Medial Opening Wedge High Tibial Osteotomy for the Treatment of Medial Unicompartmental Knee Osteoarthritis: a state-of-the-art review

Jonathan Palmer¹
Alan Getgood²
Phillip Lobenhoffer³
Ryuichi Nakamura⁴
Paul Monk ¹,⁵

¹ Unisports Orthopaedics, Auckland, New Zealand
² Fowler Kennedy Sport Medicine Clinic, University of Western Ontario, London, Ontario, Canada
³ Gelenkchirurgie Orthopädie Hannover (go:h), Hannover, Germany
⁴ Department of Orthopaedic Surgery, Harue Hospital, Sakai, Japan.
⁵ Department of Trauma and Orthopaedics, Auckland City Hospital, Auckland, New Zealand

Corresponding Author
Paul Monk: apmonk@gmail.com
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Abstract

Medial unicompartmental knee osteoarthritis is a common condition that is frequently associated with significant pain and dysfunction. Medial opening wedge high tibial osteotomy (MOWHTO) offers a unique opportunity to preserve the knee joint and potentially alter the course of the degenerative process. Recent advances in this field of surgery have enabled surgeons to perform a MOWHTO in a safe, reliable, and reproducible manner.

This state-of-the-art review highlights the most important advances in the field of medial opening wedge high tibial osteotomy. Key concepts related to patient selection, pre-operative planning, surgical accuracy, and patient outcome are considered. The importance of an individualised approach is emphasised and its influence on the future direction of the procedure is discussed.
Introduction

Osteoarthritis (OA) of the knee is common, with a worldwide prevalence estimated to be 22.9% in those over the age of 40yrs old[1]. Medial compartment OA is the most frequent pattern of tibiofemoral OA seen and it arises in isolation or in combination with patellofemoral joint OA in up to 27% and 23% of cases respectively[2]. Reliable surgical interventions for established OA of the knee are limited to joint replacement and re-alignment procedures in the form of osteotomy. The latter offers a unique opportunity to preserve the knee joint and potentially alter the course of the degenerative process.

Osteotomy surgery to treat unicompartmental knee OA (UKOA) is not a new concept. Through his work at the Mayo Clinic, Coventry popularised a lateral-closing wedge high tibial osteotomy to treat severe degenerative disease of the medial compartment[3]. The objective was to transfer load away from the compartment that is failing and shift it towards the compartment that had little or no pathology. Securing his closing wedge osteotomy with a staple, he achieved good outcomes with 75% survival at 10yrs[4] and the procedure was widely adopted. However, its popularity was short-lived, and the subsequent success of arthroplasty surgery led to the role of osteotomy becoming less well-defined, and its widespread use steadily declined[5,6].

The modern era of orthopaedics has seen a dramatic evolution in almost every facet of osteotomy surgery. A medial opening wedge high tibial osteotomy (MOWHTO) secured with a low profile high tensile strength plate can be used to achieve an accurate correction with high rates of union and reliable outcomes[7]. It is no longer a niche procedure confined to specialist centres but a viable treatment option with reproducible results. This state-of-the-art review aims to provide an overview of the most important developments in MOWHTO surgery with an emphasis on an individualized surgical approach.

Epidemiology

Central to the principle of osteotomy surgery is the concept that alignment plays a pivotal role in the natural history of OA within the knee. Epidemiological studies have consistently demonstrated that malalignment is strongly associated with both incidence and progression of UKOA[8–10]. Varus alignment is associated with progression of OA in the medial compartment and valgus alignment leads to progression in the lateral compartment.
Many pathological processes are attributed to lower limb deformity. Any pathology that causes interruption of the growth plate in youth can lead to progressive malalignment e.g. infection, trauma or tumour. Metabolic bone disorders (e.g. vitamin D deficiency (rickets)) can also lead to lower limb deformity in the skeletally immature.

It is important to note, however, that malalignment does not necessarily equate to pathology. The term ‘constitutional varus’ has been used to describe healthy individuals with an underlying varus phenotype and no apparent degenerative disease[11]. A description which accounts for up to 32% of males and 17% of females in European populations [11] and is even more common amongst Indian (34%) and Korean (35%) populations[12] whilst in Japan, ‘constitutional varus’ is equally common in males and females (35.8% and 35.3%, respectively) [13]. This tendency towards varus alignment goes some way to explaining the higher proportion of medial compartment OA seen in the general population.

The exact pathogenesis of ‘constitutional varus’ is not fully understood. A possible aetiology is increased sporting activity leading to disruption of the physeal growth plate in youth[14]. However, an exact temporal relationship between sporting activity and the onset of varus alignment is yet to be established. A similar aetiology for the development of CAM deformity in the hip has been postulated[15,16] and there is some evidence to support a higher prevalence of CAM deformity in patients with proximal tibia vara[17].

More recently a detailed description of coronal alignment has demonstrated considerable variation in proximal tibial and distal femoral geometry in non-arthritic knees[18]. As such, labelling individuals as either neutral, valgus or varus may be an over-simplification which fails to recognize the varying contributions made by the distal femur and proximal tibia. These alignment phenotypes may have distinct prognostic implications with proximal tibial alignment being more strongly associated with structural progression in the varus knee[19]. It is not known how these varying phenotypes influence outcomes following osteotomy surgery.

