome / **Time**	**Clinical (questionnaires)**				**Radiological (X-ray)**	
	NRS	KOOS	Lysholm	KSS	Knee	Full leg
Preoperative	✓	✓	✓	✓	✓	✓
1 month	✓			✓	✓	
3 month	✓	✓	✓	✓	✓	✓
6 month	✓	✓	✓			
12 month	✓	✓	✓	✓		

Table 2. The clinical and radiological data collection process (NRS, numeric rating scale; KOOS, knee injury and osteoarthritis outcome score; KSS, knee society score

Radiological data

Radiological assessment was performed on knee radiographs in three standardized views (anteroposterior (AP), lateral and Rosenberg view) and a full leg bipodal standing radiograph preoperatively and at three months after surgery. On indication, a computer tomography (CT) scan of the knee was taken when delayed union or instability of the osteotomy site were suspected. Bone graft union was evaluated at three months on AP views and the mTFA, weight-bearing line (WBL) and medial proximal tibial angle (MPTA) were measured on full leg X-rays twice by two independent observers. Accuracy of correction was defined as the difference in percentage between the WBL intersecting the tibial plateau (medial border 0%, lateral border 100%) and the position of the lateral spine, on which all osteotomies were planned. The preoperative severity of OA was scored by a single investigator according to the Kellgren-Lawrence classification. A second observer was consulted when in doubt. The results of the average intraclass correlation coefficient (ICC) for inter-rater reliability (two-way random (2,1) with single measurements) of mTFA were 0.93 [0.87-0.96] (average [95% CI]) preoperative and 0.91 [0.85-0.94] postoperative. Intra-rater reliability for mTFA was 0.96 [0.92-0.98] preoperative and 0.92 [0.87-0.95] postoperative. Intra-rater reliability for MPTA was 0.93 [0.90-0.96] preoperatively and 0.83 [0.74-0.88] postoperative.

Intra-rater reliability for lateral spine position was 0.79 [0.61-0.90] and for WBL% 0.98 [0.95-0.99] postoperative.

Planning & Surgical technique

Preoperative planning was performed on bilateral long leg standing radiographs. All HTO procedures were planned and executed in order to obtain a postoperative weight-bearing line (WBL) running through the lateral tibial spine. The method described by Miniaci et al. was used to calculate the desired angle of correction [25], which was intra-operatively converted to the required gap opening in mm by simple trigonometric calculations, as proposed by Hernigou et al. [12]. Preoperative intravenous tranexamic acid and cefazoline antibiotic prophylaxis were administered. Spinal anaesthesia was used in combination with a adductor canal block in all cases. A tourniquet on the proximal third of the thigh was inflated (250mmHg) during surgery. A biplanar medial opening-wedge high tibial osteotomy was performed as described by Lobenhoffer et al. [23]. The length and width of the osteotomy gap were measured and the 3 dimensions of the osteotomy gap (calculated height, measured length and width) were marked on a fresh frozen femoral head allograft (Figure 2.3). The structural bone allograft was then shaped to this dimensions using an oscillating saw, remainders of cartilage and soft tissue were removed, whereas the strong subchondral bone was preserved. A horseshoe-like instrument, designed to retain the osteotomy gap open (GapLocker©) was precisely secured with 4 K-wires (2mm). The laminar spreader was removed (Figure 3.1) which enabled the custom-made allograft to be firmly impacted without any loss of correction and leading to the complete filling of the osteotomy gap (Figure 3.2). The GapLocker© was removed, while the osteotomy remained stable due to the impacted allograft. Graft positioning was then checked on fluoroscopy. Finally an angular stable locking plate was introduced for fixation of the obtained correction and mainly for securing rotational stability of the osteotomy site. A compressive bandage was applied after wound closure. Acetaminophen (IV or PO, max 4g/d) and Diclofenac (IV or PO, max 150mg/d) were routinely administered postoperatively. Tramadol 50mg (PO, max 150mg/d) or Piritramide (IM, 10mg/d) were used additionally in the event of unsatisfactory pain control.

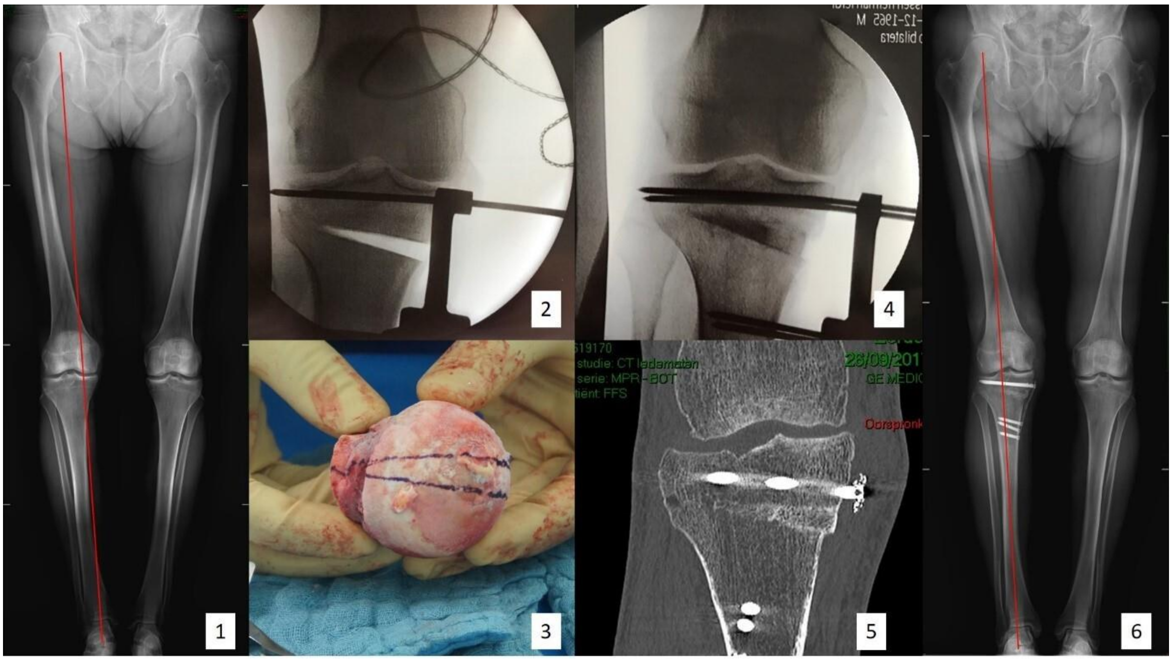


Figure 2. 1) Full leg standing x-ray with the weight bearing line (WBL) crossing the medial compartment compatible with varus alignment 2) Peroperative fluoroscopy image showing the opening wedge osteotomy 3) Typical fresh frozen femoral head allograft with patient-specific osteotomy wedge dimensions delineated with ink marker 4) Peroperative fluoroscopy image of the same patient after impaction of the custom-cut triangular bone allograft into the osteotomy gap 5) Post-operative CT-scan showing complete osseo-integration of the structural bone graft in the osteotomy gap 3 months after surgery 6) Post-operative full leg standing x-ray with the WBL crossing the lateral tibial spine indicating adequate realignment of the mechanical axis of the leg after HTO surgery.

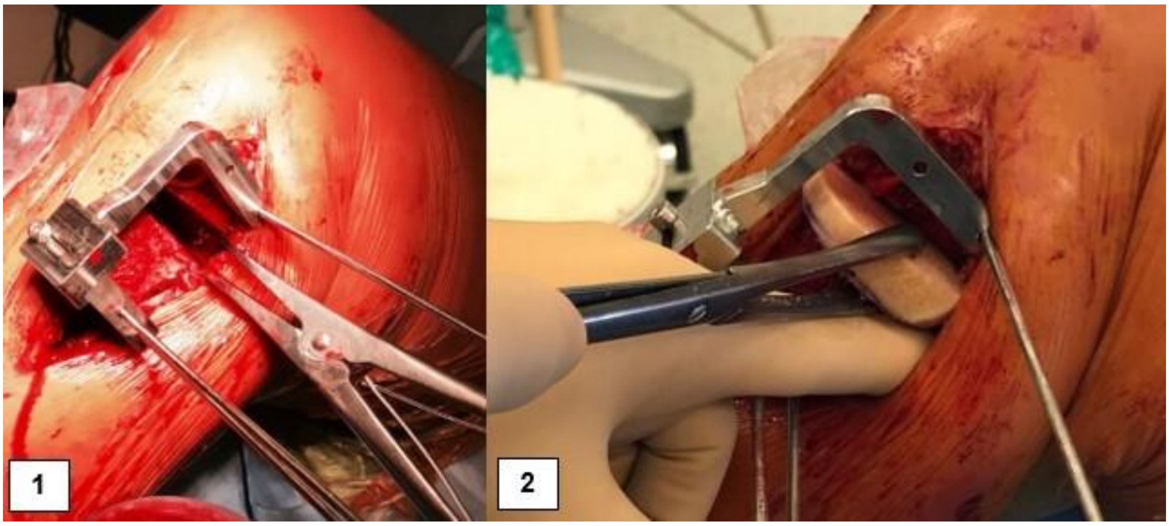


Figure 3. 1) A horseshoe-like instrument (GapLocker©) is secured with 4 wires (2mm) and designed to retain the osteotomy gap open 2) Introduction of the wedge-shaped structural allograft in the osteotomy gap.

Rehabilitation

All patients received a standardized postoperative rehabilitation protocol including instructions on weight bearing. Specifically, weight-bearing was allowed “as tolerated” by the patient (but not obligatory) from the day after surgery, and all patients had a physiotherapy session on the orthopaedic ward before discharge in order to get specific instructions on ambulation and home exercises. After four weeks, exercise therapy sessions were initiated under direct supervision of a physiotherapist. Routinely Acetaminophen (PO, max 4g/d) and Tramadol 50mg (PO, max 200mg/d) were prescribed for ambulatory pain control.

Statistical analysis

The primary endpoint of the study was the KOOS score. A minimal clinically important change of 8-10 is often taken for KOOS sample size calculations [29]. In a former study assessing the accuracy and reliability of the KOOS questionnaire for osteotomy patients specifically, a moderate effect size was found between 0.5-0.791 [11]. An One-Way repeated measures ANOVA was performed for the sample calculation. A calculated sample size of 71 patients was required to provide us with a statistical power of 0.95 and a type 1 error of 0.05. By correcting for a potential loss to follow up of 10%, we aimed to include 80 patients minimally. Sample size calculation was performed with G*Power (Version 3.1.9.2, Düsseldorf, Germany). A linear mixed-effect model was used for repeated measures over time of the clinical scores. The clinical scores (NRS, KOOS (total and all 5 subscales) and Lysholm) were treated as dependent variables, time as the independent variable and a random-effect term was included to account for the correlated measurements for each patient. This model used a direct-likelihood approach to accommodate missing data that was valid under the “missing at random” assumption [24] and prevented list-wise deletion. Statistics were computed with R (A language and environment for statistical computing; R Development Core Team, R Foundation for Statistical Computing; Vienna, Austria, https://www.r-project.org/). Alpha was set at .05 for all tests.

