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An Interactive Osteotomy Platform for Automated Planning of 3D Multiplanar Leg Malalignment-Correcting Osteotomies

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Abstract

Introduction 3D imaging technologies allow for more accurate planning of multiplanar corrective osteotomies around the knee. However, 3D planning introduces complexity. For example, varus/valgus is expressed in the coronal plane of the leg, while posterior tibial slope is expressed in the sagittal plane of the tibia. We present a software platform that deals with this complexity.

Methodology A high tibial osteotomy was parametrized using 5 parameters: hinge axis rotation in axial plane; hinge axis tilt in axial plane; hinge axis position along longitudinal axis; hinge axis distance to cortex; osteotomy opening angle. A MATLAB-algorithm was developed in which the effect of each possible combination of osteotomy parameters was obtained on change in alignment parameters expressed in coordinate systems of the tibia and leg. By finding the set of osteotomy parameters that approaches the predefined change in alignment parameters the closest, a 3D osteotomy planning can be linked to a desired outcome.

Results A digital interactive osteotomy planning platform was developed that automatically computes the required hinge axis orientation and osteotomy opening/closing angle for a given predefined outcome of change in posterior tibial slope and %-weight-bearing-line in the coordinate systems of the tibia and leg, respectively, with an error of <0.1°. During planning, the user is able to manually tweak the osteotomy and is given real-time feedback on the resulting trade-offs.

Conclusion The presented osteotomy planning platform allows for automatic and complex 3D planning of multiplanar leg malalignment correction, while integrating that alignment parameters are measured in different coordinate systems.

1 Introduction

Osteotomy around the knee is an accepted surgical method to correct malalignment. The current two-dimensional (2D) alignment measurement method focuses on performing uniplanar corrections based on 2D imaging. However, malalignment can occur in 3D [1]. While it is possible to calculate the oblique plane for 3D malalignment correction [2], 2D radiographs are not necessarily orthogonal. Additionally, calculating a required 3D hinge axis (HA) orientation for multiplanar corrections (e.g., varus leg and posterior tibial slope) [3-5] is not transferable from planning to execution with a 2D workflow.

The key to tackle these problems is the use of 3D bone models (e.g., from CT) allowing for more accurate assessment of leg malalignment. Additionally, anatomical planes can be imposed independently to establish a coordinate system, guaranteeing orthogonality. However, an extra layer of complexity is added, since alignment parameters are measured in different coordinate systems. For example, while a sagittal plane projection of the proximal tibial joint orientation (i.e., posterior tibial slope) is measured in the sagittal plane of a tibial coordinate system, a coronal plane projection of joint alignment (i.e., %-weight-bearing-line) is measured in a coronal plane of the leg coordinate system. These coordinate systems are not necessarily parallel. Effectively, pure posterior tibial slope change in the sagittal plane of the tibial coordinate system might induce unintended alignment correction in the coronal plane of the leg, resulting in varus or valgus. Although 3D malalignment analysis and correction planning enables use of 3D HA orientation, the complexity of alignment parameters measured in different coordinate systems complicates manual planning.

Therefore, the purpose of this study is to develop a digital platform that computes the required HA orientation and osteotomy opening/closing angle for a given predefined outcome of change in alignment parameters, while integrating that alignment parameters are measured in different coordinate systems.

2 Methodology

The osteotomy was parametrized using five parameters (Table 1), and limited to a range that corresponds to a surgically feasible “window”. An algorithm was developed in MATLAB R2023a (The Mathworks Inc., Natick, MA, USA) based on earlier-reported virtually simulated high tibial osteotomies [5].

Table 1 Overview of parameters defining the osteotomy and their possible values. Angles are with respect to the tibial coordinate system. 0° and 90° hinge axis rotation corresponds to parallel with the tibial sagittal and coronal plane, respectively.

Osteotomy parameters	Possible values
Hinge axis rotation in axial plane	0° to 90°; 1° steps
Hinge axis tilt in axial plane	-20° to 20°; 1° steps
Hinge axis position along longitudinal axis	Tip to circumference line fibula; 2 mm steps
Hinge axis distance to cortex	5 to 10 mm; 1 mm steps
Opening angle	0° to 10°; 0.25° steps

