

## Open wedge tibial osteotomies influence on axial rotation and tibial slope

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**Abstract** Inaccurate coronal plane and inadvertent sagittal plane realignment is a common problem after high tibial osteotomies (HTO). While the effects of an HTO on the coronal have been studied extensively, the influence on axial rotation has not been described in detail. The current study examines the effect of HTO on tibial rotation in the axial plane as determined by computed tomography. We hypothesized that high tibial osteotomies have an effect on tibial rotation in the axial plane and that depending on the predefined osteosynthetic implant used, a corresponding change in the tibial slope would occur. HTOs with a tapered 12.5 mm Puddu plate were performed on 13 limbs under computer-navigated control. All limbs were CT scanned before and after the HTO. Using specific software, the CT data was converted into 3D computer models and the following parameters compared: (a) varus-valgus leg alignment; (b) tibial axial rotation; (c) tibial slope (including determination of lateral and medial tibial slope, (d) leg length including determination of the tibial length. Results revealed: (a) a varus-valgus alignment increase of  $11 \pm 4.7^\circ$  ( $P < 0.005$ ); (b) an axial tibial rotation of  $2.7 \pm 6.3^\circ$  ( $P < 0.075$ ) occurred with external rotation in 10 out of 13 limbs ( $12^\circ$  max external;  $9.5^\circ$  max internal); (c) tibial slope revealed differences of  $4.2 \pm 5.9^\circ$  ( $P < 0.025$ ); (d) the tibial length increased after HTO by  $7.1 \pm 3.7$  mm ( $P < 0.005$ ), while there was no significant

change in overall leg length. In summary, tibial rotation does occur in high tibial osteotomies with though the degree of external rotation in this study tended not to be statistically significant. Tapered implants do not guarantee maintenance of a steady tibial slope, while tibial length changes significantly when HTOs are performed. The combined use of CT and 3D software measurement techniques is reproducible and can be used without any further invasive fixation devices.

**Keywords** Osteotomy · Malalignment · Navigation · Axial rotation · Leg alignment · CT reconstruction

### Introduction

Open wedge high tibial osteotomies (HTO) transfer the mechanical load from an arthritic medial compartment to the lateral knee compartment to help correct coronal leg alignment, and relieve pain. This procedure has become increasingly popular, particularly with advancements in mechanical, radiographic and recent navigation techniques over the past few decades. Relatively good mid- and short-term results have been shown for this technique [8, 13].

Traditional intra-operative measurement techniques have frequently shown both intra-observer variability and low reproducibility, even when considering just the coronal plane alone [10, 11, 17]. Consequently, conventional HTO techniques have demonstrated quite a high variability with regard to postoperative alignment. This may be due to imprecise pre-operative planning, inaccurate wedge cuts and poor control of intra-operative realignment [9]. In addition, multi-planar deformity may be present and can be either under- or over-corrected during the procedure. Therefore, inaccurate coronal plane and inadvertent sagittal

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plane realignment is a common problem after high tibial osteotomies. Recently, image-free computer-assisted techniques were shown to be capable of accurate measurement of leg alignment intra-operatively with especially high precision in the coronal plane [11, 17, 23, 25].

In addition to potential coronal alignment corrections, HTO corrections can also be used to alter the tibial slope [14]. This will influence the tension of both cruciate ligaments depending on whether the slope is increased or decreased [6, 7, 22]. Those studies have confirmed that increasing the slope increases anterior translation and subluxation of the tibia. Consequently increasing the slope reduces the tibial sag in a PCL deficient knee, while decreasing the slope reduces the anterior translation, as desired in patients with an elongated ACL.

Another study by Hernigou confirmed that varying the placement of a fixation device e.g. a plate or use of bone graft, either more anteriorly or posteriorly will also influence the tibial slope [12]. 3D geometric analysis of the proximal tibia has shown that the anterior gap angle of the osteotomy along the anterior-medial tibial cortex influences the tibial slope. It also simultaneously affects the tibia coronal plane by influencing the valgus correction [19]. Noyes et al. found that the anterior osteotomy gap should be ideally half that of the postero-medial gap to maintain the normal sagittal slope. They also emphasized that for every millimeter of gap-error at the level of the tibial tubercle there may be a resultant 2° change in the tibial slope. Despite the knowledge about slope affection by the osteotomy itself, various implants are currently available, including a purporting angle, in order to ensure the predefined tibial slope.