RESULTS

Clinical outcome

The mean and 95%-confidence interval (CI) of the clinical outcome scores at each time point (T_x), are presented together with the respective differences over time (T_x-T_y) in table 3 (with correction for missing data). Details of the clinical baseline parameters of the lost to follow-up group are listed in table 4. All analysed patients completed the preoperative evaluation and had at least two postoperative evaluations. Concerning patient's pain levels early after HTO, the NRS and KOOS pain subscale significantly improved with respective means of 2.1 ($p<0.01$) and 19.2 ($p<0.01$) at three months compared to baseline (Figure 4). At one month postoperatively, pain relief was already established through a decrease in NRS of 1.5 ($p<0.01$). In general, a gradual improvement over the entire follow-up period was observed in all clinical (sub)scores, except for the KSS functional score. Short-term clinical outcome showed a rise of ≥15 points from baseline to three months ($p<0.01$) in the subscales KOOS sports, activities in daily life (ADL) and quality of life (QoL). The time-dependent evolution of the KOOS including the five subscales is presented in figure 5. The Lysholm score was the only reported outcome which significantly ($p<0.01$) improved between three months and six months.

The mean KSS knee increased from preoperative to one month follow-up with 24.6 ($p<0.01$) and a further raise was observed until final follow-up. The KSS functional however declined by 28.1 (<0.01) at one month postoperatively but increased from this moment on by 41.0 (<0.01) at three months, which was significantly higher than the baseline score.

Outcome	Follow-up time					Statistical significance of differences (p-values)									
	Baseline (T0) Mean (CI)	1 month (T1) Mean (CI)	3 months (T2) Mean (CI)	6 months (T3) Mean (CI)	12 months (T4) Mean (CI)	T0-T1	T0-T2	T0-T3	T0-T4	T1-T2	T1-T3	T1-T4	T2-T3	T2-T4	T3-T4
NRS	5.3 (4.9 to 5.7)	3.8 (3.3 to 4.3)	3.2 (2.8 to 3.6)	2.7 (2.2 to 3.2)	2.7 (2.2 to 3.2)	<0.01	<0.01	<0.01	<0.01	NS	<0.01	<0.01	NS	NS	NS
KOOS	44.4 (41.6 to 47.2)	/	60 (56.6 to 63.4)	63.6 (59.3 to 67.9)	66.4 (62.6 to 70.2)	/	<0.01	<0.01	<0.01	/	/	/	NS	<0.01	NS
KOOS pain	51.1 (48.1 to 54.1)	/	70.3 (67 to 73.6)	73 (68.9 to 77.1)	74.7 (70.8 to 78.6)	/	<0.01	<0.01	<0.01	/	/	/	NS	NS	NS
KOOS symptoms	59.4 (55.9 to 62.9)	/	69.3 (65.8 to 72.8)	72.4 (68.3 to 76.5)	72.6 (69 to 76.2)	/	<0.01	<0.01	<0.01	/	/	/	NS	NS	NS
KOOS ADL	57.4 (54 to 60.8)	/	72.5 (69.1 to 75.9)	75.2 (71 to 79.4)	78.8 (75 to 82.6)	/	<0.01	<0.01	<0.01	/	/	/	NS	<0.01	NS
KOOS sports/rec	23.3 (19.1 to 27.5)	/	42 (36.6 to 47.4)	46.6 (40.3 to 52.9)	51.3 (45.9 to 56.7)	/	<0.01	<0.01	<0.01	/	/	/	NS	<0.01	NS
KOOS QoL	30.2 (27.2 to 33.2)	/	45.2 (41 to 49.4)	50 (45 to 55)	54.3 (49.8 to 58.8)	/	<0.01	<0.01	<0.01	/	/	/	NS	<0.01	NS
Lysholm	49.6 (45.9 to 53.3)	/	61.1 (56.6 to 65.6)	69 (63.9 to 74.1)	70.3 (65.9 to 74.7)	/	<0.01	<0.01	<0.01	/	/	/	<0.01	<0.01	NS
KSS knee	56.2 (52.7 to 59.7)	80.8 (76.8 to 84.8)	88.4 (85.9 to 90.9)	/	89.5 (86 to 93)	<0.01	<0.01	/	<0.01	<0.01	/	<0.01	/	NS	/
KSS functional	73.7 (70.5 to 76.9)	45.6 (39.6 to 51.6)	86.6 (83.6 to 89.6)	/	95.3 (92.1 to 98.5)	<0.01	<0.01	/	<0.01	<0.01	/	<0.01	/	0.02	/

Table 3. Clinical outcome scores, mean (95% CI), of the analysed group (n=103) at each time point (Tx) after surgery and the respective differences over time (Tx-Ty). (CI, confidence interval; NRS, numeric rating scale; KOOS, knee injury and osteoarthritis outcome score; ADL, activities of daily living; QoL, quality of life; KSS, knee society score; NS, not significant

Case nr.	NRS	Tegner	KOOS	KOOS pain	KOOS symptoms	KOOS ADL	KOOS sports	KOOS QoL	Lysholm
1	5	5	51.6	52.8	92.9	48.5	20.0	43.8	73.0
2	3	8	55.0	44.4	71.4	45.6	45.0	68.8	54.0
3	2	5	59.2	69.4	71.4	75.0	30.0	50.0	59.0
4	1	5	66.0	86.1	60.7	52.9	80.0	50.0	82.0
5	6	2	35.0	58.3	28.6	52.9	10.0	25.0	48.0
6	6	6	39.3	63.9	39.3	48.5	20.0	25.0	58.0
Mean	3.8	5.2	51.0	62.5	60.7	53.9	34.2	43.8	62.3
Range	1 to 6	2 to 8	35.0 to 66.0	44.4 to 86.1	28.6 to 92.9	45.6 to 75.0	10.0 to 80.0	25.0 to 68.8	48.0 to 82.0

Table 4. Baseline clinical scores of the lost to follow-up group (n=6) (NRS, numeric rating scale; KOOS, knee injury and osteoarthritis outcomes score; ADL, activities of daily living; QoL, quality of life; KSS, knee society score)

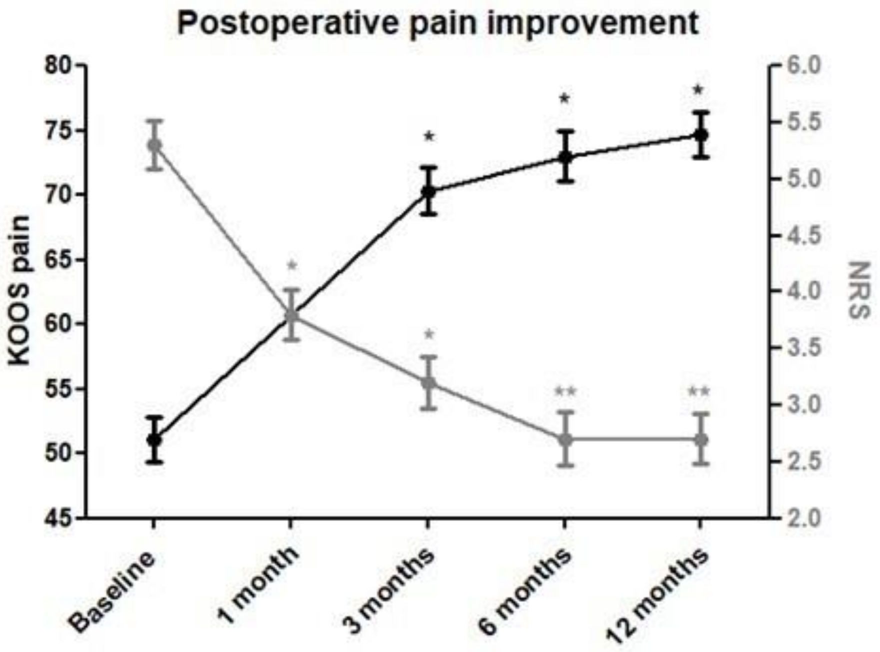


Figure 4. Pain assessment with the NRS and KOOS pain subscale, mean (SE) (NRS, numeric rating scale; KOOS, knee injury and osteoarthritis outcome score; *significant difference to baseline; **significant difference to baseline and 1 month postoperative).

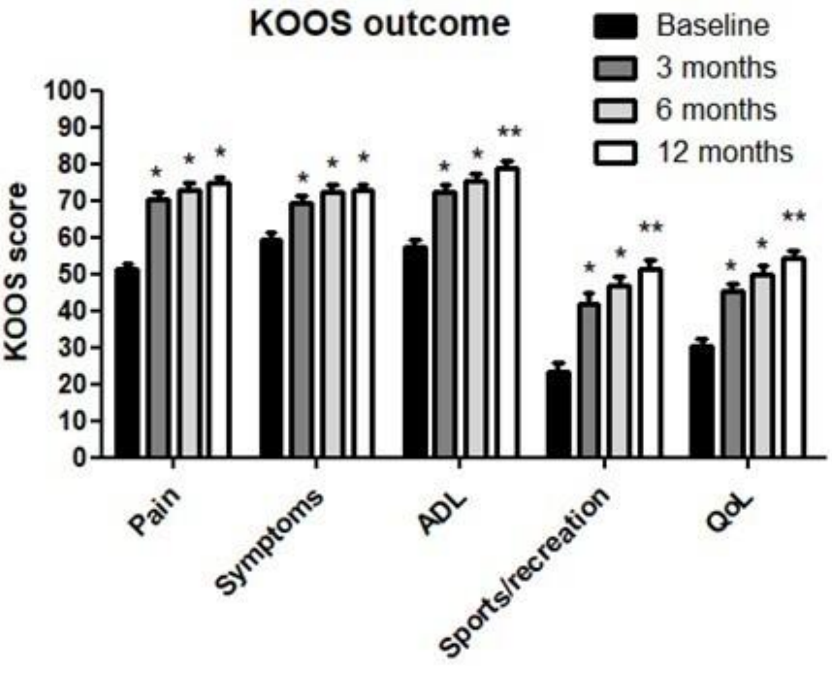


Figure 5. KOOS and KOOS subscales in time, mean (SE) (KOOS, knee injury and osteoarthritis outcome score; ADL, activities of daily living; QoL, quality of life; *significant difference to baseline; **significant difference to baseline and 3 months postoperative).

Results of the anchor questions showed that 101 (98%) patients were able to walk without any support and 102 (99%) patients succeeded to walk > 500m at three months postoperatively whereas at one month, respectively 22 (21%) and 48 (47%) patients were able to do so. Eighty-one (79%) patients could climb up and down the stairs with or without using the rail at one month, whereas all patients achieved this milestone at three months. Concerning respectively light (cooking, dusting…) and heavy (lifting boxes, scrubbing the floor…) housekeeping, 88 (85%) and 56 (54%) patients experienced mild to no difficulties at three months after HTO which was in general better than the preoperative status (55 (53%) and 23 (22%)) for the analysed group.

