DEVELOPMENT OF AN AUTOMATED SYSTEM CAPABLE OF GENERATING PRE- AND POST-OPERATIVE 3D MODELS OF DIFFERENT HALLUX VALGUS CONDITIONS

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***ABSTRACT**: The paper presents the development process of obtaining an automated system suitable for picking the proper Hallux Valgus surgical approach, based on the values of geometric parameters that define the condition. Furthermore, the system is capable of automatically generating the 3D model of the preoperative condition of the foot just through introducing several values extracted from the X-ray of the patient but also it has the possibility of the correct placement of the corrective surgical trajectories and finally generating the 3D model of the postoperative assembly.*

***KEYWORDS**: 3D parametric modelling, automated assembly generating, Hallux Valgus, geometric reconfiguration*

1 INTRODUCTION

The axial deviations within the foot are remarkably frequent, affecting around a quarter of the men population and more than a half of the women population worldwide. One of the most common axial deviations consists in the Hallux Valgus, condition characterized by physical discomfort and pain within the foot, associated with the decaying of the lower limb gait (Netto and Richter, 2020).

The Hallux Valgus conditions are categorized within three main stages: mild, moderate and severe, each condition type being associated with its suitable corrective approach. For example, mild and some of the moderate conditions can be corrected through non-invasive approaches, such as orthosis or different kineto-therapeutical exercises, whereas most of the moderate and severe conditions require surgical approaches (Angin and Demirbuken, 2020), (Tarantino and colab., 2021).

The current research focuses on the development of an easy-to-use system capable of generating pre and post operative 3D models of the most frequent surgical approaches for correcting the Hallux Valgus axial deviation, through imputing parameters characterizing each patient's condition, such as diverse angular values, relative position between bones within the foot or joint condition, all extracted for the patient's X-ray.

Furthermore, the main objectives of this paper consist in:

- Development of a generic 3D assembly of the foot, capable of generating different pre-operative Hallux Valgus conditions;
- Elaborating a system for associating Hallux Valgus conditions with suitable corrective surgical approaches;
- Parametric modelling of the most frequently used corrective surgical treatments for the Hallux Valgus axial deviation;
- Development of individual assemblies for each type of the approached surgical treatments, capable of generating post-operative configurations, in anatomical position of the foot.

In order to describe the developed process properly, several characteristic Hallux Valgus anatomical notions must be walked through, alongside with the angular parameters which describe the axial deviation in discussion, elements briefly presented within the next chapter.

2 CHARACTERISTIC BIOMECHANICAL AND GEOMETRICAL ELEMENTS OF THE HALLUX VALGUS DEVIATION

2.1 The angular parameters of the Hallux-Valgus deviation

The Hallux Valgus condition is the result of several biomechanical displacements within the first toe (the Hallux), as follows: the rotation and torsion of the 1st metatarsal within the 1st tarsometatarsal joint (Kimura and colab., 2024), (Park and colab., 2024).

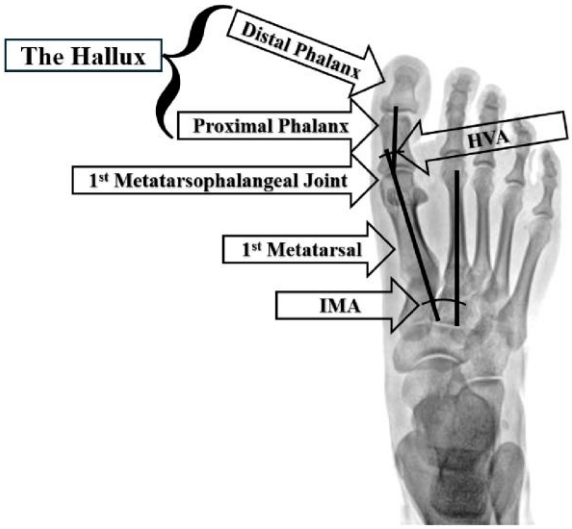

Figure 1. Relevant anatomical elements characterizing the Hallux Valgus condition

Figure 1 illustrates the main angles describing the Hallux Valgus condition, the Hallux Valgus angle (hereinafter HVA) and the Intermetatarsal Angle (hereinafter IMA). In healthy subjects, those angles are within the following limits: HVA<15° and IMA 7°-9°. (Pop and colab., 2013), overtaking these limits indicate the existence of pathological Hallux Valgus conditions.