Many studies have examined the effects of an HTO on the coronal and sagittal alignment of the tibia but to date there are only two studies, to the authors' knowledge, looking at the axial rotational influence of the osteotomy on the tibial alignment. Magyar et al. [18] looked at the axial tibial rotation comparing closed wedge high tibial osteotomies to osteotomy by hemicallostasis. They found higher axial tibial rotation with the hemicallostasis technique. However, they did not include an acute open wedge osteotomy technique with the use of an osteosynthetic plate. A second study conducted in animals for a veterinary publication showed that the tibial osteotomy angle with a subsequent osteotomy reduction did influence tibial rotation [24]. The osteotomies performed demonstrated a significant change in coronal angulation and rotation of the tibia and were influenced by the osteotomies performed.

Changes in the axial leg alignment may affect knee kinematics, contact forces and the overall gait [15, 20]. Of note, lower limb rotation has been shown to cause significant measurement inaccuracies of the leg axis, with errors as high as 4° [16].

The current study examines the effect of HTO on tibial rotation in the axial plane as determined by computed tomography (CT). We hypothesized that high tibial osteotomies have an effect on tibial rotation in the axial plane. We also hypothesized that, depending on the pre-defined osteosynthetic implant used, a corresponding change of the tibial slope will occur.

## Materials and Methods

Eight fresh-frozen cadaveric hemi-torsos including pelvises and bilateral lower extremities (13 legs) were used. Two legs were unsuitable due to prior surgery, while a third was rejected because of limited bone quality. The cadavers had no history of prior surgery, injury or arthritic changes affecting the lower extremities.

### Experimental protocol

To ensure consistent alignment during pre-operative, postoperative and CT measurements, self-expanding foam molds were created to hold each leg at 0° of femoral-tibial rotation and full extension with a consistent gravitational force on the knee during data acquisition.

Reference arrays for navigated determination of the dynamic leg alignment were applied (Fig. 1). Two surgeons performed navigated HTOs on each of the specimens and recorded pre-operative and postoperative alignment with a conventional navigation system. (BrainLAB, Feldkirchen, Germany). All osteotomies were fixated using a 12.5 mm tapered Puudu plate placed centrally in the osteotomy (Arthrex, Naples, FL, USA), with two cortical screws and two cancellous screws (Fig. 2). We ensured



**Fig. 1** Reference arrays for the navigated measurements of the leg alignment during the high tibial osteotomy were attached at the femur and tibial wise above and below the osteotomy



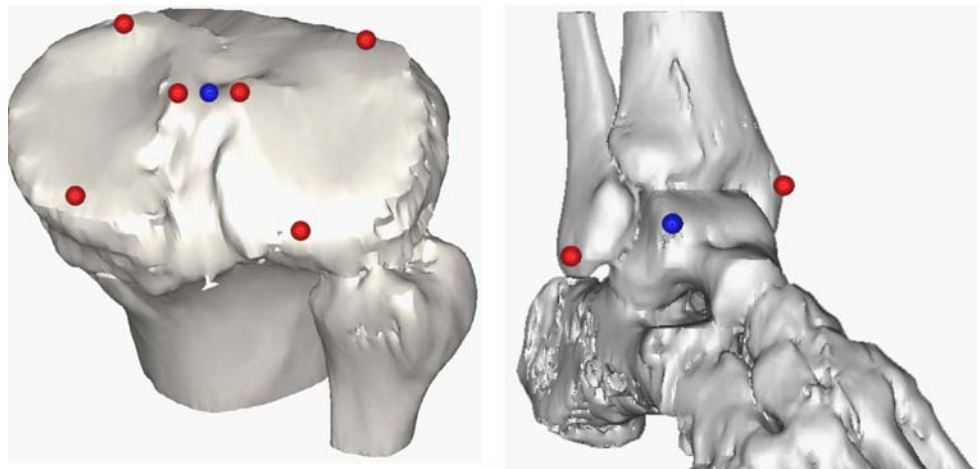
**Fig. 2** 12.5 mm tapered Puddu plates were used in all case with ensured reproducible placements and fixed with cortical and cancellous screws

reproducible plate placement by using defined distances from the tibial tubercle, before plate fixation. In three cases, cement was packed around the plate in the wedge to ensure stable fixation and allowed to harden before further manipulation. The parameters recorded via the navigation system were varus-valgus angle and change in posterior slope.