Radiological outcome

Based on the surgeons experience and preference, osteotomies were fixed with an angle-stable PEEKPower locking plate (Arthrex, Naples, USA) in 29% or with an angle-stable Königsee implant (Königsee Implantate, Allendorf, Germany) in 71%. Union of the bone graft was observed in 102 (99%) patients at three months after surgery. In all patients, the WBL was planned on the lateral spine which had an average position of 58.4% (52.0 to 63.0) on the tibial plateau and corresponded with a mTFA planning angle of 2.1° (1.0° to 3.0°) valgus. Mean postoperative WBL was 53.2% (17.0 to 80.0) and mTFA 0.6° (-7.9 to 6.0), establishing accuracy outcomes of -5.2% average correction error on the tibial plateau and 54 (52%) osteotomies falling into an acceptable range of [-2°;+2°] around the target. Mean correction size was 6.6° (-0.1° to 15.7°) Postoperative complications up to final follow-up are presented in table 5.

Postoperative complication	Frequency (%)	Intervention
Hematoma	1 (1%)	Conservative
Pulmonary thrombo-embolism	1 (1%)	Conservative
Wound infection	2 (2%)	Surgical debridement
Unstable lateral hinge fracture with non-union	1 (1%)	Revision HTO with new bone allograft
Implant loosing and failure	1 (1%)	Revision HTO with new bone allograft
Pseudoaneurysm popliteal artery	1 (1%)	Percutaneous transluminal angioplasty
Hardware irritation	12 (12%)	Hardware removal

Table 5. Postoperative complications, frequency and intervention up to final study follow-up.

DISCUSSION

The most notable findings of this study are the significantly reduced pain levels 4 weeks after surgery, the early resumption of daily life activities (walking, stairs, housekeeping) and the short-term clinical improvement (0-6 months) after opening-wedge HTO with structural allograft impaction. The accelerated rehabilitation was demonstrated by the fraction of our patients (50%) able to walk without support or by the use of only one crutch (21% and 29% respectively) after 4 weeks. All patient-reported clinical outcomes improved significantly after three months, and Lysholm score showed significant additional improvement between three and six months. These results indicate that HTO with structural impacted allograft enables patients to make their main clinical progression during the first three months after surgery, in contrast to other reports [38].

Despite the fact that postoperative pain is considered to be a major drawback for HTO, data focussing on early pain levels after knee osteotomies are surprisingly lacking in literature. In this study, NRS and KOOS pain subscales both indicated a consistent relief in pain especially during the first 4 weeks after surgery compared to baseline. One could say that early improvement in pain levels was a consequence of low patient activity due to hospitalisation [38], but since our patients were subjected to a standardized active rehabilitation protocol and were discharged the day after surgery, this was not applicable. Nerhus et al. reported early time-dependent improvements in pain outcome after HTO [7] and UKA [27] using the KOOS pain subscale and found a 35% pain improvement for HTO and 67% for UKA three months after surgery. A reasonable explanation for early reduced pain levels in UKA is the complete resection of the arthritic area contrary to HTO where the arthritic compartment is unloaded and therefore might take more time to establish pain relief [17]. With a KOOS pain improvement of 38% at three months, the results of our study were aligned with the HTO cohort of Nerhus [7]. In the absence of a KOOS pain score at 4 weeks follow-up, the NRS score revealed 28% pain relief relative to baseline. In general, for the few studies mentioning early pain levels after HTO [2, 17, 38], significant improvement can be expected until 6 months after surgery, followed by minimal pain relief up to one year.

Many contemporary rehabilitation protocols allow partial weight-bearing until 4-6 weeks after opening-wedge HTO, with permission of full weight bearing at 6-10 weeks only when initial signs of bony healing are observed [6, 8]. Potential reasons for avoiding early loading on the operated knee joint are loss of correction and delayed or non-union of the osteotomy site [19]. However, other studies have shown that early weight-bearing after opening-wedge HTO is safe and even preferable over delayed weight-bearing in terms of radiological and short-term clinical outcomes [2, 19, 30, 34]. Initiation of weight-bearing could possibly depend on the HTO surgical technique including fixation material and patient's confidence to avoid the abovementioned complications [34]. In this study, patients were allowed to start bearing weight as tolerated from the first day postoperatively which is in congruence with other recently published reports [5, 13, 18] concerning early active mobilization following HTO. Additional stability provided by the structural allograft might have lowered the threshold for patients to start walking soon after surgery. In our series, 21% patients at one month and 98% at three months after HTO, were able to ambulate without walking aids. These numbers are comparable to a recent study [26] in which an intraosseous implant was introduced to maintain the correction and with similar rehabilitation protocol. However, a correction loss of 21% was reported with this intraosseous fixation device, which questions the initial stability of the implant concerning early weight-bearing. In our study, only one case of implant failure with secondary loss of correction was observed after early weight-bearing. The exact reasons for failure could not be clarified but an acceptable correction at final follow-up was established by performing revision HTO surgery nine months after the index procedure.

Short-term clinical outcome appears to be good in the present study as all KOOS subscales significantly increased three months after surgery. Considering the literature on early results of the clinical scores KOOS and Lysholm after opening-wedge HTO [2, 7, 17, 26, 30, 38], our data showed extensive improvement of clinical scores and resumption of daily activities in the first 3 months and continued, but less extensive, additional improvements after 3 to 6 months.

A wide postoperative correction range in this trial when looking to other studies [31]. First, one case of implant failure and one of an unstable lateral hinge fracture with loss of correction were observed which are responsible for the few negative (-7.9°) postoperative values. Next, aiming for the lateral tibial spine represents a fixed anatomical reference point, however not a fixed percentage on the tibial plateau. The authors showed that aiming for the lateral spine in this study population resulted in a variation of 1° to 3° valgus alignment which might have contributed to a broader than usual correction range. Further the average effective correction in this study (6.6°) was lower than other comparable studies which can be explained by (1) the correction target (the lateral spine (+-58%) in this trial versus Fujisawa point (62.5%) in other studies) and (2) the preoperative planning method (conversion table by Hernigou) which overall caused a systematic undercorrection.

The presented surgical technique essentially utilizes a structural custom-made wedge-shaped bone allograft derived from a fresh frozen femoral head to fill the osteotomy gap before plate fixation. While bone allograft in opening-wedge HTO is traditionally cut into bone chips (cancellous bone) [31], the primary aim of this technique is to take maximal advantage of preserving the allograft's original structure for several reasons. First, impaction of the graft provides additional intrinsic stability to the initial osteotomy site which enabled some patients to start weight-bearing the day after surgery. Second, this press-fit graft is expected to redistribute axial loading forces, and thus acts as a load-sharing implant with the exact structural properties of the recipient's bone. Consequently, the screw and plate construct suffers from less load, leading to reduced pain levels while early weight-bearing is applied. Third, structural bone allograft derived from a fresh frozen femoral head maintains its osteoconductive properties and poses no potential harvesting site comorbidity compared to autograft. Additionally, it owns the unique advantage of having a physiological cortico-cancellous portion which makes this graft type a suitable option to cover the entire bone defect in opening-wedge HTO [15].

A similar grafting technique has been reported in the literature, however in these studies the structural allograft was introduced after plate fixation and in combination with allogenic bone chips which ultimately compromises the initial osteotomy construct stability for early ambulation [20, 36]. Nevertheless their radiological data about structural allograft healing indicated an average union time of 12.1 [36] and 12.7 ± 1.5 [20] weeks which was in line with the 99% healing rate observed at three months in our patients. Despite the faster union rate of autologous iliac crest bone graft in HTO, no advantages in clinical outcome were observed at 3 and 12 months which makes routine use of this graft type not recommendable [9].

In general this study showed that impaction of a wedge-shaped structural allograft in HTO enables early post-operative weight bearing accompanied by low post-operative pain levels succeeding in significantly improved clinical outcomes after only 3 months. These results can reduce the reluctancy of both surgeons and patients to consider HTO as a valid solution for treating OA in varus deformities and in our experience has led to extending indications for HTO surgery (i.e. less severe deformities, more severe degeneration in young patients).

Some limitations can be addressed to this study. First, individual dose-specific administration of analgesics was not exactly registered which might have influenced the early results concerning pain levels. However, only Acetaminophen and Diclofenac were routinely administered postoperatively in standard dosage whereas at discharge and follow-up consultations Acetaminophen and Tramadol were prescribed in the recommended dosage and frequency. Next, patients were only followed up to one year after surgery, which is short considering a clinical HTO trial. Because the only purpose was to evaluate the early recovery after HTO with this novel technique, analysis of long-term clinical data would fall beyond the scope of this study. Further, bone union was evaluated on AP knee radiographs which was useful to assess the lateral hinge area but CT scan would have been preferable to accurately assess complete allograft union. Nevertheless, bone union assessment of this allograft type was not a primary objective of this study since this was already properly evaluated by other authors [15]. Finally, a comparable control group was not displayed in this trial due to the nature of the study. In order to directly prove additional stability by the impacted allograft and its short-term clinical implications, a randomized controlled trial should be conducted comparing structural bone allograft with no graft, cancellous bone graft and bone autograft. Nevertheless, biomechanical proof was recently delivered, indicating lower initial malrotation and increased peak force and stiffness with structural allograft wedges in large biplanar MOWHTO corrections [1].

CONCLUSION

Study outcomes strongly support the initial hypothesis that the application of the structural custom-made wedge-shaped bone allograft in MOWHTO leads to low postoperative pain levels, accelerated recovery with early ambulation and excellent short-term clinical outcomes. The results of this study have the potential to alter the general perception about MOWHTO being a painful procedure with painstakingly slow recovery and consequently encourage the consideration of MOWHTO as a highly valuable joint-preserving option while treating unicompartmental knee arthritis.

ETHICAL APPROVAL

The study was approved by the ethical committee of the Antwerp university hospital and by the local ethical committee of the AZ Herentals hospital.

CONFLICT OF INTERST

Two authors of this paper are consultant for Arthrex. None received funding for participating in this study.

FUNDING

No external grants or funding was obtained for this study.

ACKNOWLEDGEMENT

None.