2.2 The condition of the foot joints

As illustrated in the image, the 1st Metatarsal and the Proximal Phalanx of the Hallux are linked through the 1st Metatarsophalangeal joint. The congruency state of this joint has an important weight in the decision-making regarding the suitable surgical approach for the Hallux Valgus correction.

Therefore, there are three stages regarding the congruency of the 1st Metatarsophalangeal joint each with their individual particularities (Gui and colab., 2001):

- 1st Type – Congruous joint.
- 2nd Type – Deviated non congruous joint.
- 3rd Type – Subluxated joint.

3 COMPUTER ASSISTED MODELLING TAKING INTO ACCOUNT THE DEFINING PARAMETERS

As previously stated, he Hallux Valgus condition is categorized into different aggravation stages, based on several angular values that define it, the Hallux Valgus Angle and the Intermetatarsal Angle but also the relative position between different bone structures within the foot assembly. Therefore, taking into account those aspects, the surgeon must select one of the following surgical approaches: the Chevron, Akin, Scarf and Lapidus procedures or the first metatarsal opening wedge operation.

Within papers (Brănescu and colab., 2022), (Brănescu and colab., 2023) and (Brănescu, 2023), we managed developing 3D parametric models of the lower limb and the foot especially, models that are a good starting point in fulfilling the development that we set up.

The values constraining bone elements within the assembly were replaced by parameters in three main steps, as shown in figure 2; starting from the X-ray, the surgeon can extract the necessary parameters which can be entered into a spreadsheet file linked to the Catia V5 software 3D model into the IMA and HVA headings and resulting in the 3D model of the desired condition.

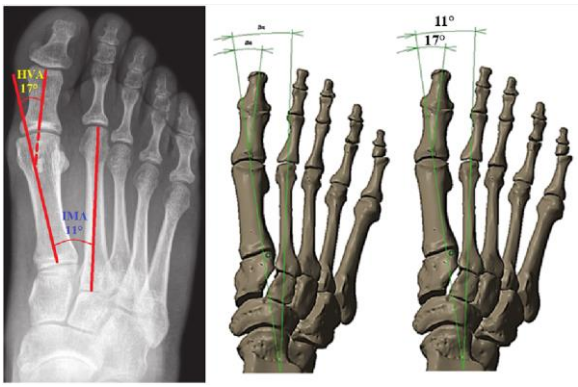

Figure 2. 3D model generation of specific Hallux Valgus condition

Starting from this approach, we further focused on developing the parametric CAD models of the main surgical correction methods. (Cofaru and colab., 2022), (Cofaru and colab., 2024)

We developed an assembly for each of the five most frequently used surgical approaches, capable of reconfiguring the foot into the anatomical position, through entering the input data (HVA and IMA).

3.1 CAD modelling of the Chevron osteotomy

The Chevron osteotomy is suitable for moderate Hallux Valgus conditions and the correction is

made at the level of the first metatarsal, having the possibility of lowering the HVA up to 10-15°. The starting model consisted in a moderate Hallux Valgus condition characterized by the several angular values, HVA=32° and IMA=16°, as presented in Figure 3.

