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THE PLANE RADIOGRAPH OF THE KNEE FOR HIGH TIBIAL OSTEOTOMY ASSESSMENT IS IN CONTRAST TO STANDING ALIGNMENT VIRTUALLY ELABORATED HANDLING BASED PRE-OPERATION PLANNING

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ABSTRACT

High Tibial Osteotomy (HTO) is a popular approach among contemporary corrective lower extremity procedures. As a surgical method in the HTO, the Open-Wedge High Tibial Osteotomy (OWHTO) preserves leg length, avoids dissection near the nerve and allows for fine-tuning of the angle by gradually inserting a wedge into a tibia. Nowadays, the gold standard approach to the OWHTO is based on the patient's Long-Leg Radiograph (LLR) assessment. These standard weight bearing views of the lower extremity have their own practical advantages. This study aims to closely look at existing gold standard OWHTO planning method and assess its accuracy compared to a true patient's weight

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bearing posture. The study attempts to introduce a method which can be used as a template for the HTO planning and has less weakness than the existing method. This method will assess the lower limb weight bearing three-dimensionally using a patient specific Computer Tomography (CT) data. The method has been validated using a Standing Alignment Virtually Elaborated Handling (SAVEH) of the lower limb using fluoroscopy giving an *in vivo* dynamic weight bearing analysis of the knee. The outcome of typical examples on assessment of the natural mechanical axis of the knee using proposed method has shown more accuracy than common two-dimensional LLR image control method. The study concluded that looking at the OWHTO without any address of the real three-dimensional orientation of the knee bones specially during standing phase of gait may be a missing point of view on OWHTO surgery.

Keywords: Knee; High tibial osteotomy; Open-wedge; Alignment; Fluoroscopy.

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INTRODUCTION

High Tibial Osteotomy (HTO) was first introduced by Jackson in 1958 to prevent or decrease the effects of osteoarthritis in the knee.[1] However, HTO may affect patellofemoral joint degeneration[2] by increasing patella-femoral pressures. The axial alignment of the lower limb on plain radiographs is used to assess the effect of HTO.[3] However, plain radiographs are static, and may not accurately represent the dynamic environments of the knee joint. Some authors have reported that static alignment of the knee joint does not predict dynamic loading during walking, and cannot be correlated with clinical results. Andriacchi and co-workers[4] determined that it is important to evaluate dynamic loading of the knee joint to understand the pathology and treatment of OA knees. According to the textbook *Campbell's Operative Orthopaedics*,[5] mechanical axis of lower limbs extends from center of femoral head to center of ankle joint and passes near or through center of knee, or a line is drawn from the center of the hip to the 62.5% coordinate over tibial plateau, the radiograph or tracing is cut through the osteotomy site, and the distal tibia is rotated until the Weight Bearing Line (WBL) passes through the 62.5% coordinate.[6] By this method, two-dimensional (2D) plain radiographs are considered the gold standard for planning and execution of the HTO procedure. However, it is believed that the three-dimensional (3D) simulation will produce more information to make a decision for alignment correction. But the question is how a 3D model can be linked to 2D gray scale images taken using X-ray or CT scanning. The basis of this approach is called 2D-to-3D registration that was introduced at first by Banks and Hodge.[7] The introduced method is performed by matching the 3D models of the femur and tibia bones on their fluoroscopic 2D images. To match the 2D images with the 3D model an algorithm was written using Fourier series. The program was comparing each 2D slices with the geometry of the 3D model until find the best match between each 2D slice and the 3D model. The program then was calculating the rotation (orientation) and displacement (motion) of the femur and tibia bones during the gait.

Another important parameter is the degree of tibial slope introduced by opening wedge HTO. This in turn can have a significant effect on the tibiofemoral contact area and contact pressure which cannot be predicted from an LLR or assessed post-operatively.[8]

However, in contrast to the above opinion, other authors[9] claimed that the LLR is a reliable method of assessing alignment and they have stated the following advantages of the LLR: it is a gold standard method, has a long track record, is readily available in most centers, is safe and is currently the only modality that is indicative of weight bearing alignment.