REFERENCES

1. Belsey J, Kaze AD, Jobson S, Faulkner J, Maas S, Khakha R, Pape D, Wilson AJ (2019) The biomechanical effects of allograft wedges used for large corrections during medial opening wedge high tibial osteotomy. PLoS One 14:1–14

2. Brinkman JM, Luites JWH, Wymenga AB, Van Heerwaarden RJ (2010) Early full weight bearing is safe in open-wedge high tibial osteotomy: RSA analysis of postoperative stability compared to delayed weight bearing. Acta Orthop 81:193–198

3. Brosset T, Pasquier G, Migaud H, Gougeon F (2011) Opening wedge high tibial osteotomy performed without filling the defect but with locking plate fixation (TomoFix™) and early weight-bearing: Prospective evaluation of bone union, precision and maintenance of correction in 51 cases. Orthop Traumatol Surg Res 97:705–711

4. Cao Z, Mai X, Wang J, Feng E, Huang Y (2018) Unicompartmental Knee Arthroplasty vs High Tibial Osteotomy for Knee Osteoarthritis: A Systematic Review and Meta-Analysis. J Arthroplasty 33:952–959

5. Darees M, Putman S, Brosset T, Roumazeille T, Pasquier G, Migaud H (2018) Opening-wedge high tibial osteotomy performed with locking plate fixation (TomoFix) and early weight-bearing but without filling the defect. A concise follow-up note of 48 cases at 10 years' follow-up. Orthop Traumatol Surg Res

6. Duivenvoorden T, van Diggele P, Reijman M, Bos PK, van Egmond J, Bierma-Zeinstra SMA, Verhaar JAN (2017) Adverse events and survival after closing- and opening-wedge high tibial osteotomy: a comparative study of 412 patients. Knee Surg, Sport Traumatol Arthrosc 25:895–901

7. Ekeland A, Nerhus TK, Dimmen S, Thornes E, Heir S (2017) Good functional results following high tibial opening-wedge osteotomy of knees with medial osteoarthritis: A prospective study with a mean of 8.3 years of follow-up. Knee 24:380–389

8. Ekhtiari S, Haldane CE, de SA D, Simunovic N, Musahl V, Ayeni OR (2016) Return to Work and Sport Following High Tibial Osteotomy. J Bone Jt Surg 98:1568–1577

9. Fucentese SF, Tscholl PM, Sutter R, Brucker PU, Meyer DC, Koch PP (2018) Bone autografting in medial open wedge high tibial osteotomy results in improved osseous gap healing on computed tomography, but no functional advantage: a prospective, randomised, controlled trial. Knee Surg, Sport Traumatol Arthrosc 27:2951–2957

10. Getgood A, Collins B, Slynarski K, Kurowska E, Parker D, Engebretsen L, MacDonald PB, Litchfield R (2013) Short-term safety and efficacy of a novel high tibial osteotomy system: A case controlled study. Knee Surg, Sport Traumatol Arthrosc 21:260–269

11. Goldhahn, S., Takeuchi, R., Nakamura, N., Nakamura, R., Sawaguchi T (2017) Responsiveness of the Knee Injury and Osteoarthritis Outcome Score (KOOS) and the Oxford Knee Score (OKS) in Japanese patients with high tibial osteotomy. J Orthop Sci 22:862–867

12. Hernigou P (2002) Open wedge tibial osteotomy: combined coronal and sagittal correction. Knee 9:15–20

13. Hernigou P, Queinnec S, Picard L, Guissou I, Naanaa T, Duffiet P, Julian D, Archer V (2013) Safety of a novel high tibial osteotomy locked plate fixation for immediate full weight-bearing: A case-control study. Int Orthop 37:2377–2384

14. Insall JN, Dorr LD, Scott RD, Scott WN (1989) Rationale of the Knee Society clinical rating system. Clin Orthop Relat Res 13–4

15. Jung KA, Lee SC, Ahn NK, Hwang SH, Nam CH (2010) Radiographic healing with hemispherical allogeneic femoral head bone grafting for opening-wedge high tibial osteotomy. Arthrosc - J Arthrosc Relat Surg 26:1617–1624

16. Kim JH, Kim HJ, Lee DH (2017) Survival of opening versus closing wedge high tibial osteotomy: A meta-Analysis. Sci Rep 7:1–7

17. Krych AJ, Reardon P, Sousa P, Pareek A, Stuart M, Pagnano M (2017) Unicompartmental knee arthroplasty provides higher activity and durability than valgus-producing proximal tibial osteotomy at 5 to 7 years. J Bone Jt Surg - Am 99:113–122

18. Lansdaal JR, Mouton T, Wascher DC, Demey G, Lustig S, Neyret P, Servien E (2017) Early weight bearing versus delayed weight bearing in medial opening wedge high tibial osteotomy: a randomized controlled trial. Knee Surg, Sport Traumatol Arthrosc 25:3670–3678

19. Lee OS, Ahn S, Lee YS (2017) Effect and safety of early weight-bearing on the outcome after open-wedge high tibial osteotomy: a systematic review and meta-analysis. Arch Orthop Trauma Surg 137:903–911

20. Leek SC, Jung KA, Nam CH, Jung SH, Hwang SH (2010) The short-term follow-up results of open wedge high tibial osteotomy with using an Aescula open wedge plate and an allogenic bone graft: The minimum 1-year follow-up results. Clin Orthop Surg 2:47–54

21. Lim JBT, Chong HC, Pang HN, Tay KJD, Chia SL, Lo NN, Yeo SJ (2017) Revision total knee arthroplasty for failed high tibial osteotomy and unicompartmental knee arthroplasty have similar patient-reported outcome measures in a two-year follow-up study. Bone Joint J 99–B:1329–1334

22. Lind M, McClelland J, Wittwer JE, Whitehead TS, Feller JA, Webster KE (2013) Gait analysis of walking before and after medial opening wedge high tibial osteotomy. Knee Surg, Sport Traumatol Arthrosc 21:74–81

23. Lobenhoffer P, Agneskirchner JD (2003) Improvements in surgical technique of valgus high tibial osteotomy. Knee Surg, Sport Traumatol Arthrosc 11:132–138

24. Molenberghs G, Kenward M (2007) Missing Data in Clinical Studies. John Wiley and Sons, Chinchester, UK

25. Moore J, Mychaltchouk L, Lavoie F (2017) Applicability of a modified angular correction

measurement method for open-wedge high tibial osteotomy. Knee Surg, Sport Traumatol Arthrosc 25:846–852

26. Morris J, Grant A, Kulkarni R, Doma K, Harris A, Hazratwala K (2018) Early results of medial opening wedge high tibial osteotomy using an intraosseous implant with accelerated rehabilitation. Eur J Orthop Surg Traumatol

27. Nerhus TK, Heir S, Svege I, Skrmm I, Jervidalo T, Madsen JE, Ekeland A (2012) Time-dependent improvement in functional outcome following Oxford medial unicompartmental knee arthroplasty. Acta Orthop 83:46–52

28. Ramappa M, Anand S, Jennings A (2013) Total knee replacement following high tibial osteotomy versus total knee replacement without high tibial osteotomy: a systematic review and meta analysis. Arch Orthop Trauma Surg 133:1587–1593

29. Roos EM, Roos HP, Lohmander LS, Ekdahl C, Beynnon BD (1998) Knee Injury and Osteoarthritis Outcome Score (KOOS)—Development of a Self-Administered Outcome Measure. J Orthop Sport Phys Ther 28:88–96

30. Schröter S, Ateschrang A, Löwe W, Nakayama H, Stöckle U, Ihle C (2017) Early full weight-bearing versus 6-week partial weight-bearing after open wedge high tibial osteotomy leads to earlier improvement of the clinical results: a prospective, randomised evaluation. Knee Surg, Sport Traumatol Arthrosc 25:325–332

31. Slevin O, Ayeni OR, Hinterwimmer S, Tischer T, Feucht MJ, Hirschmann MT (2016) The role of bone void fillers in medial opening wedge high tibial osteotomy: a systematic review. Knee Surg, Sport Traumatol Arthrosc 24:3584–3598

32. Stukenborg-Colsman C, Wirth CJ, Lazovic D, Wefer A (2001) High tibial osteotomy versus unicompartmental joint replacement in unicompartmental knee joint osteoarthritis: 7-10-year follow-up prospective randomised study. Knee 8:187–94

33. Takeuchi R, Aratake M, Bito H, Saito I, Kumagai K, Ishikawa H, Akamatsu Y, Sasaki Y, Saito T

(2008) Simultaneous bilateral opening-wedge high tibial osteotomy with early full weight-bearing exercise. Knee Surg, Sport Traumatol Arthrosc 16:1030–1037

34. Takeuchi R, Ishikawa H, Aratake M, Bito H, Saito I, Kumagai K, Akamatsu Y, Saito T (2009) Medial Opening Wedge High Tibial Osteotomy With Early Full Weight Bearing. Arthrosc J Arthrosc Relat Surg 25:46–53

35. Tegner Y, Lysholm J (1985) Rating systems in the evaluation of knee ligament injuries. Clin Orthop Relat Res 43–9

36. Yacobucci GN, Cocking MR (2008) Union of Medial Opening-Wedge High Tibial Osteotomy Using a Corticocancellous Proximal Tibial Wedge Allograft. Am J Sports Med 36:713–719

37. Yim JH, Song EK, Seo HY, Kim MS, Seon JK (2013) Comparison of High Tibial Osteotomy and Unicompartmental Knee Arthroplasty at a Minimum Follow-Up of 3 Years. J Arthroplasty Elsevier Inc. 28:243–247

38. Yokoyama M, Nakamura Y, Onishi T, Hirano K, Doi M (2016) Healing period after open high tibial osteotomy and related factors: Can we really say that it is long? 5:1–6

39. The United Kingdom Knee Osteotomy Registry (UKKOR) The First Annual Report (2018).

40. National Joint Registry for England, Wales and Northern Ireland. 13th Annual Report (2016).

Discussion

This PhD thesis contributes to the field of knee osteotomies by an in-depth investigation of several underexposed aspects regarding medial opening-wedge high tibial osteotomy (MOWHTO). A structured chapter-based overview on patient selection, surgical planning, surgical accuracy and rehabilitation was provided, comparable to the practical flow of a MOWHTO itself. The goal of this discussion section is to recreate a contemporary frame around medial opening-wedge high tibial osteotomy directed by these novel scientific insights.

1. *Is symptomatic lower limb varus accompanied by structural bony malalignment in the sagittal (tibial slope) or axial plane (femoral or tibial rotation) in a male Caucasian osteotomy population?*

The answer to the first research question is that the symptomatic varus knee in the Caucasian male population is mainly characterized by a malalignment in the coronal plane and is rarely accompanied by structural malalignment in the sagittal (tibial slope) or axial plane (femoral or tibial rotation) when compared to neutrally aligned healthy subjects. In the coronal plane, a significant difference was found between cohorts for the LDFA° (resp. 88.2° ±2.0 and 86.5° ±1.4, $p<0.0001$), the MPTA° (resp. 85.2° ±2.5 and 86.4° ±1.7, $p=0.001$) and the mTFA° (resp. 174.6° ±2.2 and 179.0° ±1.3, $p<0.001$). In the sagittal plane, no significant differences were found for the medial or lateral TS° between the symptomatic varus cohort (resp. 94.7° ± 3.3 and 95.1° ± 3.4) and the healthy neutral cohort (resp. 94.1° ± 3.3 and 94.8° ± 3.2). A 3D study by Pangaud et al. found an increased (medial) tibial slope (1.9° difference) in combination with varus malalignment compared to neutrally aligned individuals [38]. This contrasts our 3D study results, however, both varus and neutrally aligned patients in the study by Pangaud et al. were asymptomatic. Furthermore, they considered a tibial slope > 102° to be pathological since this was only present in <3% of individuals which is in line with our results (3.3%) [38].