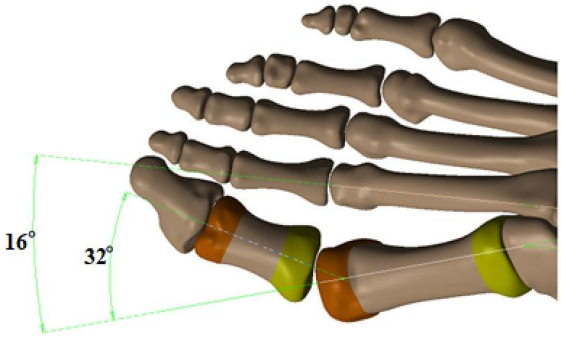

Figure 3. 3D model of moderate Hallux Valgus condition

By respecting all the surgical guidelines of the Chevron intervention: displacements, excessive bunion removal and fixation with screw, we were able to generate the corrected post-operative condition, illustrated in Figure 4.

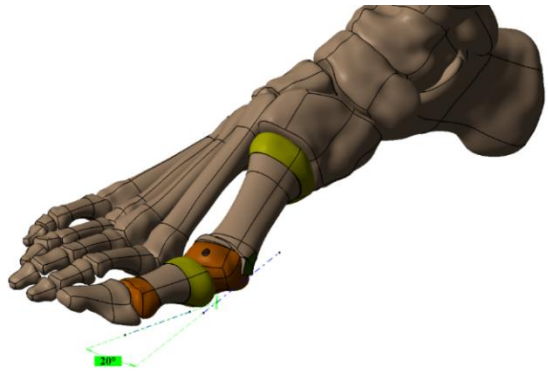

Figure 4. 3D model of post-operative Chevron surgical treatment

Through a 2 mm lateral shifting of the anterior side within the first metatarsal we managed obtaining a correction of the HVA from 32° to 20°.

3.2 CAD modelling of the Akin osteotomy

This surgical approach is also suitable for moderate Hallux Valgus conditions, but the correction is done within the proximal phalanx of the hallux.

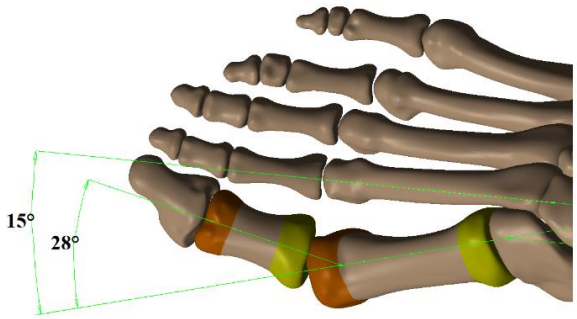

Figure 5. Preoperative 3D model of moderate Hallux Valgus condition

The starting condition is presented in figure 5 and is characterized by the following angular parameters: HVA=28° and IMA=15°.

The correction for this type of surgical approach consists of removing a wedge out of the proximal phalanx of the hallux, removing the excessive bunion and repositioning the first toe into the anatomical configuration, preserving the position with Kirschner wires. The final post-operative assembly is illustrated in figures 6 and 7.