On the other hand, other researchers[10,11] have used a bi-planar osteotomy instead of common mono-planar osteotomy as the bi-planar retrotubercle open-wedge Proximal Tibial Osteotomy (PTO) technique prevents patella infera and tibial slope changes. The idea of the recent method is more close to 3D alignment observation.

The aim of this research is to introduce a 3D measurement technique as a template for the HTO. The study continues to compare the outcome of this method with the standard LLR alignment measurement method using typical examples. The proposed method is going to suggest a pre-operation planning template which can help to restore the natural kinematics of the knee. The technical aspect of single-plane fluoroscopy that have been used in this research have been documented by previous researchers.[12] Current study introduces Standing Alignment Virtually Elaborated Handling (SAVEH) OWHTO pre-operation planning technique and tries to compare the proposed method with the routine OWHTO Pre- and Post-Operatively.

MATERIAL AND METHODS

Patient Specification

Three subject patients were involved in this study: a 24 years old female who was suffering from deformity in her left knee and two male patients of 22 and 42 years, both

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suffering from left knees geno-varum. The female subject did not take the surgery while both male patients took the retrotubercle HTO at the time of this research.

The study followed a local ethical policy of the hospital where the subject patients participated for the experimental evaluation of this study. The intention of the institutional review board (IRB) for this research was to focus on assessment technique rather than case study. Therefore, subject cases were used as typical examples to examine the hypothesis of the study.

The plain radiograph of the subject female patient which was taken at the Akhtar Hospital is as shown in Fig. 1(A). The patient was then asked to participate in a clinical gait assessment.

According to Fig. 1(B), the WBL passes through or near the midpoint of the tibial plateau.

Although the simple alignment can be obtained from a 2D plain radiographs, this study believes the information that is needed to accurately diagnose the patient's lower extremity malalignment is more than those which can be obtained from the plain radiographs. Figure 1 shows the distinction of real 3D restoration of standing feature of lower extremities and 3D mechanical axis in contrast to long leg 2D radiograph.