In our study, a larger variability in femoral anteversion angle (FAVA°) and tibial external version angle (TEVA°) was observed with a medium positive correlation between these angles, which were both absent in healthy individuals. The combination of a high FAVA° with high TEVA° or low FAVA° with low TEVA° can be attributed to maintain foot external rotation within normal ranges, hereby preserving normal gait. The clinical relevance of this observation in relation to MKOA however seems currently unclear. Nevertheless, these data should evoke a certain awareness that symptomatic varus malalignment can be associated with excessive rotational malalignment of the femur or tibia. This is considered highly relevant information regarding knee osteotomy or arthroplasty planning, especially in the early symptomatic Caucasian individual [6, 22, 41]. When an associated rotational malalignment is clinically suspected, further investigations by low-dose CT-scan is warranted to take into account any additional malalignment during knee osteotomy planning [41]. Results of these scans might further direct towards a simple uniplanar coronal osteotomy or if a more complex biplanar correction is required. It remains unclear if these rotational malalignments need to be surgically addressed in MKOA, as it significantly increases the surgical complexity. Since data on this topic are currently lacking, future studies should direct attention to set an interval to which degree of bony malrotation associated with varus malalignment can be accepted.

Furthermore, it must be emphasized that this study was performed in a Caucasian male population, mainly because of the known differences in lateral distal femoral angle (LDFA°) and femoral/tibial version for both sex and ethnicity [32, 33, 44, 45]. Mathon et al. found that Caucasians have less anteversion in the femur but more external rotation in the tibia compared to Asians [32]. The latter was earlier found in a small population-based study of healthy individuals by Hovinga et al. [17]. The findings of our study can therefore not be extrapolated to females and individuals from non-Caucasian races. A future study/systematic review investigating the race and ethnic-specific variability of these angles in symptomatic varus knees would be of great interest in the extent to our findings. Especially in the Asian population where the prevalence of knee osteotomies has been dramatically increased over the past 10-15 years [27].

Altogether, when planning knee realignment surgery for MKOA, correcting malalignment in the coronal plane remains the key priority for clinical success [4].

Since malalignments in the sagittal or axial plane were considered to be of minor clinical significance, we focused in the second part of chapter 1 strictly on the coronal plane for the determination of different varus malalignment phenotypes in MOWHTO. The CPAK classification was used to categorize both the preoperative and postoperative lower limb alignment with the respective radiological and short-term clinical outcomes (2 year) [30]. Although not verified for knee osteotomies, the CPAK takes into account both the medial proximal tibial angle (MPTA°) and LDFA° to calculate the joint line obliquity (JLO°) and arithmetic hip-knee-ankle angle (aHKA°). Most osteotomy studies however only focus on the measured MPTA° and JLO° to correlate clinical outcomes [50]. Subjects with Kellgren and Lawrence grade 4 MKOA were excluded for analysis. A review article from 2016 stated that severe OA of the medial compartment (Ahlback grade III or higher) is a contraindication for HTO surgery [42]. However, according to recent osteotomy consensus statements by the UK knee osteotomy consensus group (2021) and the European Society of Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA, 2022), Kellgren and Lawrence grade 4 (bone on bone) MKOA is not considered a contraindication since most survival studies do not show a clear association with MKOA severity [8, 37, 47]. However in our study, a pre-analysis of this grade 4 cohort showed a conversion rate to arthroplasty of 14% within 36 months. It was decided that these subjects could worsen clinical outcomes up to 2 year by allocation according to the CPAK classification and were therefore excluded.

2. *What are the most prevalent varus phenotypes for MOWHTO and does the tibial-driven varus phenotype provides both superior radiological and short-term clinical outcomes compared to other phenotypes?*

The answer to the second research question is that CPAK 1 (52%) was the most common preoperative varus phenotype before knee osteotomy while CPAK 6 (49%) was most prevalent after accurate MOWHTO realignment (mTFA 180-184°). CPAK 1 was indeed featured by preoperative tibia-driven varus (84.6° ±1.5 MPTA) and mild intra-articular (IA) varus (2,0° ±1,4 JLCA). Postoperative realignment showed an MPTA of 91,9° ±1,9 and an mTFA of 181,9° ±1,2 which can be considered as highly favourable radiological outcomes after MOWHTO. Although significant improvement was observed in both pain (NRS) and functional (KOOS) outcomes, the TRR at 2 year was 67% for CPAK 1.

Preoperatively, CPAK 4 (13%) was less prevalent and had a normal preoperative MPTA of 87,7° ±1,0, an LDFA of 91,4° ±1,1 (femoral varus) and a JLCA of 2,3° ±1,5 (mild IA varus). The postoperative MPTA° of CPAK 4 was 94,3° ±2,0. Of interest was that the TRR rate of CPAK 4 was 87% at 2 year, despite the current concept of impaired clinical outcomes after MOWHTO once exceeding 95° postoperative MPTA [23]. However, this statement was not confirmed in our study. Although, no significant differences were found for the NRS rest/activity, the KOOS and the TRR%, clinical outcomes of CPAK 4 (femoral-driven varus) were surprisingly in favour compared to CPAK 1 (tibia-driven varus) as was shown by the TRR% difference.

Regarding phenotype comparison after MOWHTO, CPAK 6 and CPAK 9 were significantly different for the preoperative LDFA°, MPTA° and mTFA° and postoperatively only for the MPTA°. Again at 2 year, no significant differences were found for clinical outcomes NRS rest/activity or KOOS and in TRR (CPAK 6: 64% and CPAK 9: 80%). To assess the relevance of postoperative JLO°, an additional comparison between CPAK 5/6 (apex neutral) and CPAK 8/9 (apex proximally) was performed and again showed no differences in any of the given clinical outcomes at 2 year. Recently, a systematic review by Xie et al. concluded a rather doubtful association between the postoperative JLO° and clinical outcome after HTO, which finally supports the outcomes of our study [50]. However, it needs to be emphasized that overcorrections (mTFA > 184°) were excluded in our analysis and that the evidence for poor clinical outcomes after overcorrected osteotomies is fairly robust [21, 23, 26]. Based on these findings, when considering the overall alignment within target boundaries, an overcorrection on the tibia does not seem to negatively influence clinical outcomes at 2 year follow-up. However, long-term follow-up is needed to confirm this statement.

The key message from this chapter is that knee surgeons practicing realignment surgery should be aware of the different varus phenotypes, its estimated distribution in an osteotomy population, and the relative importance of joint line obliquity. The presence of tibial-driven varus has been overestimated as shown by our data as well as by other studies [11, 40]. The frequency of valgus-producing osteotomies at the level of the femur is expected to increase in the near future by this knowledge. Nevertheless, an accurately performed MOWHTO (mTFA 180-184°) seems at least as effective for femoral-driven as for tibia-driven varus based on short-term clinical outcomes. Long-term data are certainly needed before suggesting that the unloading effect of a diseased knee compartment is the main priority, while the applied technique for achievement might deserve less attention.

3. *What is the 2D and 3D location of the lateral tibial spine on the tibial plateau in an eligible Caucasian MOWHTO population?*

Research on the lateral tibial spine (LTS) position and its reliability as a planning target was largely imposed due to the emerging use of the LTS in our own practice and in several clinical HTO studies [13, 28, 31, 39]. The answer to the third research question is that the LTS is located at 57-58% with a 10% maximal variation range (53-63%) on the tibial plateau in a Caucasian HTO population. Good agreement was found between 2D and 3D imaging modalities while evaluating its position in the coronal plane. Martay et al. corresponded the apex of the LTS with 55% (1.7-1.9° mTFA valgus) on the tibial plateau[31]. In line with these results, Tripon et al. recently found an average LTS position of 54% on 3D models from different ethnicities [49]. Although a similar variation of 10% (48.9-57.2%) was found, its average position is contrasting our results that showed the LTS to be located beyond 54% in 90% cases using 3D model projection. Reasons for discrepancy however have not been found. Exactly in line with our results is the study by Xu Jiang et al. which showed a 57.7%±2.1 of the LTS top [19]. Planning realignment surgery with the WBL on the LTS yielded 182.1°±0.5 in a Chinese population compared to 181.8°±0.3 in our study on Caucasians. The similarity of LTS position among ethnicities, as suggested by Tripon et al., seems therefore confirmed [49].

4. *Is the lateral tibial spine a consistent and clinically relevant anatomical reference point for aiming the weight-bearing axis in MOWHTO planning and determination of postoperative accuracy of correction?*

When aiming the WBL through the LTS during MOWHTO planning, a consistent realignment of 181-183° mTFA can be expected when performing accurate surgery. So, the 10% of maximal LTS variety on the tibial plateau corresponds approximately with a 2° mTFA valgus range. This can be considered a safe target zone for alignment restoration, while avoiding excessive overcorrection. The systematic review by our research team found that the overlapping correction target considered 'acceptable' for all included HTO studies was 2-3° mTFA valgus [3]. In addition, Heijens et al. described a 2° valgus threshold ('coronal hypomochlion') after which the JLCA° makes a linear decrease (the point after which the medial compartment gets radiographically 'unloaded') [15]. His team proposed an ideal correction between 2-5° valgus based on preoperative JLCA° status. The osteotomy consensus (2022) by ESSKA recommends an individualized approach based on the degree of deformity, radiographic osteoarthritis severity and the indication for knee osteotomy surgery [8]. However, this recommendation was scored as ‘Grade D – expert opinion’ evidence without giving further guidelines on personalized target preference. Although the position and reliability of the lateral tibial spine in MOWHTO planning has been verified now, there is no evidence that realignment to the LTS should produce superior clinical outcomes compared to the Fujisawa-point (62.5%) [29]. Therefore, surgeons that aim for slight valgus overcorrection between 181°-183° can safely use the lateral tibial spine as a reliable anatomic and radiographic landmark during osteotomy planning and intraoperative control for each individual patient despite a 10% variation range.

5. *Which are the most relevant factors to take into account while making an opening-wedge osteotomy cut in order to obtain an accurate bony correction?*

The answer to the fifth research question is that the osteotomy depth is the main parameter for obtaining bony accuracy in the coronal plane (MPTA°) and controlling the hinge axis in the axial plane is crucial for maintaining the native tibial slope. The latter can be obtained by creating an equal osteotomy depth for the anterior and posterior tibial cortices. A difference of approximately 7mm between anterior and posterior cortical depth (longer anterior cortex) was found to result in 10° of anterolateral hinge axis rotation. This corresponds to a tibial slope increase of 1.0-1.3° when performing a commonly performed gap distraction of 10mm in MOWHTO.

Under-corrections are more commonly seen after MOWHTO compared to overcorrections [3]. This can partially be explained at the bony level by not including the sawblade thickness during osteotomy planning, and due to unnoticed lateral hinge fractures that unintentionally extend the depth of the osteotomy. It has been shown that only half of the lateral hinge fractures are identified on conventional fluoroscopy or postoperative radiographs relative to their presence on CT-scan [25]. Recently, avoiding a fracture of the lateral cortex can by managed by ‘prophylactic’ placement of a single K-wire which protects the bone from excessive compression-distractions forces [9]. More importantly however is the coronal position of the hinge axis itself in order to reduce the risk for hinge fractures. This was studied by Nakamura et al. and found that the lateral-lower quadrant (proximal to the proximal tibiofibular joint) was the safest zone for hinge axis placement in the coronal plane [35]. According to our simulation study, having surgical accuracy as primary outcome, the depth of the osteotomy was the most relevant parameter in MPTA° correction.