In addition to ‘constitutional varus’, the concept of ‘meniscal hoop stress’ has received considerable attention due to its relationship with progressive OA[20]. Among the various types of meniscal disruptions, medial meniscus posterior root tear (MMPRT) is common among Asian populations who sit on the floor in deep knee flexion[21,22]. In Japan, over 80% of MMPRT cases occur in women and onset age is approximately 60 years[23,24]. Not only is the prevalence of ‘constitutional varus’ in Japanese women twice that of European women[13], but knee OA in Japan is also 1.5 times more prevalent among women than men according to a large population-based cohort study[25]. Accordingly, in certain Asian populations, the
mean age of patients undergoing MOWHTO is over 60 years and more than 80% are women[26,27]. In contrast, in Europe, the majority of MOWHTO procedures are performed in those aged 40 to 50-years and less than 50% are performed in women[28,29]. Consequently, the aetiology and epidemiology of knee OA in Asia may differ from those in Europe. As MMPRT is considered a critical event in the acceleration of knee OA, repair combined with MOWHTO[30] is increasingly applied to medial OA in Asian countries. However, the efficacy of the combined surgery is controversial and future long-term outcome studies are required [31].

**Clinical assessment and physical examination**

The primary complaint of a patient with medial UKOA is pain localised to the medial joint line and will inevitably lead to a loss or reduction in function. Other common symptoms include stiffness, joint instability, reduced movement, crepitus and pain-related psychological distress[32]. Laterally based knee pain should be carefully assessed. Stretch pain from the lateral collateral ligament seen in marked varus deformity or in patients with a varus thrust must be distinguished from intra-articular pain generators such as a torn lateral meniscus or chondromalacia. The former maybe improved by an osteotomy whilst the latter will rapidly deteriorate once load bearing is transferred to the lateral compartment. A valgus producing medial unloader brace can be a useful tool to help differentiate between the two. Pain relief from the use of the brace is a very helpful indication for patient and clinician as to the potential positive treatment effect of the osteotomy.

There is no strict duration that a patient should have symptoms for before being considered appropriate for osteotomy surgery. It is, however, important to inform patients that OA progresses slowly. A patient with symptomatic mild to moderate OA is most likely to experience no change in terms of symptom or structural progression over a two-year period[19]. Non-operative interventions such as weight loss and low impact exercise should be recommended in the first instance[33]. Again, a brace can be a useful adjunct. However, many patients can find them uncomfortable and difficult to wear during work or sport. It is vital to make patients aware that an osteotomy for medial UKOA is not a quick fix and requires significant commitment from the patient in terms of post-op recovery and rehabilitation.

Traditionally, osteotomy surgery was reserved to those patients with grade 4, ‘bone-on-bone’ osteoarthritis[34]. However, those presenting with severe symptoms and only early radiographic changes should not be ignored. Patients with early to moderate OA often have symptom profiles that are as severe as those with end-stage disease[35]. Furthermore, realignment surgery in younger patients with less severe
disease has been demonstrated to improve survivorship of MOWHTO[36]. For the early diagnosis of knee OA, it is crucial to pay attention to signs of MMPRT, which in certain populations is considered the ‘switch’ for progressive knee OA.

Once the symptom profile of a patient has been established it is important to consider the patients age, smoking status, BMI and associated medical conditions as well as any significant previous trauma or surgery to the knee or lower limb. In addition, it is vital to gain an understanding of a patient’s current activity level and their expectations following surgical intervention. Whilst a return to sport is expected following osteotomy surgery the level of activity may not reach that achieved pre-pathology[37] and patients should be warned of this possibility.

Clinical examination requires an evaluation of alignment, gait, range of movement, ligamentous stability, and neurovascular status. Particular attention should be paid to asymmetric alignment and any dynamic component of gait such as a varus or hyperextension thrust. The correctability of varus deformity, the integrity of the lateral collateral ligament, the integrity of the cruciate ligaments and the presence of any fixed flexion deformity should all be determined.

To reflect the evolution of modern osteotomy surgery an expert panel from ISAKOS defined the criteria for a patient undergoing HTO for medial compartment OA to include younger patients and those with less severe disease [38]. These criteria are helpful but do not represent an exhaustive list. For example, the ideal osteotomy candidate is described as between 40 and 60yrs of age. However, clinical results from Asia have clearly shown, that excellent results of osteotomy can be expected in a much broader range of age groups including those patients in the 7th and 8th decade of their life[39]. As mentioned in the Epidemiology section above, differing knee OA aetiologies between Europe and Asia may influence the surgical indications in each region. Therefore, it is likely that indications for MOWHTO surgery will continue to evolve in line with developments in surgical technique.

**Diagnostic Imaging**

Detailed radiological assessment of all patients undergoing MOWHTO is essential to identify the extent of OA within the knee and establish the presence of any correctable deformity.

Pre-operative assessment should include weight bearing antero-posterior, lateral and skyline views. A Rosenberg view (45-degree flexion, weight bearing postero-anterior view) is more sensitive than weightbearing AP radiographs at determining joint space narrowing and should be requested routinely.
Where there is diagnostic uncertainty or concern that there may be significant pathology in the neighbouring compartments of the knee, an MRI scan should be obtained. MRI is a highly specific and sensitive investigation for pathology within the knee and can be used to identify structural changes consistent with OA before they are visible on plain radiographs[40].