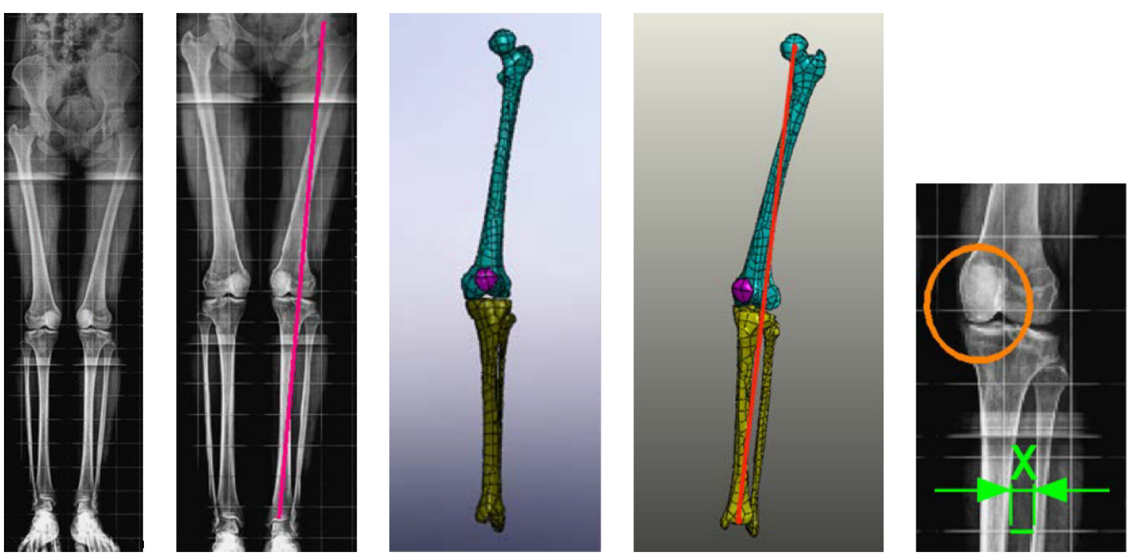
3D Model

Orthopedic surgeons would value a more accurate system for deciding the osteotomies and degree of wedging in order to achieve the best clinical outcomes. In order to provide an accurate method to assess the lower extremity malalignment, the study decided to create a true *in-vivo* 3D model of the patients. The purpose for 3D modeling of the lower extremity was to visualize the real orientation of the knee joint and measure the relative dimensions and distances.

The 3D anatomical geometry of the patient's whole leg (left) was generated using the DICOM images obtained from CT scans (Toshiba System, Helical, Activion 16 Model) with 1.0 millimeter thick slices and 1.186 pixels per millimeter resolution. The CT-based patient specific bone models were created in Mimics software (Materialise, NV) from 1161 CT dataset slices[13] and in order to mesh the created 3D models and repair the irregularities of the models, they were imported to SolidWorks software (Simulia Dassault Systems) and repaired as shown in Fig. 1(C).

Fluoroscopy

Recent studies including the authors own experience has found that the fluoroscopic 2D-to-3D registration technique is a valid solution to evaluate the natural weight bearing posture at the knee.[4,5] Some researches[14,15] have used the 2D-to-3D registration technique to find *in-vivo* pattern of the contact zone at articulating surfaces of the intact and pathologic knee. As it was mentioned earlier, with the 2D-to-3D registration process, the created 3D CT-based model will be matched with each 2D fluoroscopic images using an image processing algorithm and then the movement of the 3D model from one slice to next slice will be calculated to find the translations and rotations of the knee during a dynamic movement such as a gait. Furthermore, the calculated kinematics from fluoroscopic shape-matching



(A) (B) (C) (D) (E)

Fig. 1 **(A)** The patient's LLR, **(B)** weight bearing line on LLR, **(C)** supine A-P, **(D)** SAVEH A-P female patient. **(E)** Details obtained from LLR.

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procedures[16] can be used to assess the ligament deficient knees. Although some other researchers used the method to evaluate the stress–strain pattern of the knee's articulating surfaces,[17] the current study is going to use the registration technique to create a pre-operative planning template and help to restore the patient's natural weight bearing axis.

Possible errors on 2D-to-3D registration to use single-plane fluoroscopic images have been previously studied by Chen.[12] They have reported that the measurement of the knee kinematics with an *in vivo* dynamic weight bearing technique, may come with standard errors of 2.2 mm for translations and 1.8 degrees for rotation.[18] In this study, only the load bearing line at full standing position was investigated therefore the errors of the 2D-to-3D registration should be less than those reported by Chen.[12]

To obtain the 2D fluoroscopic images, an angiographic advanced unit (Innova 3100-IQ) was used to assess the patient's knee in standing anatomical position. This scanning unit was used because the unit was included with a high performance digital detector which provides very accurate data without the need of any mechanical calibration which is normally necessary when an analogue C-Arm fluoroscopy unit is used.

The recorded images were stored in DICOM format. The fluoroscopic images were then used to find the mid-stance frame. The mid-stance frame of the patient's knee was converted from DICOM to TIF format using the ImageJ software (rsb.info.nih.gov/ij) and then was imported to JointTrack (www.sourceforge.com). The frame was then used to be registered to the 3D model of the knee using JointTrack software. Prior to import of the 3D models of bones including the femur, tibia and patella into the JointTrack, a coordinate system was assigned to the 3D model based on the method introduced by Banks.[9] The registration process was then performed.