Important to understand for the knee surgeon is that nor the inclination, nor the shift of the osteotomy plane in the sagittal plane played a significant role on bony accuracy (MPTA° and tibial slope) [48]. After correction for sawblade thickness, our simulation data showed good compatibility with the conversion table by Hernigou [16]. This table includes osteotomy depth in order to reliably determine the required wedge opening (mm) at the medial cortex. The use of this table seems even after 20 years highly recommended if not applying 3D technology, on the condition that saw blade thickness is included. Surprisingly, anterolateral hinge axis rotations in the axial plane revealed no relevant differences on the MPTA outcome.

On the other hand, the tibial slope was strongly affected by the axial hinge axis position. A tibial slope increase of 1.0-1.4° per 10° axial hinge rotation at 10mm wedge opening was found. Slope changes are expected to be higher in small tibias and for increasing size of gap distraction. As illustrated by our simulations and by Noyes et al. previously (2005), the axial rotation of the hinge axis is a consequence of unequal anteroposterior cortical breaching/gap distraction during MOWHTO [36]. The anteromedial tibial approach for MOWHTO, the posterior neurovascular bundle and incomplete transection of the superficial medial collateral ligament (MCL) are potential reasons that compromise sufficient posterior corticotomy. From a biomechanical perspective, a true decompression of the medial compartment after MOWHTO is only possible when releasing all distal fibers of the MCL [1]. Surgeons should be aware that these mandatory surgical steps largely determine correct axial orientation of the hinge axis and so secure containment of the native tibial slope, if intended.

6. *Can surgical accuracy of MOWHTO corrections be improved with 3D planning and by the availability of patient-specific instrumentation for preparing structural bone graft during surgery?*

The answer to the sixth research question is that the investigated 3D printed instrumentation to personalize structural bone allograft is a viable alternative method in MOWHTO. Surgical accuracy outcomes were 1.1°±0.7 absolute ΔMPTA with 63% of cases falling within [-1°;+1°] and 90% within [-2°;+2°] around the target. Since no conventional control group was included in our study, the absolute accuracy outcome in our series appears to be at least numerically in favor compared to a navigation (2.1° ±1.4) and a gap measurement cohort (1.7° ±1.2) as described in a high-level RCT [43]. Regarding other published patient-specific (PSI) techniques, the 3D accuracy outcomes in both coronal and sagittal plane were comparable with the pilot study by Munier et al. [34]. They found 100% MPTA accuracy within 2° around the planning while showing 90% accuracy in the sagittal plane (MPTS) [34]. This PSI technique was later investigated on a large population and showed relative accuracy outcomes of 0.5°±0.6 ΔMPTA and 1.0°±0.9 ΔmTFA [7]. Although the ΔMPTA was significantly different in our series ($p=0.04$), it was unlikely to be clinically relevant. Moreover, our accuracy outcomes appear comparable with previous HTO PSI series [12, 14, 34].

In the sagittal plane, a minor tibial slope increase of 1.2°±1.2 ΔMPTS was found relative to the planning which was clearly better compared to the initial PSI study (2.7°±1.8 ΔMPTS) [14]. Modifications to guide design have facilitated graft preparation intraoperatively with special attention to maximize filling of the osteotomy gap (antero-posterior) and so to assure correct posterior slope.

Although the planning method and kit preparation logistics (external 3D printing company) looked seemingly time-consuming, a minimal time-interval of 14 days was required before surgery could be performed. The 3D kit was used in combination with three different locking plate systems which supports the accessibility of using this 3D kit with multiple off-the-shelf locking plate systems, hereby contrasting other 'plate-inclusive' PSI techniques [7, 18]. Other advantages of this 3D technique include the surgical freedom for plate positioning, less need for fluoroscopy control, instant obtainment of the desired correction by introduction of the customized structural bone allograft and limited periosteal stripping. The decision for not including a 3D cutting guide was mainly based on the good accuracy results of the initial PSI study and on the 3D simulation study which showed only limited relevance of replicating the exact same osteotomy plane as planned on 3D. Of course, as is true for every PSI technique in MOWHTO, an additional cost can be expected for guide design and 3D printing as well as the impossibility to change the desired correction intraoperatively. Finally, structural bone allograft needs to available (a femoral head or condyle) for applying our technique which might not be evident in all countries or worth the additional cost in corrections <10mm [46]. Nevertheless, pain levels rapidly decreased in the first 4 weeks after surgery while 'weight-bearing as tolerated' was allowed from the first postoperative day.

7. *Does the implementation of structural impacted bone grafting enables fast rehabilitation and early pain relief after MOWHTO surgery?*

The technique of structural bone allograft impaction was extensively studied in the final chapter, without the use of the described 3D planning and matching 3D guides. Study focus was directed towards early pain levels, timing of weight-bearing and speed of rehabilitation. The MOWHTO is known to facilitates high rates of return to sport (90-100%) and return to work (81-96%) [10], however, the osteotomy literature is surprisingly scarce regarding clinical outcomes and pain levels early after surgery. Certainly because painful and slow recovery are presumed disadvantages after MOWHTO and play a role in favoring arthroplasty as treatment for moderate isolated MKOA.

The study strongly affirmed the seventh research question that applying structural triangular bone allograft in MOWHTO leads to low postoperative pain levels, early ambulation and excellent short-term clinical outcomes. NRS and KOOS pain subscales both indicated a consistent relief in pain, especially during the first 4 weeks after surgery compared to baseline. One could say that early improvement in pain levels was a consequence of low patient activity due to hospitalization [51]. However, since our patients were subjected to a standardized active rehabilitation protocol and were discharged the day after surgery, this was not applicable. Moreover, patients were allowed and stimulated to bear weight from the first postoperative day. By doing so, 98% of subjects were able to walk without any support and 99% succeeded to walk > 500m three months after surgery. A fraction of our patients (50%) was even able to walk without support or by the use of only one crutch (21% and 29% respectively) after 4 weeks. 99% showed progressive callus formation at 3 months without showing notable complications. The safety of early full weight-bearing on locking plate systems after MOWHTO surgery is hereby once more confirmed [5, 24].

The presented surgical technique essentially utilizes a structural custom-made wedge-shaped bone allograft derived from a fresh frozen femoral head to fill the osteotomy gap before plate fixation. While bone allograft in opening-wedge HTO is traditionally cut into bone chips (cancellous bone) [46], the primary aim of this technique is to take maximal advantage of preserving the allograft's original structure for several reasons. First, impaction of the graft provides additional intrinsic stability to the initial osteotomy site which enabled some patients to start weight-bearing the day after surgery [2]. Second, this press-fit graft is expected to redistribute axial loading forces, and thus acts as a load-sharing implant with the exact structural properties of the recipient's bone. Consequently, the screw and plate construct suffers from less load, leading to reduced pain levels while early weight-bearing is applied. Third, structural bone allograft derived from a fresh frozen femoral head maintains its osteoconductive properties and poses no potential harvesting site comorbidity compared to autograft. Additionally, it owns the unique advantage of having a physiological cortico-cancellous portion which makes this graft type a suitable option to cover the entire bone defect in MOWHTO [20].

Altogether, our study results have the potential to alter the general perception about HTO being a painful procedure with painstakingly slow recovery. Consequently, this encourages the consideration of the MOWHTO being a highly valuable contemporary joint-preserving option for treating unicompartmental knee osteoarthritis.

REFERENCES

1. Agneskirchner JD, Hurschler C, Wrann CD, Lobenhoffer P (2007) The Effects of Valgus Medial Opening Wedge High Tibial Osteotomy on Articular Cartilage Pressure of the Knee: A Biomechanical Study. Arthroscopy 23(8):852–861

2. Belsey J, Diffo Kaze A, Jobson S, Faulkner J, Maas S, Khakha R, Wilson AJ, Pape D (2019) Graft materials provide greater static strength to medial opening wedge high tibial osteotomy than when no graft is included. J Exp Orthop Journal of Experimental Orthopaedics 6(1):13

3. Van den Bempt M, Van Genechten W, Claes T, Claes S (2016) How accurately does high tibial osteotomy correct the mechanical axis of an arthritic varus knee? A systematic review. Knee Elsevier B.V. 23(6):925–935

4. Birmingham TB, Moyer R, Leitch K, Chesworth B, Bryant D, Willits K, Litchfield R, Fowler PJ, Giffin JR (2017) Changes in biomechanical risk factors for knee osteoarthritis and their association with 5-year clinically important improvement after limb realignment surgery. Osteoarthritis and Cartilage 25(12):1999–2006

5. Brinkman J-M, Luites JWH, Wymenga AB, van Heerwaarden RJ (2010) Early full weight bearing is safe in open-wedge high tibial osteotomy. Acta Orthop 81(2):193–8

6. Castelli CC, Falvo DA, Iapicca ML, Gotti V (2016) Rotational alignment of the femoral component in total knee arthroplasty. Annals of Translational Medicine 4(1):2–10

7. Chaouche S, Jacquet C, Fabre-Aubrespy M, Sharma A, Argenson JN, Parratte S, Ollivier M (2019) Patient-specific cutting guides for open-wedge high tibial osteotomy: safety and accuracy analysis of a hundred patients continuous cohort. Int Orthop International Orthopaedics 43(12):2757–2765

8. Dawson MJ, Ollivier M, Menetrey J, Beaufils P (2022) Osteotomy around the painful degenerative varus knee: a 2022 ESSKA formal consensus. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 31(8):3041-3043

9. Dessyn E, Sharma A, Donnez M, Chabrand P, Ehlinger M, Argenson JN, Parratte S, Ollivier M

(2020) Adding a protective K-wire during opening high tibial osteotomy increases lateral hinge resistance to fracture. Knee Surg Sports Traumatol Arthrosc 28(3):751–758

10. Ekhtiari S, Haldane CE, De Sa D, Simunovic N, Musahl V, Ayeni OR (2016) Return to work and sport following high tibial osteotomy: A systematic review. J Bone Joint Surg Am 98(18):1568–1577

11. Feucht MJ, Winkler PW, Mehl J, Bode G, Forkel P, Imhoff AB, Lutz PM (2020) Isolated high tibial osteotomy is appropriate in less than two-thirds of varus knees if excessive overcorrection of the medial proximal tibial angle should be avoided. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(10):3299-3309

12. Fucentese SF, Meier P, Jud L, Köchli GL, Aichmair A, Vlachopoulos L, Fürnstahl P (2020) Accuracy of 3D-planned patient specific instrumentation in high tibial open wedge valgisation osteotomy. J Exp Orthop Journal of Experimental Orthopaedics 7(1):1–7

13. Van Genechten W, Van den Bempt M, Van Tilborg W, Bartholomeeusen S, Van Den Bogaert G, Claes T, Claes S (2020) Structural allograft impaction enables fast rehabilitation in opening-wedge high tibial osteotomy: a consecutive case series with one year follow-up. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 28(12):3747–3757

14. Van Genechten W, Van Tilborg W, Van Den Bempt M, Van Haver A, Verdonk P (2020) Feasibility and 3D Planning of a Novel Patient-Specific Instrumentation Technique in Medial Opening-Wedge High Tibial Osteotomy. J Knee Surg 34(14):1560–1569