Bilateral weightbearing long leg radiographs (LLR) are the accepted gold standard for assessing lower limb alignment in the coronal plane. To ensure the measurements obtained from these radiographs are consistent it is important to standardise the methods by which these radiographs are acquired. The presence of malrotation or fixed flexion can have a significant impact on the usability of an LLR[41], and it is important that these deformities are recognised prior to any surgery to reduce the chance of surgical error. The LLR should prioritise a true AP projection of the tibiofemoral joint rather than focussing on the position of the foot or patellae. This reflects the plane in which the osteotomy is performed and will also highlight any underlying malrotation that may be present. [42] (Figure 1).

Alternative imaging modalities are available. Computed Tomography (CT) is an attractive option as it enables a 3-dimensional assessment of the lower limb to be obtained. The Imperial Knee Protocol[43] was originally designed for the planning and assessment of knee arthroplasty surgery. It enables deformity to be assessed in the sagittal, axial and coronal planes whilst only exposing the patient to the radiation dose equivalent to a long leg radiograph[43]. It is not routinely used for osteotomy surgery as it has been found to be less accurate than conventional long leg radiographs in measuring alignment in the coronal plane [44]. Proprietary software (PREP Tech™, BodyCAD, Quebec) is now available that can co-register the 3-dimensional CT assessment along with the weight bearing long leg alignment view that may ultimately provide a more accurate planning tool.

**Deformity Analysis**

To plan the required osteotomy correction, surgeons should be familiar with the mechanical axes of the lower limb and the principles of deformity correction described by Paley[45].

The weightbearing axis (WBA) of the lower limb can be determined by drawing a straight line, termed the Miculicz line, from the centre of the femoral head to the centre of the ankle. In broad terms if this line passes through the medial compartment, then the limb is confirmed to be in varus and the patient is a potential candidate for MOWHTO. The point at which the WBA crosses the tibial plateau can be expressed as a percentage of the medial to lateral tibial plateau width.
In medial UKOA the varus deformity can relate to one of three different phenotypes which vary in severity based on the inherent tibiofemoral anatomy and associated soft tissue laxity [46]:

1. **Primary varus:** correlates with constitutional varus deformity in addition to any intra-articular varus caused by loss of medial joint space
2. **Double varus:** separation of the lateral joint space due to attenuation of lateral soft-tissue restraints in addition to primary varus
3. **Triple varus:** Chronic excessive tensile forces in the posterolateral ligament structures, or traumatic injury leading to a varus recurvatum deformity in addition to double and primary varus

Tibiofemoral geometry is best assessed by means of a bilateral LLR. The mechanical axis of the femur is denoted by a line from the centre of the femoral head to the centre of the knee and the mechanical axis of the tibia relates to a line connecting the centre of the knee to the centre of the ankle. Using these mechanical axes, the medial proximal tibial angle (MPTA), mechanical Lateral Distal Femoral angle (mLDFA), mechanical Lateral Proximal Femoral Angle (mLPFA) and mechanical Lateral Distal Tibial Angle (mLDTA) can be calculated (Figure 1). The site of deformity is identified by establishing which of these alignment variables falls outside the expected physiological range (85-90°)[45].

It is possible for surgical planning to reveal a patient with marked varus deformity and mechanical axes that are within normal physiological limits. As previously discussed, constitutional varus deformity is primarily determined by alignment of proximal tibia and distal femur[11]; however, in the presence of medial compartment osteoarthritis then intra-articular varus deformity will also contribute and so too may lateral ligament insufficiency.

Joint Line Congruence Angle (JLCA) (normal considered to be less than or equal to 2 degrees) will indicate either the presence of an intra-articular deformity caused by either medial compartment cartilage loss and/or increased lateral soft tissue laxity.

It is critical that lateral joint space opening is recognised prior to surgery. As the lateral joint space opening will be reduced following the osteotomy, failure to recognise its presence will potentially lead to a significant over-correction[47]. Lateral joint space opening of more than 5mm on a weightbearing long leg radiograph should be recognised as contributing to a severe varus deformity and accounted for[48]. A simple method
to account for this is to measure the difference in lateral joint space width compared to the contralateral limb and subtract this from your calculated opening gap measurement.

Broadly speaking, deformity analysis will identify two types of patients who are candidates for isolated MOWHTO. Those who have a varus proximal tibial deformity that is outside the expected physiological range (MPTA <85°) and those in whom a MOWHTO can be performed without introducing a proximal tibial deformity[49]. Over-correction of the proximal tibia should be avoided as it introduces an obliquity to the joint line and increases shear stresses in the medial compartment[50,51]. In such cases it may be necessary to perform a double level osteotomy to prevent over-correction of the proximal tibia and maintain joint line obliquity [52].

The addition of a distal femoral osteotomy has associated surgical morbidity. As such there is a compromise to be reached. Satisfactory clinical results have been reported if the MPTA is kept below 94°[53] a threshold that is supported by biomechanical studies and if breached leads to significant mediolateral tibiofemoral subluxation and alterations in tibiofemoral contact pressures[51]. A surgical plan that keeps the MPTA ≤93° should enable satisfactory outcomes to be achieved whilst protecting against the risk associated with inadvertent over-correction.