#### CT measurements

All limbs were CT-scanned using a Lightspeed VCT (GE Medical Systems, Buckinghamshire, UK) before and after HTO, with image slices taken 2.5 mm apart at three sites: hip, knee and ankle. The CT data was then converted into 3D computer models of the hip, knee and ankle using Mimics 10.11 software (Materialize, Leuven, Belgium) (Fig. 3). Landmark points were placed directly on the

**Fig. 3** The CT data before and after HTO was converted into 3D computer models of the hip, knee and ankle using Mimics 10.11 software, while landmark points were placed directly on the surface of the 3D models and verified by visual inspection of the CT slices



surface of the 3D models and verified by visual inspection of the CT slices.

Using a spherical-center tool, landmark center points of the femoral head and distal femoral condyles were calculated (Geomagic) (Fig. 4). This was performed in order to obtain values for femoral length and anteversion. From both types of models, the following parameters could be measured both pre- and postoperatively:

- Varus-valgus leg alignment
- Tibial axial rotation
- Tibial slope including determination of lateral and medial tibial slope
- Leg length including determination of femoral and tibial length.

The tibial slope measurements were defined by an angle between a line perpendicular to the mid-diaphysis of the tibia and the posterior inclination of the tibial plateau sites.

#### Statistical analysis

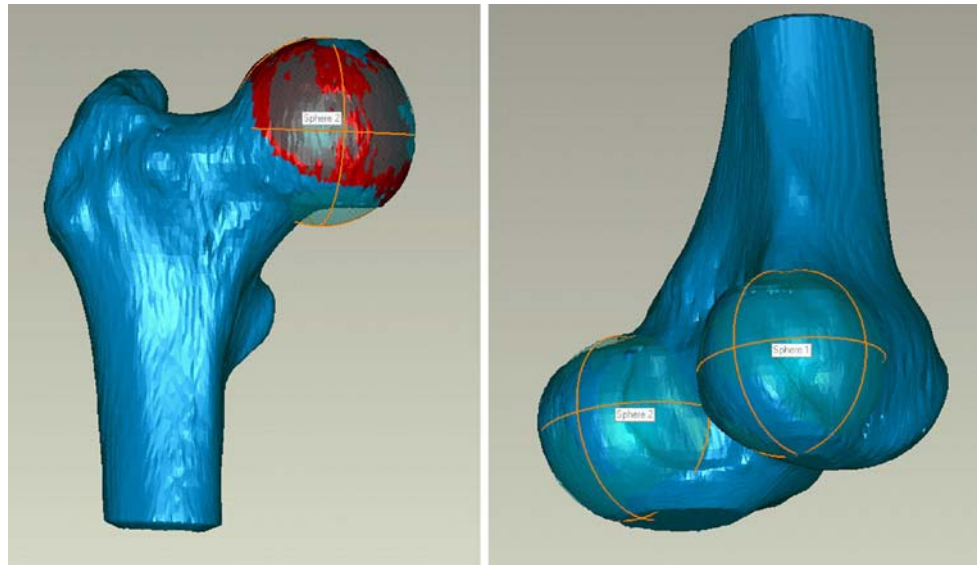
The statistical software used for all analyses was SPSS 15.0 (SPSS, Chicago, USA). We used a paired Student's *t* test with a *P* value of less than 0.05 regarded as indicative of statistical significance.

## Results

#### Varus valgus leg alignment

The varus-valgus alignment was statistically different ( $P < 0.005$ ) between pre- and post-op groups due to the insertion of the tapered plate. Each limb had an average increase in valgus angulation of  $11 \pm 4^\circ$ .

**Fig. 4** Using spherical center tool, landmark center points of the femoral head and distal condyles were calculated to measure the femoral length and anteversion



#### Tibial rotation

The average values for pre- and post-op axial tibial rotation were  $26 \pm 10^\circ$  and  $28 \pm 7^\circ$ , respectively. The distal tibia was externally rotated with respect to the proximal tibia in 10 of the 13 limbs. The average rotation increased by  $2 \pm 6^\circ$ , (max  $12^\circ$  external rotation, maximum  $9^\circ$  internal rotation). However, there was not a statistically significant difference when compared to the pre-op group ( $P < 0.075$ ).