LLR Surgical Approach

The LLR is measured on weight bearing image which should be included with the hip, knee and ankle, with the patella facing forwards, and the X-ray beam parallel to the joint-line. The alignment is calculated as the difference between the femoral mechanical axis, defined by a line connecting the center of the femoral head and the femoral intercondylar notch, and the tibial mechanical axis, being a line connecting the interspinous intercruciate midpoint of the tibial plateau and the midpoint of the tibial plafond.[9]

On the example cases of this study, the LLR line was drawn starting from the center of the femur head and finished at the talus midpoint as shown in Fig. 1(B). While, for the 3D alignment concept, the weight bearing line is drafted from the center of the femoral head (center of the ball) to the center of tibiotalar contact zone as shown in Fig. 1(D).

SAVEH Approach

Among the three subject patients, it was decided that the two male patients will be operated. The surgical operation of the first patient (42 years, male) was

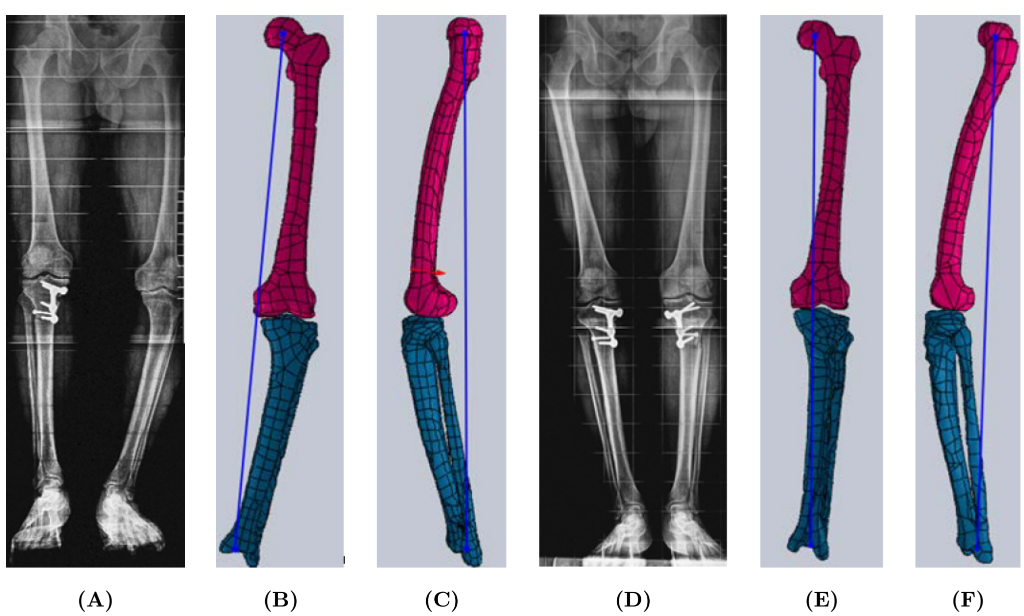

Fig. 2 **(A)** The LLR; **(B)** the left knee SAVEH A-P; **(C)** the left knee SAVEH — lateral view of 42 years old patient pre-operatively; **(D)** the LLR; **(E)** the left knee SAVEH A-P; **(F)** the left knee SAVEH — lateral view of 42 years old patient post-operatively.

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subject to LLR 2D radiograph which was the routine gold standard of the subject hospital. A pre-operation planning based on 3D concept was performed on the second patient (22 years, male). The third patient (24 years, female) did not take an operation at this stage.

The left knee of the first patient was operated according to his LLR as shown in Figs. 2(A)–2(C) and the left knee of second patient (22 years, male) was operated according to the new pre-operation planning using LLR and SAVEH methods as shown in Figs. 3(A)–3(C).

According to the biomechanical concepts, the AB line [as shown in Figs. 3(B) and 4(A)] which is the initial load bearing line of the subject patient before any osteotomy correction, should be shifted to the AC line which is the weight bearing axis as after the correction. After the correction, the AC line should start from femoral head center and pass through the knee weight bearing position then finish at the center of tibial plateau.