**Planning the correction**

Traditionally, surgeons have aimed to over-correct patients with medial UKOA into a valgus position to offload the failing medial compartment as much as possible. The so-called Fujisawa point equates to a weight-bearing axis of approximately 65-70% and has been widely adopted after early reports suggested that such a technique afforded improved symptoms and reduced cartilage degeneration[54]. Over-correction, however, leads to a significant distortion of the local anatomy and has led to some concern over the survivorship of any future arthroplasty surgery. Much of this concern is related to outcomes for arthroplasty following a closing wedge HTO which were reported as being significantly poorer than arthroplasty surgery in the native knee[55]. Whilst not all patients who undergo osteotomy will require a knee replacement procedure in the future it is important to consider this possibility and not introduce a deformity that might compromise the outcome of later arthroplasty.

Recently, an individualised approach to surgical correction has been advocated bringing the desired correction point closer to neutral depending on the severity of OA at baseline[56]. Patients with early
osteoarthritis are recommended to have a correction closer to neutral whilst those with more severe OA would be pushed further into the lateral compartment indicating the potential for an individualised approach. Once the desired correction point has been established the opening gap required to achieve this correction can be calculated. Two techniques that are commonly used to determine the required opening wedge were popularised by Miniaci[57] and Dugdale[47]. There are several user-friendly proprietary software packages incorporating these measurement algorithms and have excellent inter and intra-observer reliability[58]; providing a simulated osteotomy and the resultant mechanical angles. As such the introduction of any unwanted deformity (e.g MPTA >93deg) can be anticipated and the surgical plan adjusted. Furthermore, JLCA can be calculated and intra-articular corrections simulated to avoid over correction. Once the opening gap is determined an additional gap of 0.7-1mm should be added to account for the thickness of the saw blade. Failure to do so will lead to consistent under-correction of the lower limb.

General treatment concepts
MOWHTO has several advantages over the traditional closing wedge high tibial osteotomy (CWHTO). The approach requires minimal muscle stripping, there is no leg length shortening and once the osteotomy is performed it can be fine-tuned and adjusted mid-procedure. The addition of a biplanar component to the osteotomy is advantageous and recommended as routine practice (Figure 2). This increases the surface area for bony union, provides rotational stability and acts as a buttress against sagittal tilting of the osteotomy in extension[7]. Angle stabilised locking plates offer a rigid, stable construct that allows early weight-bearing and reliable union at the osteotomy site without the need for bone graft in most cases[7]. These plates enable a much simpler surgical procedure without fibular osteotomy, unlike traditional CWHTO, in which fibular shortening must be performed to close the lateral cortex (Figure 3A and 3B). This is not necessary in MOWHTO due to the recommended position of the hinge point just proximal to the proximal tibiofibular joint (PTFJ). If the hinge for MOWHTO is set distal to the (PTFJ), the fibula would revolve around the hinge (Figure 3C) and necessitate a fibular osteotomy to prevent unintended fracture (Figure 3D). The proximal fragment can only be opened without shortening of the fibula if the hinge point is located above the PTFJ (Figure 3E and 3F). Maintaining the fibula integrity in this way is advantageous as it helps to maintain stability of the MOWHTO[59]. These basic structural characteristics of MOWHTO are essential to understand the pathogenesis of lateral hinge fracture (LHF) described in the next section.
Avoiding Complications

Hinge fractures

A common technical problem in MOWHTO is disruption of the lateral cortical hinge on the opposite side of the osteotomy. Three types of LHFs have been defined\(^{[60]}\) and validated\(^{[59]}\), essentially corresponding to the level to which the fracture extends. Hinge instability may cause intraoperative problems by translation or rotation of the two osteotomy fragments and secondary problems in osteotomy healing due to instability of the fixation. Corrections greater than 11-12mm have been associated with an increased risk of LHF\(^{[59]}\). The key to LHF prevention is identification of the optimal hinge position to protect against intraoperative fracture\(^{[61,62]}\). As shown in detail in Figure 4, placing the hinge just above the PTFJ is safest; a hinge which is lower, higher, or shallower may increase the risk of an unstable type II or III LHF\(^{[62]}\). In larger corrections the use of angular stable locking plates reduces much of the instability of fixation that may occur. Additional technical steps that can help prevent a hinge fracture from occurring; the insertion of a K-wire at the opposite cortex bridging the planned osteotomy site to avoid overcutting and hinge disruption\(^{[63]}\) and a supplemental lag screw directed from anterolateral to posteromedial will increase the stability of the hinge significantly and enhance healing\(^{[64]}\). Regardless of the presence or absence of LHF, in cases with a large correction, plate position is critical for preventing implant related complications of screw breakage, correction loss, and increased posterior tibial slope. Care is needed to ensure medial plate installation to maximise stability of the proximal fragment\(^{[65,66]}\) and avoid excessive anteromedial installation of the plate that may generate repetitive posterior pendular micro-motion of the proximal fragment\(^{[65]}\).