#### Tibial slope

Averaging the tibial pre- and post-op slope groups revealed a difference of  $4 \pm 5^\circ$ . This proved to be statistically significant ( $P < 0.025$ ). The average pre-op lateral and medial tibial slopes were  $4 \pm 5^\circ$  and  $5 \pm 3^\circ$ . The post-op lateral and medial tibial slopes were  $0.8 \pm 7^\circ$  and  $1 \pm 7^\circ$ , respectively. The post-op lateral tibial slope was significantly different from pre-op ( $P < 0.05$ ) with an average  $4^\circ$  increase in anterior tilt. Ten of 13 limbs exhibited this increase in anterior tilt. Similarly, the medial tibial slope exhibited a significant difference from pre-op ( $P < 0.005$ ) with an average  $4^\circ$  increase in anterior tilt. Again, 10 of 13 limbs exhibited this increase in anterior tilt, though not necessarily within the same limb as the lateral group.

#### Leg length

Landmarks selected by CT showed that the length of the femur did not significantly change after HTO ( $-0.5 \pm 1$  mm). This result confirmed the accuracy of our CT measurement protocol. The length of each tibia significantly

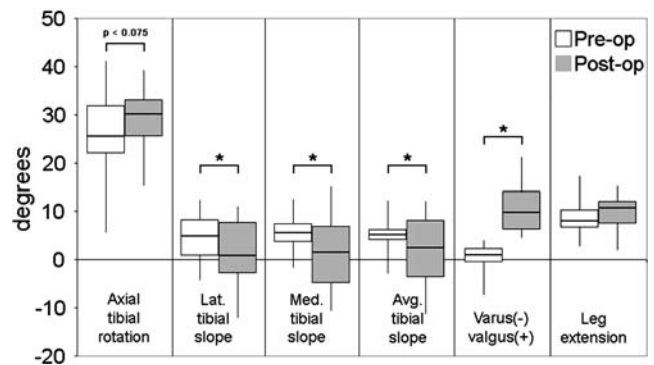
increased after HTO by  $7 \pm 3$  mm ( $P < 0.005$ ), though there was no significant change in overall leg length.

All combined results are demonstrated in Fig. 5.

#### Discussion

Various studies have focused on the resultant leg alignments after different tibial osteotomy techniques [5, 8, 13]. They have primarily studied the resultant change in leg alignment in the coronal plane as well as the corresponding change in the tibial slope. Apart from the alignment, the ligamentous structures of the knee and the impact of changes in tibial slope on these soft-tissue anchors has been studied in depth [1, 6, 7, 19, 22].

Radiographic, mechanical and navigation techniques have, so far, been used to determine the pre-, intra- and postoperative coronal and sagittal planes. Determination



**Fig. 5** Pre- and post-op comparison of measured angles ( $n = 13$ ) for axial tibial rotation, tibial slope, valgus-varus alignment and overall leg extension



of tibial rotation has, so far, only been described by using 3D digitizing instruments or radio-stereometric analysis [18, 24]. Although the general accuracy of those techniques has been established, CT measurements based on 2 mm cuts/imaging slices through the anatomic region of interest may be more reliable and reproducible. The authors believe this to be the first article, in which a CT technique is used to measure and determine the appropriate axial tibial rotation and slope correction before and after a HTO procedure.

Our study demonstrated a new technique which allowed measurement of combined axial rotation and tibial slope changes following HTO with a predefined fixation device. The results demonstrated that axial rotation did occur in all of our 13 cadavers. Despite the amount of rotation we found in a larger number of trials an external rotation, which we expected. However, the lower incidence of internal tibial rotation may be due to potential soft tissue retraction, especially involving the medial collateral ligament (MCL). Although we did not find a significant difference between the pre- and post-operative values, we do believe that this factor acknowledged intraoperatively. Maximal values of 12° and 9.5°, respectively can cause significant changes in the axial leg alignment and affect the knee kinematics, contact forces and the overall gait [15, 20]. As shown in a previous study by some of the current author's lower limb rotation can cause significant measurement inaccuracies of the leg axis, resulting in measurement failures as high as 4° [16].

Our results concur with previous studies, showing that open wedge osteotomies do influence the axial rotation. A study by Baumgarten demonstrated that in a denuded specimen, axial rotation was significantly larger than 0° and that a linear increase in internal rotation of the proximal tibia was associated with degree of valgus correction [3]. However, they only used denuded, embalmed specimens, without any soft tissues which may change the results especially within the medial compartment.