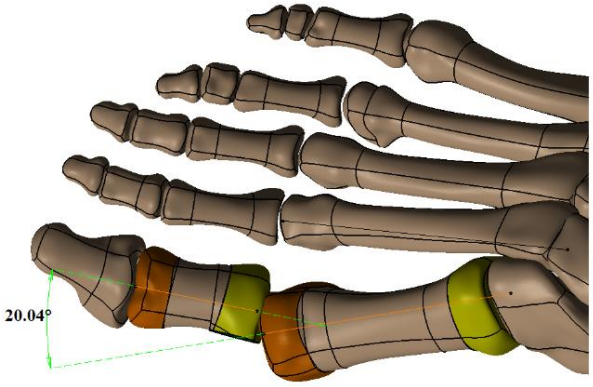

Figure 6. 3D model of post-operative Akin surgical treatment

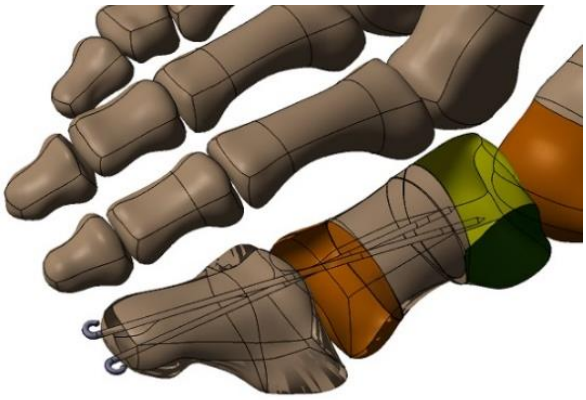

Figure 7. Assembly fixation with Kirschner wires

The angular correction was done within the HVA, reducing it by around 8° through a 3.5 mm wedge removal.

3.3 CAD modelling of the Scarf osteotomy

The Scarf osteotomy is recommended for moderate cases of Hallux Valgus but additional, with lateral displacements of the sesamoid bones and joint incongruency. As the Chevron approach, the Scarf surgical treatment consists in correcting the position of the foot through the lateral shifting of the 1st metatarsal bone, but the incision shape is a Z-type one, rather than a L-type for Chevron. The considered condition of Hallux Valgus for reproducing this modelling consists in a moderate one, having the parameters HVA=25 and IMA=14, as presented in figure 8.

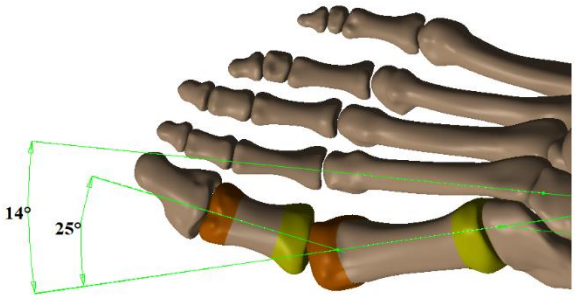

Figure 8. 3D model of pre-operative Scarf surgical treatment

After a 1mm Z-shape incision within the 1st metatarsal and a 5mm shift of the anterior part of it, we manage to obtain a correction for both of the parameters IMA and HVA, accordingly to figure 9.

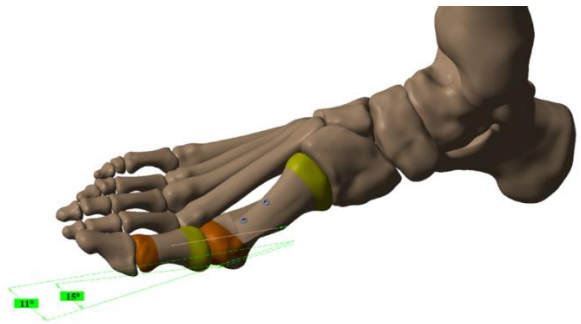

Figure 9. 3D model of post-operative Scarf osteotomy

The Scarf osteotomy is capable of correcting both problematic parameters of the presented case, having the following set of post-operative parameters: HVA=15° and IMA=11°.

3.4 CAD modelling of the Lapidus osteotomy

In cases of severe Hallux Valgus conditions, the Lapidus approach is one of the most frequently used by surgeons, having a high success rate. This surgical treatment is very versatile, being capable of correcting high angular values, HVA up to 55° and IMA up to 20°. For exemplifying, we considered a severe HV condition, having the HVA=35° and the IMA=19°, configuration presented in figure 10.

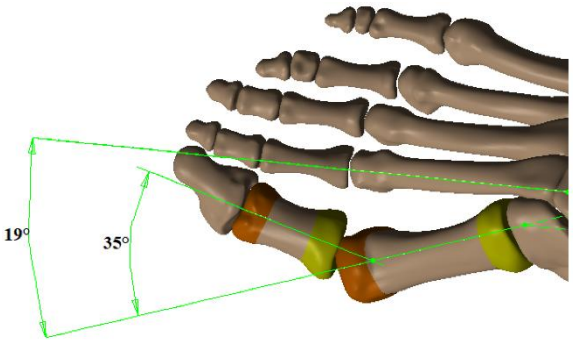

Figure 10. 3D model of pre-operative Lapidus osteotomy

The correction in this case is done through removing a wedge from the posterior side of the 1st metatarsal and further fixation of it with the 2nd metatarsal and medial cuneiform bones. Through a wedged placed at 30° angle at the base of the 1st metatarsal we managed to obtain important correction of both angular parameters, presented in figure 11.