Vascular Injury

Surgeons who perform osteotomies around the knee should be aware of the risk of vascular injuries\(^{[67,68]}\). Adequate protection is mandatory when the saw cuts are performed, and it is important to recognise that not all oscillating saw blades perform in the same manner. Saw blades with double row teeth are widely used for arthroplasty but are not suitable for osteotomies around the knee. Specific blades with single teeth rows and rounded edges have been developed to avoid the risk of tissues being pulled into the saw by the edge teeth. The vascular anatomy of the proximal tibia should also be appreciated. The popliteal artery trifurcates into the anterior tibial artery, the posterior tibial artery, and the peroneal artery in the region of the knee joint. Both popliteal artery and vein are located posterior to the popliteus muscle in most patients, thus separated...
from the HTO saw cut by this muscle, which is densely attached to the posterior flare of the proximal tibia[69,70].

There are two problems that a surgeon may encounter during HTO surgery. First, it is not easy to place a retractor anterior to the vascular structures as the retractor will easily glide to the posterior surface of the popliteal muscle and may even end posterior to the vessels, thus pressing them against the posterior tibia. Second, around 2% of patients have a high division of the popliteal artery which means that the trifurcation is high on the femur and the anterior tibial artery then is located anterior to the popliteus muscle directly on the periosteum of the proximal tibia[69,70]. In this case there is an extremely high risk of injuring this main vessel when performing the sawcut. The resulting arterial bleeding is significant and difficult to control.

The vascular anatomy in the region of the proximal tibia can be visualized in a standard MRI scan of the knee. Fat-suppressed scans in the sagittal and coronal plane will identity a patient with a high division of the popliteal artery[69] and we recommend an MRI scan be performed routinely to look for this vascular anomaly.

An appropriate retractor for the posterior tibia is mandatory when HTO is performed. We recommend placing this retractor anterior to the popliteus muscle directly on the periosteum of the tibia. A specific soft-tissue window has been developed for this step and a radiolucent retractor is available which gives optimum protection against injuries to the vascular structures during the osteotomy of the posterior tibia cortex[71].

**Surgical accuracy**

Successful MOWHTO is predicated on the ability of the surgeon to achieve a surgical correction that matches the pre-operative plan. To accomplish this, the hinge point and direction of the osteotomy must be consistent. Inadvertently changing either of these variables mid-procedure will invalidate the pre-operative plan and introduce error.

Intra-operative estimates using an alignment rod or diathermy cable to replicate the WBA have limited accuracy in the non-weightbearing limb and should not be used as definitive measurement tools but can be helpful as an adjunct to assessing alignment.

A variety of methods are available to measure the medial cortex opening, including a ruler, an osteotomy wedge measuring device and callipers[72]. The latter has been shown to have equivalent accuracy to computer navigation when measuring alignment in the coronal plane[72]. These techniques rely on setting the osteotomy gap at the posterior aspect of the medial tibial cortex and then estimating the height of the
anterior opening wedge. A smaller opening wedge anteriorly is required to offset the fact that the anterior cortex lies closer to the hinge point than the posterior cortex. If the anterior and posterior opening wedge heights are kept the same, then the tibial slope will be increased. In the case of a MOWHTO the anterior opening wedge height will often require 2/3rd of the opening wedge height at the posterior cortex[73].

The hinge axis has also recently garnered attention due to its impact on posterior tibial slope. Rotating the hinge axis externally, i.e making the hinge more posterolateral will tend to increase tibial slope and internally rotating the hinge axis has the opposite effect[74]. If posterior tibial slope maintenance is desired, then a neutral hinge position in relation to the anteroposterior axis is desired.

The evolution of novel 3D printed patient specific wedges and guides have the potential to enhance accuracy of planning and surgical execution. A patient-specific 3D printed wedge used as a temporary spacer in the osteotomy gap can be used to set the desired correction in both coronal and sagittal planes (Figure 5). This requires 3-dimensional planning in the form of CT or MRI based anatomical landmark acquisition to generate a customised spacer which is designed to fit in the planned osteotomy and is manufactured to conform only to that patient’s proximal tibia. This conforming surface provides the surgeon a way of ensuring the wedge is in the correct place when performing the operation.

Patient-specific cutting guides using three-dimensional planning have been used to execute MOWHTO for medial UKOA. By using the patient’s own anatomical landmarks, the cutting guides have the advantage of ensuring the planned osteotomy site, hinge point, hinge axis and opening gap are kept consistent with the surgical plan. They have been shown to be safe, reliable, and accurate[75] and may prove to be beneficial, particularly if more complex multiplanar corrections are required.

A key issue with surgical innovations which seek to improve the accuracy of osteotomy in three planes is that they are frequently assessed using 2-dimensional post-operative imaging. Plain film radiographs have inherent limitations in terms of reproducibility and as such they may not adequately reflect the advances being made. This limitation is overcome by using weight bearing HKA alignment radiographs co-registered with 3D CT scans post-operatively.

**Outcomes**

Complication rates for MOWHTO are low. In a series of 533 patients who underwent MOWHTO using the Tomofix™ (Depuy Synthes) locking plate system only 6% of patients experienced a complication; delayed union (1.5%), infection (2%), haematoma (2.7%) and thromboembolism (0.2%)[28].
A series of 126 patients corrected to near neutral with MOWHTO demonstrated clinically significant improvements in Knee Injury and Osteoarthritis Outcome Scores (KOOS) across all domains in most patients at 2 years[29]. This improvement, however, takes time to be realised with the greatest clinical gains being made 12 months after surgery[76]. Similar improvements are seen in older age groups as evidenced by a prospective multi-centre cohort study from Japan in which the mean patient age was 15 years older than in the aforementioned studies from North America and Europe[26].