15. Heijens E, Kornherr P, Meister C (2016) The coronal hypomochlion: A tipping point of clinical relevance when planning valgus producing high tibial osteotomies. Bone Joint J 98(5):628–633

16. Hernigou P, Ma W (2001) Open wedge tibial osteotomy with acrylic bone cement as bone substitute. Knee 8(2):103–110

17. Hovinga KR, Lerner AL (2009) Anatomic variations between Japanese and caucasian

populations in the healthy young adult knee joint. Journal of Orthopaedic Research 27(9):1191–1196

18. Jeong SH, Samuel LT, Acuña AJ, Kamath AF (2022) Patient-specific high tibial osteotomy for varus malalignment: 3D-printed plating technique and review of the literature. European Journal of Orthopaedic Surgery and Traumatology Springer Paris 32(5):845–855

19. Jiang X, Li B, Xie K, Ai S, Hu X, Gao L, Wang L, Yan M (2021) Lateral tibial intercondylar eminence is a reliable reference for alignment correction in high tibial osteotomy. Knee Surg Sports Traumatol Arthrosc 31(4):1515-1523

20. Jung KA, Lee SC, Ahn NK, Hwang SH, Nam CH (2010) Radiographic healing with hemispherical allogeneic femoral head bone grafting for opening-wedge high tibial osteotomy. Arthroscopy Elsevier Inc. 26(12):1617–1624

21. Kang BY, Lee DK, Kim HS, Wang JH (2022) How to achieve an optimal alignment in medial opening wedge high tibial osteotomy? Knee Surgery and Related Research BioMed Central 34(1):1-11

22. Kfuri M, Crist BD, Stannard JP (2022) Preoperative Planning and Preservation of the Knee with Complex Osteotomies. Missouri medicine 119(2):144–151

23. Kim JS, Lim JK, Choi HG, Jeong HW, Park SB, Shim SJ, Lee YS (2022) Excessively Increased Joint-Line Obliquity After Medial Opening-Wedge High Tibial Osteotomy Is Associated With Inferior Radiologic and Clinical Outcomes: What Is Permissible Joint-Line Obliquity. Arthroscopy 38(6):1904–1915

24. Lansdaal JR, Mouton T, Wascher DC, Demey G, Lustig S, Neyret P, Servien E (2017) Early weight bearing versus delayed weight bearing in medial opening wedge high tibial osteotomy: a randomized controlled trial. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 25(12):3670–3678

25. Lee BS, Jo BK, Bin S Il, Kim JM, Lee CR, Kwon YH (2019) Hinge Fractures Are Underestimated

on Plain Radiographs After Open Wedge Proximal Tibial Osteotomy: Evaluation by Computed Tomography. Am J Sports Med 47(6):1370–1375

26. Lee S-S, Kim JH, Kim S, Jung EY, Ryu DJ, Lee DK, Wang JH (2022) Avoiding Overcorrection to Increase Patient Satisfaction After Open Wedge High Tibial Osteotomy. Am J Sports Med 50(9):2453–2461

27. Lee SH, Seo HY, Kim HR, Song EK, Seon JK (2021) Older age increases the risk of revision and perioperative complications after high tibial osteotomy for unicompartmental knee osteoarthritis. Sci Rep Nature Publishing Group UK 11(1):1–9

28. Lee SS, Lee H Il, Cho ST, Cho JH (2020) Comparison of the outcomes between two different target points after open wedge high tibial osteotomy: The Fujisawa point versus the lateral tibial spine. Knee Elsevier B.V. 27(3):915–922

29. Lee SS, Lee H Il, Cho ST, Cho JH (2020) Comparison of the outcomes between two different target points after open wedge high tibial osteotomy: The Fujisawa point versus the lateral tibial spine. Knee Elsevier B.V. 27(3):915-922

30. MacDessi SJ, Griffiths-Jones W, Harris IA, Bellemans J, Chen DB (2021) Coronal Plane Alignment of the Knee (CPAK) classification a new system for describing knee phenotypes. Bone Joint J 103 B(2):329–337

31. Martay JL, Palmer AJ, Bangerter NK, Clare S, Monk AP, Brown CP, Price AJ (2018) A preliminary modeling investigation into the safe correction zone for high tibial osteotomy. Knee 25(2):286–295

32. Mathon P, Micicoi G, Seil R, Kacaoglu B, Cerciello S, Ahmad F, LiArno S, Teitge R, Ollivier M (2021) Healthy middle-aged Asian and Caucasian populations present with large intra- and inter-individual variations of lower limb torsion. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(4):1083–1089

33. Micicoi G, Jacquet C, Sharma A, LiArno S, Faizan A, Kley K, Parratte S, Ollivier M (2021)

Neutral alignment resulting from tibial vara and opposite femoral valgus is the main morphologic pattern in healthy middle-aged patients: an exploration of a 3D-CT database. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(3):849–858

34. Munier M, Donnez M, Ollivier M, Flecher X, Chabrand P, Argenson JN, Parratte S (2017) Can three-dimensional patient-specific cutting guides be used to achieve optimal correction for high tibial osteotomy? Pilot study. Orthop Traumatol Surg Res Elsevier Masson SAS 103(2):245–250

35. Nakamura R, Komatsu N, Fujita K, Kuroda K, Takahashi M, Omi R, Katsuki Y, Tsuchiya H (2017) Appropriate hinge position for prevention of unstable lateral hinge fracture in open wedge high tibial osteotomy. Bone Joint J 99B(10):1313–1318

36. Noyes FR, Goebel SX, West J (2005) Opening wedge tibial osteotomy: The 3-triangle method to correct axial alignment and tibial slope. Am J Sports Med 33(3):378–387

37. Ollivier B, Berger P, Depuydt C, Vandenneucker H (2021) Good long-term survival and patient-reported outcomes after high tibial osteotomy for medial compartment osteoarthritis. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(11):3569–3584

38. Pangaud C, Laumonerie P, Dagneaux L, LiArno S, Wellings P, Faizan A, Sharma A, Ollivier M (2020) Measurement of the Posterior Tibial Slope Depends on Ethnicity, Sex, and Lower Limb Alignment: A Computed Tomography Analysis of 378 Healthy Participants. Orthop J Sports Med 8(1):1–7

39. van de Pol GJ, Verdonschot N, van Kampen A (2012) The value of the intra-operative clinical mechanical axis measurement in open-wedge valgus high tibial osteotomies. Knee 19(6):933–938

40. Razak HRBA, Micicoi G, Khakha RS, Ehlinger M, Faizan A, LiArno S, Ollivier M (2021) Patients with varus knee osteoarthritis undergoing high tibial osteotomy exhibit more femoral varus but similar tibial morphology compared to non-arthritic varus knees. Knee Surg Sports

Traumatol Arthrosc Springer Berlin Heidelberg 30(2):680-687

41. Reif TJ, Humphrey TJ, Fragomen AT (2022) Osteotomies About the Knee: Managing Rotational Deformities. Operative Techniques in Sports Medicine Elsevier Inc. 30(3):1–11

42. Sabzevari S, Ebrahimpour A, Roudi MK, Kachooei AR (2016) High tibial osteotomy: A systematic review and current concept. Archives of Bone and Joint Surgery 4(3):204–212

43. Schröter S, Ihle C, Elson DW, Döbele S, Stöckle U, Ateschrang A (2016) Surgical accuracy in high tibial osteotomy: coronal equivalence of computer navigation and gap measurement. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 24(11):3410–3417

44. Shahi A, Bs PP, Reza H, Hosseinzadeh S, Chen AF, Restrepo C Diversity of the Lower Limb Alignment ; A Population-based Multi-national Diversity of the Lower Limb Alignment : A Population-based Multi-national Study. Conference paper (November 2014)

45. Siboni R, Vialla T, Joseph E, LiArno S, Faizan A, Martz P, Ollivier M (2022) Coronal and sagittal alignment of the lower limb in Caucasians: Analysis of a 3D CT database. Orthop Traumatol Surg Res Elsevier Masson SAS 108(3):103251

46. Slevin O, Ayeni OR, Hinterwimmer S, Tischer T, Feucht MJ, Hirschmann MT (2016) The role of bone void fillers in medial opening wedge high tibial osteotomy: a systematic review. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 24(11):3584-3598

47. Snow M, Jermain P, Mandalia V, Murray J, Khakha R, McNicholas M, Dawson M (2021) A 2021 consensus statement on osteotomies around the knee by the UK Knee Osteotomy consensus Group (KOG). Knee Elsevier B.V. 33(December):73–83

48. Teng Y, Mizu-uchi H, Xia Y, Akasaki Y, Akiyama T, Kawahara S, Nakashima Y (2021) Axial But Not Sagittal Hinge Axis Affects Posterior Tibial Slope in Medial Open-Wedge High Tibial Osteotomy: A 3-Dimensional Surgical Simulation Study. Arthroscopy Arthroscopy Association of North America 37(7):2191–2201

49. Tripon M, Sautet P, Argenson J, Jacquet C, Martz P, Ollivier M (2022) Is the lateral tibial spine a reliable landmark for planning tibial or femoral valgus osteotomies ? Orthop Traumatol Surg Res 108:1–5

50. Xie T, Brouwer RW, Akker I Van Den, Hugo S (2023) Clinical relevance of joint line obliquity after high tibial osteotomy for medial knee osteoarthritis remains controversial : a systematic review Hospital for Special Surgery Knee Score. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 31(10):4355-4367

51. Yokoyama M, Nakamura Y, Onishi T, Hirano K, Doi M (2016) Healing period after open high tibial osteotomy and related factors: Can we really say that it is long? SpringerPlus Springer International Publishing 5(1):1–6

Gratitude

A PhD thesis is never the work of a single person. The PhD candidate needs to be surrounded by positive and inspiring promotors, reliable people with research experience and good friends that make this piece of work a joined venture. I would personally like to reveal my gratitude to several individuals and research organisation who stimulated my scientific and personal evolution over the past years.

First, I would to thank my promotors Peter Verdonk (MD, PhD), Steven Claes (MD, PhD) and Jozef Michielsen (MD, PhD) as they were most closely related to the creation of my thesis. Peter Verdonk supervised my master thesis as a medical student and warmed me up for more scientific work concerning 3D knee osteotomies. He intensively guided me through my first two years of PhD research and offered the opportunity to work one year overseas at Mayo Clinic, MN, USA. His keen interest for implementing 3D technology for osteotomies around the knee was driven by the quote “We measure with a millimeter, but we cut with an axe”. Steven Claes really sparked my interest for knee osteotomies by identifying a gap in knowledge regarding poor accuracy outcomes of high tibial osteotomy surgery. He described it as a ‘black box’ surgery which could be planned and postoperative realignment could be measured, but during surgery, there was poor control over the accuracy of realignment. His general interest in joint preservation surgery, our elaborate discussions about surgical osteotomy planning and ‘black box’ unravelling kept me inspired over the entire thesis period. He truly loves performing realignment surgery as showed by his quote “Personally, high tibial osteotomy is the most rewarding orthopaedic procedure for both patient and surgeon”. Jozef Michielsen supervised my scientific progress from a little distance since spine surgery is his core business. Nevertheless, because he recently obtained his PhD degree, he was able to set the pace while providing me with practical tips and tricks to bring my PhD journey back home. I would like to thank him for the opportunity to integrate my research ambition into my orthopaedic residency program and to offer the required financial support when necessary.