Additional explanations for the external rotation may be found in the anatomy. Open wedge osteotomies do not include a fibular osteotomy or the tibio-fibular joint. The fibula may act as a strut resisting angular corrections. Consequently, coronal plane osteotomies including a fibula osteotomy alter the tibial axial rotation to a lesser degree.

Another possible reason for rotational movements of the tibia may be patients' specific leg alignment. As shown in previous studies of osteoarthritis of the medial compartment of the knee, especially involving extreme narrowing of the joint space and severe medial ligamentous tensioning, there is a significant effect on the leg alignment after a HTO procedure [4, 21]. Although we were not able to find any correlation in our series between the initial leg alignment, the joint condition and the subsequent axial rotation

after HTO, it may be important to address this issue in a larger prospective clinical study.

In this study, a tapered Puddu plate was used. The taper is designed to ensure the slope of the tibia to a 'neutral' position by raising the posterior aspect of the proximal tibia, whereas a straight plate would leave the proximal tibia sloping down posteriorly. In this study, the tapered Puddu plate exhibited a significant overcorrection of both the medial and lateral plateau slope values. Despite the use of a predetermined stable implant, these results suggest that even predefined slope angles might not be useful in a clinical setting. Consequently, the specific slope-retaining plate we used does not display significant advantages over other conventional fixation osteosynthetic plate. We found a significant change for the combined as well as the divided medial and lateral plateau slope values. Although the slope does change we found no consistent correlation with the amount of correction. We did only expect to find a minor variation of the slope in general, however mean changes of  $4^\circ \pm 6^\circ$  were unexpected when one considers the predetermined angulation of the implant. As described in previous studies, the placement of a tapered Puddu plate can effect the physiologic slope [2].

The tapered implant used in our study does not allow for a precise adjustment of the tibial slope in a HTO procedure. Problems therefore might occur in cases where the physiologic slope should be preserved in combination with single frontal alignment corrections.

Limitations of our study included the use of fresh frozen cadavers. Even if these do not reflect the clinical situation, due to their intact soft tissues, they should be in theory more relevant to the clinical situation than the embalmed or stripped cadavers, used in previous studies. However, our cadavers obviously could not replicate certain varus malalignments observed in vivo and only a non weight bearing environment was simulated, which CT thresholding values and 2.0 mm scan spacing may also affect landmark placement. Placement of landmarks may also have intra- or inter-observer variance, but we were interested only in the absolute values before and after HTO. Another limitation was the use of the described foam model to achieve 0° rotation at the beginning of our testings. That could have influenced the ligament tension and even the rotation effect during osteotomy.

The general segmentation of the femoral head and femoral condyles in with the software could also be a possible source of error.

We used navigation to control our valgus angulation in combination with the tapered Puddu plate. Navigation has been shown to be accurate in determination of the coronal leg alignment during HTO, determination of the tibial slope and axial tibial rotation [10]. Navigation techniques provided valuable information during the actual HTO

procedure allowing greater control of the dynamic valgus process, intraoperatively. Given the established history of imprecise calculation we did not attempt to control the axial rotation or tibial slope. Our navigation system was not image-based, thus an accurate non-invasive measurement of the tibial slope and tibial rotation is less likely, image-based systems might be more making in making those measurements. Clinical studies in general will have to improve our findings, however clinically navigation is already able to provide intraoperative information to correct rotational deformity according to the preoperative plan.

In summary we were able to show that tibial rotation does occur in high tibial osteotomies with a higher tendency to external rotation of the distal fragment. However we did not find a significant change compared to physiologic axial rotation. Due to observed maximal variations of up to 12° we still think intraoperative considerations should be taken and relevant rotations should be avoided. It should be realized that favoring an open wedge over a closed wedge procedure might have a higher chance for an unintentional tibial rotation. Since navigation is capable of measuring also multiplanar deviations, it should also be used to control those intraoperatively. That might help in the future to reduce relevant rotational malalignments. The combined use of CT and 3D software measurement techniques is reproducible and can be used without any further invasive fixation devices. Based on multiplanar CT image data, individual measurements can be obtained. Although this system cannot be employed intra-operatively, it can be used as an effective measurement tool both pre- and post-operatively. Therefore, this technique may allow further relevant clinical data measurements and have an important role in a clinical setting.

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