In most cases following osteotomy surgery patients will return to sport[77], however, the level of sporting activity achieved may not be the same level they enjoyed pre-surgery[37,76,78]. This is particularly relevant to elite athletes. Whilst there are examples in the literature of people returning to professional sporting activities these are the exception rather than the rule.

Survivorship of MOWHTO is usually reported in the context of conversion to total knee replacement. A series of 556 MOWHTO performed for medial compartment OA showed 79% survivorship at 10 years and identified baseline severity of OA as the strongest positive predictor for knee replacement[36]. Where knee replacement surgery follows osteotomy, it does not appear to affect its long-term survival[79].

Surgical accuracy in osteotomy surgery is not widely reported. Where accuracy is reported the degree of precision can vary widely with up to 10-74% of individuals obtaining a degree of correction that is outside the target range[80]. Reporting accuracy in osteotomy surgery is contingent on multiple factors including the measurement used, the planned correction and the acceptable range that this correction can fall in for the surgery to still be considered a success.

The effect of a biplanar MOWHTO on the patellofemoral joint remains unclear. Whilst the patella is lowered in relation to the proximal tibia after this procedure, it is not known what effect this has on subsequent patellofemoral joint degeneration and clinical outcome. Some second-look arthroscopy studies have observed patellofemoral joint degeneration 2 or more years after MOWHTO[81–84]; however, not all studies support this observation[85,86]. Furthermore, these degenerative changes when observed do not appear to compromise the clinical result[84]. In our opinion it is important to examine the patellofemoral joint closely prior to any proposed osteotomy. In the presence of patella baja, patellofemoral pain or if a large correction is planned then an inverse biplanar technique (Figure 2C) or CWHTO should be considered. Here the anterior osteotomy is directed inferiorly and exits the tibial tuberosity around 3 cm inferior to the horizontal cut[87]. This distal tuberosity osteotomy is then fixed with one or two bicortical small-fragment lag screws to eliminate the force created by the patella tendon. With this variation of the technique, the patella is not
distalised and the complication of patella baja is reduced compared to an osteotomy where the anterior limb exits proximal to the tibial tuberosity[88].

The main principle of biplanar MOWHTO to understand is that the pes anserinus and patellar tendon work as medial and anterior tension bands, respectively, which apply a compressive force to the coronal osteotomized plane[89] (Figure 2A and 2B). Conversely, in the distal tuberosity osteotomy, the patellar tendon provides a traction force to the coronal osteotomized plane (Figure 2C), which may increase the complication rate[90]. Therefore, even when the tuberosity is fixed with a screw, special care is required to avoid eccentric quadriceps muscle contraction before bone union.

**Future perspectives**

There have been many significant advances in MOWHTO surgery that have led to a steady increase in its popularity. As discussed, there is a move away from a single surgical correction point being suitable for all and a move towards an approach that is tailored towards the needs of the individual. It is likely that future developments in osteotomy surgery will reflect this need for an individualized approach. When advocating for a personalized approach to osteotomy surgery, the planned correction will vary based on the individual surgical plan and acceptable range around this desired correction point must then be calculated.

A key part of individualizing the approach to osteotomy surgery is to understand the effect that altering a person’s alignment will have on the mechanics of their knee. Ultimately, a compromise must be reached between off-loading the medial compartment sufficiently to gain effective pain relief whilst not overloading the lateral compartment too much to cause symptoms or deformity. This ‘sweet spot’ is hard to determine using conventional imaging.

Finite element modelling offers a more dynamic assessment of knee mechanics and can give a unique insight into how the contact pressures within the knee are at baseline and how they vary as a simulated osteotomy is introduced. The process involves co-registering a segmented MRI scan of the lower limb with a weightbearing long leg radiograph (Figure 6). This produces an anatomically detailed and weight-bearing model of the lower limb. A rigid body analysis is then performed where the proximal tibia is pushed into the distal femur through a vector force from the estimated ankle joint centre to the estimated hip joint centre with a magnitude adjusted to the patient’s body weight.

The result of this simulation is to provide estimates of the pressure on the tibial cartilage in the medial and lateral compartment (Figures 7a & 7b). The pressures between the two compartments are expressed
graphically and a safe correction zone can be estimated (Figure 7a). Alternatively, pressure distribution can be illustrated using topographical heatmaps, enabling the surgeon to visualise peak contact pressures on the tibial plateau as the weightbearing axis moves from varus to valgus (Figure 7b).

Continued evolution in technology will also see improvements in patient specific guides and implants, enhancing preoperative planning and surgical correction accuracy. Multiplanar deformity correction and balancing of soft tissues may also benefit from technological advancements in robotics. The costs associated with the implementation of these new technologies will need to be balanced against the clinical effectiveness, requiring more high-level clinical evidence to support their use.