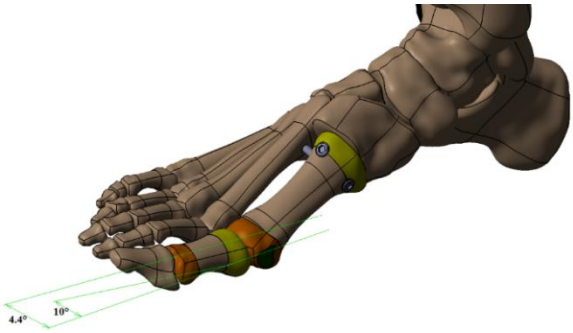

Figure 11. 3D model of post-operative Lapidus surgical treatment

As presented in the previous figure, the resulting angular parameters were IMA=4° and HVA=10°.

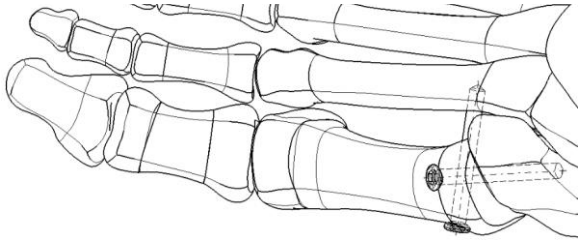

Figure 12. Detail of fixing screws

The fixation was done with a couple of M3.5x34mm, shown in detail in figure 12.

3.5 CAD modelling of the 1st metatarsal opening wedge osteotomy

This approach is also a very versatile one, being capable of correcting different types of Hallux Valgus, including moderate ones and for incongruent joints conditions as well (Hyer and colab., 2017). The main geometrical parameters for the current modelling, are: HVA=24° and IMA=15°, presented in figure 13.

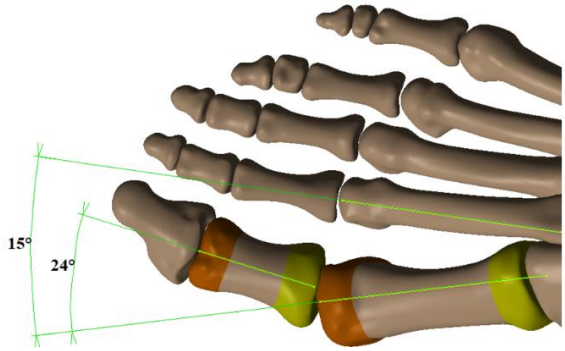

Figure 13. 3D model of pre-operative 1st metatarsal opening wedge osteotomy

This approach consists in drilling a hole and milling a slot within the first metatarsal and widening the gap up to the desired angle that assures positioning the assembly in the anatomical configuration. The position is preserved with a special device named *BOW plate* and fixed through 4 screws. The post-operative configuration is presented in figure 14, illustrating the fixing device as well.

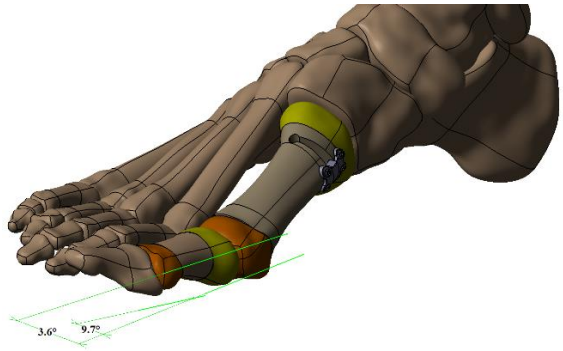

Figure 14. 3D model of post-operative 1st metatarsal opening wedge osteotomy

The final parameters after the surgery through a 4mm gap (corresponding to a 12° angular opening of the wedge) resulted in the IMA=3.6° and HVA 9.7°.