To ensure the accuracy of the coordinates while the weight bearing line is drafted from the center of the femoral head to the center of the tibiotalar contact zone, the CT-based image processing method was used. The measurement approach has been already assessed in previous publication of the authors and it is believed that the method can provide appropriate accuracy and is reliable to carry on the analysis.[27]

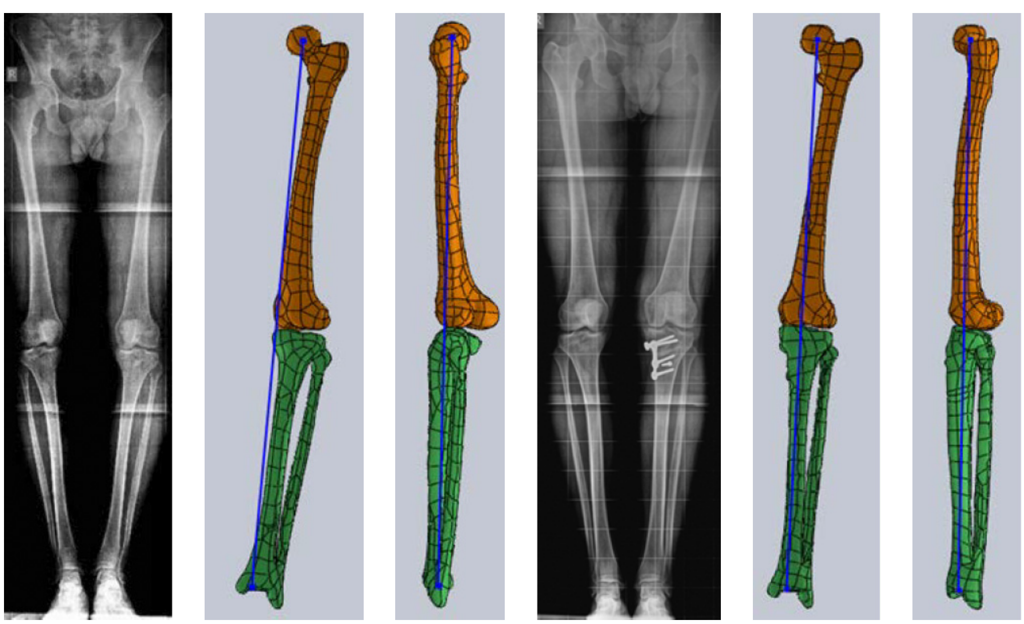
To apply the correction, from point D [as shown in Fig. 4(B)], which is the center of proximal fibula, two lines were drawn to points B and C. The measured angle between these two lines was 18 degrees. After passing a plane from these two lines, Axis 1 was drawn from point D perpendicular to the S plane.

To complete the retrotubercle HTO surgical process, the distal end of the tibia was rotated about 18 degrees with reference to the Axis 1 and parallel to the S plane. The 18-degree angle was based on the angle measured between DB and DC lines. As it is shown in Fig. 4(B), the opening distance of the wedge at the midpoint of the bones was 15 mm and this amount of opening is enough to complete the pre-operation planning. The surgeon then used the pre-operation information to carry on the operation on the second patient (22 years, male) as illustrated in Fig. 4(C).