**Conclusion**

MOWHTO surgery has evolved rapidly. Innovations in this field have led to the procedure becoming safe, reliable, and reproducible. Future developments should focus on tailoring the procedure to the individual needs of the patient. A one size fits all policy such as correcting all comers to the *Fujisawa point* [54] is no longer appropriate and may lead to a significant over-correction in most cases. These patient-specific approaches are an extension of a significant body of evidence supporting the use of a MOWHTO secured with a fixed angle locking plate. Whilst some of the innovations remain labour intensive and are not widely available, it is hoped that future developments will make access to such technology more widely available. In the meantime, the concept of an individualized approach is still valid and surgeons should work towards tailoring their osteotomy to the individual.

**Contributors**

All the authors (GV, FC, KA and PDH) have made the following contributions: substantial contributions to the conception and structure of the work; including the acquisition, analysis and interpretation of data. In addition all authors have critically appraised and revised the final version to be published and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

**Funding**
The authors have not received any specific grant for this research from any funding agency in the public, commercial or not-for-profit sectors.

Patient consent for publication
Not required

Competing interests
JP, PL, AG declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. PM has no financial disclosures to declare but does hold intellectual property rights for an osteotomy system. RN has a consultancy with Olympus Terumo Biomaterials and AUSPICIOUS.
Box 1 Key articles

Box 2 Validated outcome measures and classifications

Symptoms
- Knee injury and Osteoarthritis Outcome Score (KOOS)
- Oxford Knee Score (OKS)
- Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)
- Japanese Orthopaedic Association score for osteoarthritic knees
- Tegner activity scale
- Lysholm knee scale
- Short form 12 or Short form 36
- EQ-5D-3L
- Visual analogue scale

Structure
- Medial joint space narrowing

Surgical Outcomes
- Union at osteotomy site
- Conversion to TKR
- Surgical failure/revision rate
Box 3 Epidemiological concepts

- Varus alignment is associated with incidence and progression of medial compartment OA
- Varus alignment is not necessarily pathological and constitutional varus alignment is common in a healthy adult population
- Considerable variation exists in proximal tibial and distal femoral geometry in non-arthritic varus knees
- Varus deformity can relate to one of three different phenotypes:
  - Primary varus: correlates with constitutional varus deformity in addition to any intra-articular varus caused by loss of medial joint space
  - Double varus: separation of the lateral joint space due to attenuation of lateral soft-tissue restraints in addition to primary varus
  - Triple varus: Chronic excessive tensile forces in the posterolateral ligament structures, or traumatic injury leading to a varus recurvatum deformity in addition to double and primary varus
Box 4 Essential features of MOWHTO

- A MOWHTO has advantages over the traditional closing wedge osteotomy
  - minimal muscle stripping
  - no leg length shortening
  - the osteotomy can be fine-tuned and adjusted mid-procedure
- The addition of a biplanar component to the osteotomy is advantageous and recommended as routine practice
- Angle stabilised locking plates such as the Tomofix™ (Depuy Synthes) plate offer a rigid, stable construct that allows early weight-bearing and reliable union at the osteotomy site without the need for bone graft in most cases
- The vascular anatomy of a patient should be investigated using an MRI to look for a high division of the popliteal artery resulting in an anterior tibial artery anterior to popliteus. A radiolucent retractor should be placed between the posterior tibial cortex and popliteal artery when saw cuts are performed.
Box 5 Key issues for patient selection

- Age
- Sex
- Location of pain
- Patient expectation and activity level
- Associated ligament insufficiency
- Smoking status
- Location and grade of osteoarthritis within the knee
Box 6 Tips and Tricks for optimizing surgical accuracy in MOWHTO

- Proprietary software programmes that enable the surgeon to calculate the gap measurement and simulate the osteotomy in the coronal plane have excellent inter and intra-observer reliability.
- The hinge point and direction of the osteotomy must be consistent with the pre-operative plan. Inadvertently changing either of these variables mid-procedure will invalidate the pre-operative plan and introduce error.
- Lateral joint space opening should be recognised prior to surgery. Failure to recognise its contribution to varus alignment will potentially lead to a significant over-correction.
- Once the opening gap is determined an additional gap of 0.7-1mm should be added to account for the thickness of the saw blade.
- Gap measurements must be taken from the posterior cortex and the anterior gap needs to be reduced to offset the fact that the anterior cortex lies closer to the hinge point than the posterior cortex.
- Any hinge fracture must be recognised and corrected failure to do so will lead to an under-correction of the osteotomy as the lateral hinge opens.
- Intra-operative alignment estimates using an alignment rod or diathermy cable have limited accuracy in the non-weightbearing limb and should not be used as definitive measurement tools but can be helpful as an adjunct to assessing alignment.
Box 7 Major pitfalls of MOWHTO

- Bilateral weightbearing long leg radiographs (LLR) are the accepted gold standard for assessing lower limb alignment in the coronal plane. The presence of malrotation or fixed flexion can have a significant impact on the usability of an LLR.
- A common technical problem in MOWHTO is disruption of the lateral cortical hinge on the opposite side of the osteotomy. The key to preventing this complication is accurate placement of the lateral hinge just above the proximal tibiofibular joint.
- Surgeons who perform osteotomies around the knee should be aware of the risk of vascular injuries. The vascular anatomy in the region of the proximal tibia can be visualized in a standard MRI scan of the knee and we recommend an MRI scan be performed routinely to look for vascular anomalies such as a high division of the popliteal artery.
- Successful MOWHTO is predicated on the ability of the surgeon to achieve a surgical correction that matches the pre-operative plan. To accomplish this, the hinge point and direction of the osteotomy must be consistent. Inadvertently changing either of these variables mid-procedure will invalidate the pre-operative plan and introduce error.
- The patellofemoral joint must be examined closely prior to any proposed osteotomy. In the presence of patella baja, patellofemoral pain or if a large correction is planned then an inverse biplanar technique or close wedge high tibial osteotomy should be considered.
Box 8 Future perspectives