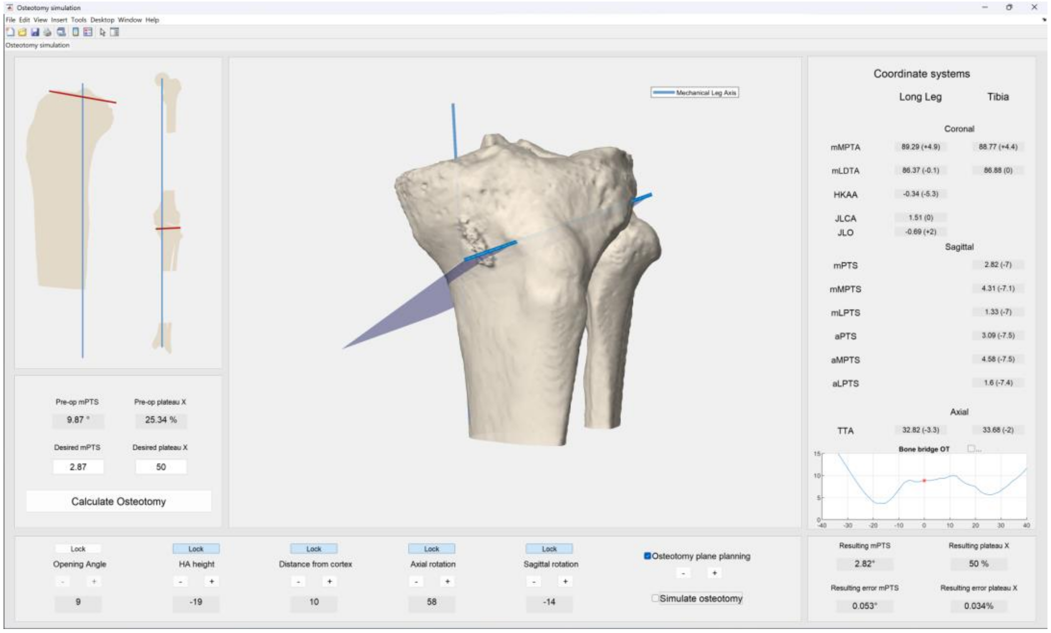
For each possible combination of parameters (Table 1), an opening wedge high tibial osteotomy was simulated in a segmented 3D model of a human tibia/fibula to investigate their effect on posterior tibial slope and %-weight-bearing-line in the coordinate systems of the tibia and leg, respectively. By storing the result of the simulations, each possible combination of osteotomy parameters can be linked to a unique set of corrections in the mentioned alignment parameters.

Because an osteotomy relocates landmarks (e.g., distal tibial joint center) that are used to define the coordinate systems and alignment parameters, the coordinate systems and axes were updated for every simulation, before calculation of the resulting alignment parameters.

3 Results

The graphical user interface of the platform is presented in Figure 1. After giving input of the desired change in coronal plane joint alignment (i.e., the %-weight-bearing-line) in the leg coordinate system and sagittal plane joint orientation (i.e., the posterior tibial slope) in the tibial coordinate system, the platform automatically computes the osteotomy parameters that most closely approach the desired changes. Thereafter, the 3D HA orientation can manually be adapted to further increase surgical feasibility, and its effect on the resulting change in alignment parameter is reflected to the user in real-time.

When finished, all osteotomy parameters including the (manually chosen) entry point of the osteotomy plane can be exported and used as input for 3D surgical planning (e.g., patient-specific instrumentation). The platform can achieve every (virtual) combination of increase of %-weight-bearing-line and decrease of posterior tibial slope (limited by the defined windows of possible osteotomy parameter values) with an error of <0.1°. For this level of precision, the algorithm requires a one-time calculation of approximately 20 minutes.



Pre-op mPTS 9.87 °
Pre-op plateau X 25.34 %
Desired mPTS 2.87
Desired plateau X 50

Coordinate systems

	Long Leg	Tibia
Coronal		
mMPTA	89.29 (+4.9)	88.77 (+4.4)
mLDTA	86.37 (-0.1)	86.88 (0)
HKAA	-0.34 (-5.3)	
JLCA	1.51 (0)	
JLO	-0.69 (+2)	
Sagittal		
mPTS		2.82 (-7)
mMPTS		4.31 (-7.1)
mLPTS		1.33 (-7)
aPTS		3.09 (-7.5)
aMPTS		4.58 (-7.5)
aLPTS		1.6 (-7.4)
Axial		
TTA	32.82 (-3.3)	33.68 (-2)

Opening Angle	HA height	Distance from cortex	Axial rotation	Sagittal rotation
9	-19	10	58	-14

Resulting mPTS 2.82°
Resulting plateau X 50 %
Resulting error mPTS 0.053°
Resulting error plateau X 0.034%

Figure 1 Osteotomy planning platform. The algorithm automatically finds an osteotomy planning that achieves a predefined change in alignment with the lowest error. The planning is manually adaptable to a surgically more feasible option while giving real-time feedback on the change in alignment.

4 Discussion

The primary finding of this study, is that the platform allows automatic and complex 3D planning of a multiplanar leg alignment correction, while integrating that alignment parameters are measured in different coordinate systems. The osteotomy planning result can be virtually achieved with an error of <0.1°.

To the authors' knowledge, this is the first paper that takes into account that alignment parameters are measured in different coordinate systems, and that coordinate systems are affected by the osteotomy and thus need to be updated prior to calculating resulting alignment parameters. While Rosso et al. [6] showed how 3D preoperative planning for alignment correction could be implemented with existing software, they focus on correcting the medial proximal tibial angle and posterior tibial slope in one undefined coordinate system, and do therefore not link the effect of the osteotomy in the tibia to alignment in the coronal plane of the leg. Müller et al. [7] show the complexity of planning and performing a biplanar alignment correction with conventional 2D radiographs, requiring two tibial osteotomy cuts to achieve the end result, circumventing the use of a 3D HA orientation. In the planning, they use a 2D weight-bearing leg radiograph (i.e., a coronal plane of the leg coordinate system) and a 2D lateral knee radiograph (i.e., a sagittal plane of the tibia coordinate system), and do not take into account any non-orthogonality between the two.

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