Combination Method

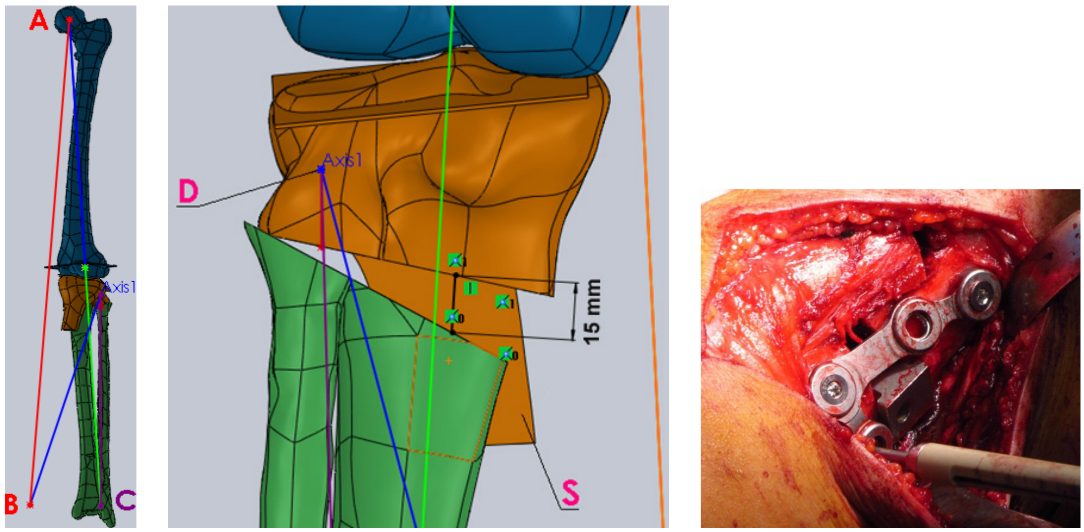
For the third subject patient (24 years, female), the pre-operation lower extremity biomechanical variable measurement on the patient has been summarized in Table 1.

According to the routine LLR method, the osteotomy correction would be based on a two-dimensional measurement of the alignments.[1] However, the 2D LLR can give the similar frontal WBLA% and assume similar bone cuts while the intersection of the tibial plateau from patient to patient can vary. This kind of inaccuracy affects the biomechanics of the articulating surfaces. In addition, this osteotomies uncertainty may reduce the



(A) (B) (C) (D) (E) (F)

Fig. 3 **(A)** The LLR; **(B)** the left knee SAVEH A-P; **(C)** the left knee SAVEH — lateral view of 22 years old patient pre-operatively; **(D)** the LLR; **(E)** the left knee SAVEH A-P and **(F)** the left knee SAVEH — lateral view of 22 years old post-operatively after pre-operative planning.

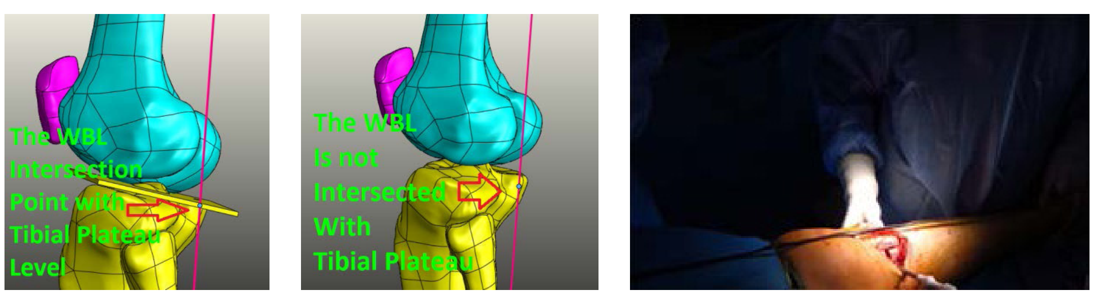


(A) (B) (C)

Fig. 4 **(A)** The mechanical axis correction by rotation of distal tibia from point B to point C around center point of D that is on Axis 1. The Axis 1 is perpendicular to surface S; **(B)** Medial opening is about 14 (mm) of 22 years old male subject patient. **(C)** The correction amount of 15 (mm) medial opening performed on 22 years old male subject patient.

Table 1. Comparison of the Amount of Mechanical Axis Correction in a Routine and SAVEH Methods.