- The future of MOWHTO should focus on an individualized approach accounting for the patient’s own anatomy and severity of osteoarthritis
- A customised spacer using three-dimensional imaging and anatomical landmarks enable the surgeon to set the MOWHTO in both the coronal and sagittal plane
- Patient specific cutting guides are a novel development that enable the osteotomy site, hinge point and gap measurement to be kept consistent with the surgical plan
- Finite element modelling offers a more dynamic assessment of knee mechanics and can give a unique insight into how the contact pressures within the knee are at baseline and how they vary as a simulated osteotomy is introduced
Figure Legends

Figure 1.

A long leg radiograph of the left leg. A true AP projection of the tibiofemoral joint has been achieved. The Miculicz line from the centre of the femoral head to the centre of the ankle is shown. Measurement variables in the coronal plane are shown; mLPFA, mLDFA, mMPTA, mLDTA. Measurements obtained using TraumaCad® (Brainlab, Westchester, USA).
Figure 2. Stability of medial opening wedge high tibial osteotomy (MOWHTO) and distal tuberosity osteotomy (DTO).

A. In the pes-preserving MOWHTO, the traction force of the pes anserinus (red arrow) can be separated into two component forces: posterior (blue arrow) and proximal (green arrow). The posterior component places a compressive force on the osteotomy site.

B. In MOWHTO, traction force of the patellar tendon during knee flexion can be converted to a compressive force on the osteotomy site.

C. In DTO, traction force of the patellar tendon during knee flexion can tear off the tuberosity.
**Figure 3.** Reasons why fibular osteotomy is unnecessary in medial opening wedge high tibial osteotomy (MOWHTO).

A. In the traditional closed wedge high tibial osteotomy, the wedge is removed from the lateral side.

B. Fibular shortening (green arrow) is necessary to close the lateral wedge.

C. MOWHTO with a hinge point distal to the proximal tibiofibular joint (PTFJ).

D. When the medial cortex is opened, the fibula revolves around the hinge because it and the proximal tibial fragment are connected by the PTFJ. Theoretically, fibular shortening (green arrow) is therefore required.

E. MOWHTO with a hinge point immediately proximal to the PTFJ.

F. The proximal fragment revolves around the hinge point without shortening of the fibula.
Figure 4. The relationship between the hinge point and the type of lateral hinge fracture (LHF).

A. An appropriate hinge just above the proximal tibiofibular joint (PTFJ) minimizes the possibility of LHF. The hinge is close to the lateral cortex around the PTFJ, which has dense connective tissue (yellow area).

B. When LHF occurs, there is a high likelihood it is a stable type I fracture. These fractures involve an extension of the osteotomy line and are just proximal to or within the PTFJ.

C. A hinge point lower than the PTFJ and closer to the lateral cortex readily induces a lateral cortical fracture because of the poor elasticity of the cortex.

D. If the fibular length is kept without a fibular osteotomy, medial opening induces lateral impaction of the fracture site, causing a displaced type II LHF in which the fracture line reaches the distal portion of the PTFJ.

E. In the medial opening wedge high tibial osteotomy (MOWHTO) with a high hinge adjacent to the tibial joint surface, the fracture line tends to run towards the lateral tibial plateau.

F. The proximal fragment revolves around the hinge point at the joint surface (type III LHF).

G. MOWHTO with a shallow hinge—as the lateral portion of the hinge is thick and has dense connective tissue, the hinge point easily escapes to the joint surface.

H. A type III fracture with a shallow hinge has a larger gap between the lateral and the medial part of the fracture than a type III fracture with a high hinge. The more ‘floating’ proximal part may cause severe instability after MOWHTO.
Figure 5
The subject specific 3D spacer is designed in computer aided design software, Fusion 360 (Fusion 360 2013, Autodesk Inc). The tibia mesh is imported and edited to reflect the planned osteotomy cut. The spacer is then designed to fit in the gap created and a patient specific section of the wedge conforming to that patient’s proximal tibia is generated.
Figure 6

Computer-aided design (CAD) models (c) of the lower limb are developed by co-registering a long leg radiograph (a) to a segmented MRI scan (b). This is currently completed manually using CloudCompare (CloudCompare 2003, EDF R&D).
Figure 7
A finite element mesh subdivides the CAD model and is then used to generate a mechanical model of the knee simulating the pressure distribution between the medial and lateral compartments (FEBio Software 2007, MRL and MBL). The results can be displayed graphically and a safe correction zone can be determined (Figure 7a). Alternatively the pressure distribution can be illustrated using a topographical heatmap (Figure 7b). This enables the surgeon to visualise peak contact pressures on the tibial plateau as the weightbearing axis moves from varus to valgus.


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