Through these five parametric modelling of the main Hallux Valgus surgical treatments, we were able to cover a wide range of conditions. It must be taken into account that within all the developed modeling processes it was taken into consideration the real bone structure, delimitations made through previous approaches, important fact in case of further FEM analysis.

4 THE DESIGN OF THE AUTOMATED SYSTEM

As stated, the main goal of the paper consisted in elaborating an easy-to-use system capable of recommending surgical treatment approaches and generating post-operative 3D models of the configurations.

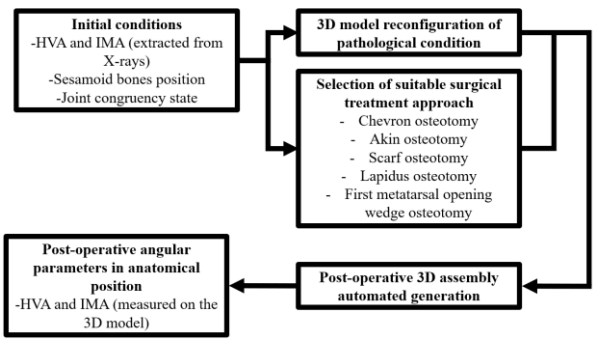

Figure 15. Working scheme of the system

Starting from given angular parameters and mutual positions of bones, therefore, we managed to develop 3D assemblies of the five main surgical approaches for the Hallux Valgus conditions, fully controllable and reconfigurable through several parameters. The system working principle is presented in figure 15.

Considering the initial conditions of the patient, such as angular positioning, sesamoid bone disposition and the congruency state of the joint, through the system, the surgeon is recommended one or two of the five possible approaches and through entering the HVA and IMA parameters into the spreadsheet file, the 3D model is reconfigured into the current pathological condition. Furthermore, after the medical staff laid upon a specific approach, based on the correction angles that are needed to reconfigure the assembly into the anatomical shape, which must be entered into the system as well, the new assembly is generated, in the post-operative variant. Since all the surgical trajectories are parametrically controlled, the new assembly is generated instantly.

Aided by virtual reality devices, the surgeons and medical staff could comprehend the specific particularities of each case and practice the surgery in advance.

Also, in accordance with the latest trends in the medical industry (Gherman and colab., 2019), (Caprariu and colab., 2023), (Covaciu and colab., 2020), (Maskeliūnas and colab., 2023) (Covaciu and colab., 2023), (Covaciu and colab., 2024) through augmented and virtual reality, the medical staff could have side by side the theoretical and practical versions of the surgery with real time updates on the ongoing procedures. This approach might lead to an increase in the precision of the medical act.

5 CONCLUDING REMARKS

The original contribution within this paper consists in developing a system suitable for aiding orthopaedic surgeons and the medical staff in a wide range of applications regarding the Hallux Valgus problematic particularities. The system is user-friendly and easy to use, having the capability of conferring a better imaging of the pathological bone configuration within the foot, but also the final post-operatory result.

Through modern technique and equipment such as VR and AR devices, both the starting and ending configuration can be presented side-by-side with the actual surgery, with real-time updating of the procedure.

The only input data necessary for the system to propose the suitable surgery variants and to

generate the pre- and post-operative assemblies consist in the HVA and IMA parameters extracted from the X-rays, through a spreadsheet type file (i.e. Microsoft Excel).

Furthermore, in this regard, the engineering approach of the problematic attributes this paper a remarkable level of innovation and creativity, and can be further extrapolated for other affections too, through its high level of generalization conferred by the replacement of the angular and dimensional numeric constraints with parametric and formula ones.

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