Plan	Routine OWHTO, (Fig. 2)	SAVEH Method, (Fig. 3)
Sagittal	13.42%	20.2%
Coronal	33.13%	37.62%



(A) (B) (C)

Fig. 5 **(A)** Weight bearing line and tibial plateau level; **(B)** lack of intersection of WBL with tibial plateau of the 24 years old female patient. **(C)** The weight bearing axis estimation by a sterile wire intra-operatively.

satisfaction of the operation. Figures 5(A) and 5(B) show the real pathway of the 3D alignment for the third subject patient (24 years, female).

HTO Pre-Operation Planning of a Patient and Comparison with the Routine HTO Patient

As shown in Figs. 2(A)–2(C), the 3D tibiofemoral joint and orientation pre-operation is compared with Figs. 2(D)–2(F) that shows the post operation of the first patient (42 years, male) who underwent the routine retrotubercle knee corrective surgery.

RESULTS AND DISCUSSIONS

Comparison of the Two Methods

Pre-operation and post-operation result of the patient who has taken the HTO based on the routine surgical

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procedure shows that the mechanical axis at A-P plane has been corrected while lateral plane still needs further correction. While for the patient who took WBL using the 3D observation of the alignment, the position of the mechanical axis has been clearly corrected in all plans. A comparison on the amount of correction between the two methods has been summarized in Table 1.

LLR, Advantages and Disadvantages

As reported in Table 1, the LLR measurements are used to assess the patients alignment parameters including: FA (Femoral Axis Angle), TA (Tibial Axis Angle), TPA (Tibial Plateau Angle), TV (Tibia Vara), TT (Talar Tilt), FTA (Femorotibial Angle), and CEA (Center-Edge Angle).[19]

To ensure the application of the LLR for a statistical trend assessment, Aratake[20] studied 42 cases and concluded a negative correlation between the DA which can be derived from (pre-FTA–post-FTA)–(pre-TV–post-TV) and pre-operative TA ($R^2 = 0.148$, $p < 0.05$). This negative correlation between the pre to post-operative correction for the patients may affect clinical outcomes.

The current study believes that the reliability of the index (CEA) that is extracted from plain radiograph should be checked again after looking at the 3D model of the patient specific lower extremity. This is vital to ensure the accuracy of the variables.

Regardless of the disadvantages of the LLR, some advantages are presented here. In Fig. 1(E), it can be seen that the bright region around the medial femoral condyle and another point is distance X between the fibula and tibia that seems to be more than normal. It can be judged that the first effect is the effect of the patella that is oriented to the medial border of the distal femur and the X proportionally great distance is due to tibial rotation besides two other availability and reduced radiation exposure.

3D Model, Advantage and Disadvantage

Figures 5(A) and 5(B) show the 3D alignment of the patient's lower extremity or the 3D that is indicated as a reliable patient specific Standing Alignment Virtually Elaborated Handling. *In-vivo* weight bearing analysis of the patient is an important advantage of the 3D simulation which has been created based on 2D-To-3D registration technique. Also, obtaining the natural alignment of the patient provides a realistic data to decide about the osteotomy correction.

The next advantage of the 3D alignment [Fig. 5(B)] is its ability to detect small tibial/femoral congenital torsion which is not possible to see it in a plain 2D LLR method.

Figures 5(A) and 5(B) show the natural 3D weight bearing line of the patient's left leg. It shows that there is no intersection point between the WBL and the tibial plateau as it passes postero-laterally. This helps to find the correct angle by connecting a line to the center of the femoral head and the middle of the knee (midpoint of the tibial spines) to the center of contact area of the talus.[21] This could not be achieved with the plain 2D LLR method.

On the other hand, if the 3D observation method is replaced with the existing 2D templating procedure in a high tibial osteotomy surgery, the 3D method may need an *in vivo* examination (CT scan) and engineering technology (3D modeling), although, for the HTO surgical treatment, one of the common requirement is to take a CT scan of the knee of the patient. The current research has assumed that the CT data of the patient is already available and therefore only a computer modeling should be added to establish the new assessment method proposed by this study. Although another step has to be added to the HTO surgical procedure, the study believes that it is very important to get accurate results and prevent common mistakes and it is worth to think about it.