Next, I would like to thank Prof. dr. Matthieu Ollivier (Institute of movement and locomotion, Marseille, France) and Prof. dr. Johan Vanlauwe (UZ Brussel, Belgium) for accepting the invitation as external jury. I’m truly honored that two internationally renowned knee surgeons examined and reviewed my PhD thesis to improve the quality of this work.

Further, I had the opportunity to collaborate with several members of the More Institute research team and I’m grateful for the one year of financial support provided by the foundation. I learned all 3D skills from Annemieke Van Haver (PhD) and she inspired me for designing a novel 3D guide for MOWHTO. I want to thank Kristien Vuylsteke for helping me to deal with ethical committee applications and study logistics. From the AZ Herentals research, I thank Nathalie Van Beek (PhD) for several critical reviews on my work and for statistical analysis. I appreciate the osteotomy discussions with Stijn Bartholomeeusen (MD) and Antoon Claes (MD) in Herentals and their vision on surgical technique and how to improve early patient outcomes. I thank my colleague orthopaedic resident Gino Mestach, and master student Yannick Vanneste for their effort on raw data collection of radiological parameters. My good friends Wouter Van Tilborg and Maxim Van den Bempt that were on my side during preceding PhD research while we were medical students. From my first year abroad at Mayo Clinic, MN (USA), I want to thank my supervisor Prof. dr. Daniel Saris for introducing me in basic science research and for pushing my limits in order to maximize the scientific output and learning curve of this wonderful year.

Finally, I want to direct my appreciation to my family; my mother, Frieda Fierens, my father, Jozef Van Genechten, my brother, Joris Van Genechten and his fiancé Frieke Trompet, and my girlfriend Laura Goetschalckx. I also want to thank my unofficial family of the Sanderus co-housing group who supported and respected my long working hours despite my absence on several social activities. Especially Pieter Meeussen made a significant contribution by reviewing every chapter from a critical layman perspective and by finetuning the layout of my thesis.

Abbreviations

2D	Two-dimensional
3D	Three-dimensional
CT	Computer tomography
DFO	Distal femoral osteotomy
DICOM	Digital Imaging and Communications in Medicine
DLO	Double-level osteotomy
ESSKA	European Society of Sports Traumatology, Knee Surgery and Arthroscopy
FAVA	Femoral anteversion angle
FLSR	Full-leg standing radiograph
HNC	Healthy neutral cohort
HTO	High tibial osteotomy
HU	Hounsfield unit
JLCA	Joint line convergence angle
K-L	Kellgren and Lawrence classification
LDFA	Lateral distal femoral angle
LTS	Lateral tibial spine
mm	Millimetre
MKOA	Medial knee osteoarthritis
MOWHTO	Medial opening-wedge high tibial osteotomy
MPTA	Medial proximal tibial angle
MRI	Magnetic resonance imaging
mTFA	Mechanical tibiofemoral angle
OA	Osteoarthritis
OR	Operating room
PSI	Patient-specific instrumentation
STL	Standard triangle language
SVC	Symptomatic varus cohort

TEA	Trans-epicondylar axis
TEVA	Tibial external version angle
WBL	Weight-bearing line

Appendix

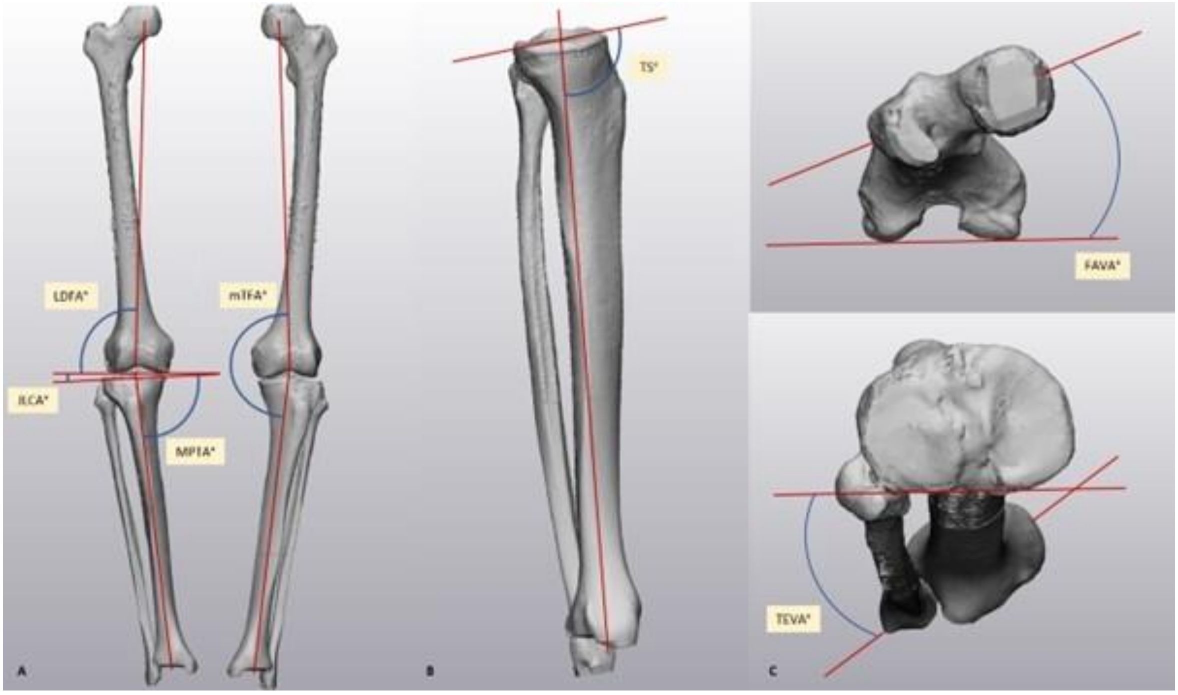


Illustration of relevant angles around the knee joint in the coronal plane (A), the sagittal plane (B) and the axial plane (C). LDFA, lateral distal femoral angle; MPTA, medial proximal tibial angle; JLCA, joint line convergence angle; mTFA, mechanical tibiofemoral angle; TS, tibial slope; FAVA, femoral anteversion angle; TEVA, tibial eversion angle.

Publications

Preceding PhD period

- Van den Bempt M, **Van Genechten W**, Claes T, Claes S (2016) How accurately does high tibial osteotomy correct the mechanical axis of an arthritic varus knee? A systematic review. Knee Elsevier B.V. 23(6):925–935
- **Van Genechten W**, Van Tilborg W, Van Den Bempt M, Van Haver A, Verdonk P (2020) Feasibility and 3D Planning of a Novel Patient-Specific Instrumentation Technique in Medial Opening-Wedge High Tibial Osteotomy. J Knee Surg 34(14):1560–1569

During PhD period – topic related

- **Van Genechten W**, Van den Bempt M, Van Tilborg W, Bartholomeeusen S, Van Den Bogaert G, Claes T, Claes S (2020) Structural allograft impaction enables fast rehabilitation in opening-wedge high tibial osteotomy: a consecutive case series with one year follow-up. Knee Surg Sports Traumatol Arthrosc 28(12):3747–3757
- **Van Genechten, W.**, Van Haver, A., Bartholomeeusen, S. *et al.* Impacted bone allograft personalised by a novel 3D printed customization kit produces high surgical accuracy in medial opening wedge high tibial osteotomy: a pilot study. *J EXP ORTOP* **10**, 24 (2023).
- **Van Genechten W**, Mestach G, Vanneste Y, Van Haver A, Michielsen J, Verdonk P, Claes S (2023) The position of the lateral tibial spine and the implications of high tibial ostoeotomy planning. Acta Orthop Belg, 89(2) (published online 12/08/2023).
- **Van Genechten, W**., van Haver, A., Verdonk, P. (2022). Patient-Specific Instrumentation and 3-D Osteotomy. In: Nakamura, N., Marx, R.G., Musahl, V., Getgood, A., Sherman, S.L., Verdonk, P. (eds) Advances in Knee Ligament and Knee Preservation Surgery. Springer, Cham.

During PhD period – not topic related

- **Van Genechten W**, De Cock L, Sys J, van den Broek M (2023) A novel patient-specific 3D printed guide for accurate femoral derotation osteotomies: a case report. Annals of Translational Medicine 11(6):268
- **Van Genechten W**, Hevesi M, Olson N, Carstens M, Krych AJ, Verdonk P, van Wijnen AJ, Saris D (2021) Anterior cruciate ligament graft healing by peptide-based vascular endothelial growth factor and bone morphogenetic protein recruitment. J Cartil Jt Preserv Elsevier B.V. 1(4):100030
- **Van Genechten W**, Verdonk P, Krych AJ, Saris DBF (2020) Biologic Adjuvants in Meniscus Repair: A Review of Current Translational and Clinical Evidence. Operative Techniques in Sports Medicine Elsevier Inc. 28(3):150758
- **Van Genechten W**, Vuylsteke K, Martinez PR, Swinnen L, Sas K, Verdonk P (2021) Autologous micro-fragmented adipose tissue (Mfat) to treat symptomatic knee osteoarthritis: Early outcomes of a consecutive case series. Journal of Clinical Medicine 10(11)
- **Van Genechten W**, Vuylsteke K, Struijk C, Swinnen L, Verdonk P (2021) Joint Surface Lesions in the Knee Treated with an Acellular Aragonite-Based Scaffold: A 3-Year Follow-Up Case Series. Cartilage 13(1_suppl):1217S-1227S
- **Van Genechten W**, Vuylsteke K, Swinnen L, Martinez PR, Verdonk P (2021) Autologous protein solution as selective treatment for advanced patellofemoral osteoarthritis in the middle-aged female patient: 54% response rate at 1 year follow-up. Knee Surg Sports Traumatol Arthrosc Springer Berlin Heidelberg 29(3):988–997
- Hevesi M, Crispim JF, Paggi CA, Dudakovic A, **Van Genechten W**, Hewett T, Kakar S, Krych AJ, Van Wijnen AJ, Saris DBF (2019) A Versatile Protocol for Studying Anterior Cruciate Ligament Reconstruction in a Rabbit Model. Tissue Engineering – Part C: Methods 25(4):191–196
- Hevesi M, **Van Genechten W**, Krych AJ, Saris DBF (2021) The Sound of Cartilage Repair: The Importance of Using Pitch and Volume Cues in Cartilage Restoration Surgery. Arthroscopy Techniques Arthroscopy Association of North America 10(9):e2049–e2052
- Struijk C, **Van Genechten W**, Verdonk P, Krych AJ, Dietz AB, van Wijnen AJ, Saris DBF (2022) Human meniscus allograft augmentation by allogeneic mesenchymal stromal/stem cell injections. Journal of Orthopaedic Research 40(3):712–726