The SAVEH as a Robust Tool for the HTO Pre-operation Planning

According to the outcomes from the pre-operation and post-operation of the first patient (42 years, male) who took the HTO based on the routine retrotubercle surgical procedure, in spite of that the mechanical axis at A-P plane [Figs. 2(B) and 2(E)] has been corrected but in lateral plane [Figs. 2(C) and 2(F)] still a correction is needed. While for the second patient (22 years, male) who took WBL using the 3D observation of the alignment, the position of the mechanical axis has been clearly changed [compare Figs. 3(A)–3(F)]. The A-P and lateral views of the mechanical axis can clearly show the effect of correction on the mechanical axis of the lower limb. A comparison on the amount of correction between the two methods has been summarized in Table 1. According to the result, the correction with 3D process was more effective.

In general, the realignment usually aims towards having a straight mechanical axis in the coronal plane where the knee is in full extension. The axis should pass

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through the center of the femur head and center of the knee then finish by the center of the tibiotalar joint.[22,23] In a recent investigation, Byun *et al.*[24] evaluated the reliability of the real-size paper template method of HTO pre-operation planning. Although it is the LLR-based pre-operation planning method, the sagittal alignment and posterior slope of the proximal tibia could not be evaluated because the method was limited to the coronal plane only. The current study believes the most important factor in HTO is observing the weight bearing line in a 3D environment. While the existing gold standard only analyzes the alignment in coronal plane.

Hence, it has been shown that 3D alignment assessment provides a more accurate result. The 3D segmentation and 2D-to-3D registration is a novel pre-operation planning method which can help to improve the HTO treatment method. The study believes that the quality of the proposed method is independent from the quantity of the cases.

Lack of this Study and Future Work

Authors believe that further investigation is required to desire an accurate practical HTO method. This study has tried to identify some of the pitfalls with the LLR but not all of them have been identified.

There are some important factors that influence the medial open wedge osteotomy like surgical technique and the accuracy of the mechanical axis correction intra-operatively.[10] It has been shown that the lateral side of the proximal tibia could be the better marker to adjust the mechanical axis alignment intra-operatively.[25] This poses significant practical problems for surgeons intra-operatively. Estimating the correct alignment path intra-operatively is challenging and may be the source of error in the OWHTO corrective surgery as it is shown in Fig. 5(C). Error in supine posture of the patient is compounded by inaccurate intra-operative wire alignment and hence incorrect osteotomies.

An accurate method to plan for a lower extremity mechanical axis correction was presented and practiced on the subject patient. The method shows an improvement to obtain an accurate outcome in comparison with a routine HTO. Up to this point, it has been proposed as a patient-specific method to generate a 3D platform for the subject patient alignment's measurement. The introduced 2D-to-3D registration allows osteotomies to achieve an accurate WBL that is biomechanically sound.[26]

The CT scans of the subject patients were obtained while the patients were lying on the bed of the scanning machine. This position is a rest position and may not apply the full weight bearing on the joints. As the scanning of the body at standing position was not available at the time of this study, we have used an alternative loading on the joint contact surface in our computer model to recover the body right on the joints. It is suggested to use a CT data at standing position for future study.

As the focus of this study was on presenting a bioengineering method for evaluation of a surgical problem rather than reporting cases and generating data, the number of subjects has been reasonable for the purpose of this study but to get absolute results, a case study needs to be done using proposed method.

CONCLUSION

HTO pre- and post-operation result of two patients using routine surgical procedure and the 3D observation method suggested by this study has been performed and the latter method shows better correction on the knee load bearing. The current study believes the most important factor in HTO is observing the weight bearing line in a 3D environment. While the existing gold standard only analyzes the alignment in a 2D coronal plane. It is strongly suggested that the 3D observation method should be replaced with the existing 2D templating procedure in a HTO surgery.

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