A COMPARATIVE STUDY OF HIGH TIBIAL OSTEOTOMY USING TAGUCHI METHOD

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***ABSTRACT**: High Tibial Osteotomy (hereinafter HTO) is a treatment method of goanarthrosis of the human knee. There are several HTO types, but the most frequent ones are the monoplanar Opening Wedge High Tibial Osteotomy (hereinafter OWHTO), the biplanar Opening Wedge High Tibial Osteotomy (hereinafter BOWHTO) and the Closing Wedge High Tibial Osteotomy (hereinafter CWHTO). This paper aims to carry out a comparative study of these procedures using engineering research methods (CAD, FEM, DOE). Specifically, a static analysis of the stress state will be performed on the intraoperative behaviour of the tibia during the realization of the corrective angulation through the prism of three variables, i.e.: HTO type, angular value and distance to the lateral cortical side of the tibia. The results obtained are eloquent and clearly presented and may constitute important elements for orthopaedic physicians.*

***KEYWORDS**: Uniplanar Opening Wedge High Tibial Osteotomy, Biplanar Opening Wedge High Tibial Osteotomy, Closing Wedge High Tibial Osteotomy, Taguchi method, Centre of the Rotation of the Angulation (CORA).*

1 INTRODUCTION

High Tibial Osteotomy (hereinafter HTO) is an established surgical procedure for the treatment of both knee osteoarthritis and deviations due to a change in the shape of the human leg bones. (Insall and colab., 1984), (Amis, 2012), (Amendola and colab., 2009), (Liu and colab., 2019)

One of the strengths of the HTO is that it is also recommended for younger patients suffering from osteoarthritis, as it has a relatively quick recovery and does not exclude the possibility of future partial or total prosthetic interventions.

The aim of this surgery is to realize a bone wedge to realign the mechanical axis of the lower limb and, consequently, to redistribute the forces in the joint, with the unloading of the affected compartment. (Cofaru, 2013)

In surgical practice there are several types of HTO. The most common ones are monoplanar Opening Wedge High Tibial Osteotomy, biplanar Opening Wedge High Tibial Osteotomy and Closing Wedge High Tibial Osteotomy. Since each of these techniques has advantages or disadvantages, arguments or counterarguments, we consider it very useful to make a comparative study of these operations using computer assisted engineering research methods such as: Computer Aided Design (hereinafter CAD) for the geometric modelling of the tibia taking into account the real bone structure, the finite element method (hereinafter FEM) for the numerical analyses performed or design of the experiment (hereinafter DOE) for the design of the researches.

Comparisons have been made in the literature of the three types of HTO listed above. These comparisons generally come from clinical studies and show the superiority of OWHTO, as a surgical intervention, because of the complications that can occur in the case of the other type of HTO: limb shortening, neurological problems, detachment of the lateral muscle or proximal fibula osteotomy etc. (Lee and colab., 2010), (Staubli and colab., 2003)

In addition to these clinical studies, we consider of major importance also biomechanical research on the states of tension existing during the realization of the corrective angulation, thus the creation of the osteotomy wedge for the three types of HTO for different correction angles and different positions of the apex of the HTO wedge, the apex around which the corrective angulation will be performed called the centre of the rotation of the angulation (hereinafter, "CORA").

The aim of this research is to analyse the stress states in the CORA in relation to the variables listed in the previous paragraph, their influence on the response function but also to highlight the optimal combination to minimize the stress state in the CORA. The objectives of this research are as follows:

- FEM analysis for the three types of osteotomies - determination of the geometrical elements of the deviation
- Design of an experimental program using the Taguchi method with the realization of the combinations of variabilities, levels of variation necessary for the study
- Collecting the Von Mises stress values for each combination and making optimizations for their minimization.

2 METHOD AND MATERIALS

2.1 HTO types

This article is a computer-aided biomechanical approach aiming to analyse the stress state in the CORA for the three types of osteotomies presented: monoplanar OWHTO, biplanar OWHTO and CWHTO, respectively. (Cofaru and colab., 2022), (Cofaru and colab., 2024)

Figure 1. Monoplanar OWHTO (Pape and colab., 2013)

In the Monoplanar OWHTO case (Figure 1) a single cut is made resulting in a single osteotomy plane and the HTO wedge is created by angular opening of the two resulting surfaces. As can be seen, the corrected position is preserved with osteosynthesis plates. An important negative aspect is that in most cases the osteotomy plane crosses the tibial tuberosity.

Figure 2. Biplanar OWHTO (Pape and colab., 2013)

Figure 2 illustrates the Biplanar OWHTO in which there are two sectioning planes, one in which the osteotomy wedge is made and another one that makes an angle of approximately 110° with the first one and longitudinally sections the tibial tuberosity. Although slightly more complex, it has the advantage of preserving the integrity of the outer surface of the tibial tuberosity and because of the larger sectioned surfaces it can lead to a faster recovery through greater vascularization.

The lateral closing osteotomy consists of making two concurrent cuts and removing the bone wedge (Figure 3).

Figure 3. CWHTO (Alagha, 2009)

The disadvantage of the procedure is the final length of the bone, which becomes shorter, the geometric non-overlapping of the corrected fragments and the possibility of the need for sectioning the fibula as well. On the other hand, the use of bone grafts sometimes necessary in opening osteotomies is avoided.

The study and research methods used in this paper are Computer Aided Design (hereinafter CAD), Finite Element Method (hereinafter FEM) or Design of the Experiment (hereinafter DOE).

Regarding the CAD modelling, 3D geometric models of a human tibia have been developed using the Catia V5R20 program, considering the real bone structure of the tibia, and then the three types of HTO presented above have been modelled and simulated. This research has been carried out in previous research to the one presented in this paper (Cofaru and colab., 2022)

2.2 The FEM analysis of the stress state in the CORA during HTO interventions

The achievement of corrective angulation after setting up the osteotomy wedge is an important moment in the successful surgical intervention. This angulation can be achieved by elastically deforming the bone with a specialized spacer in the case of

OWHTO or by superimposition in the case of CWHTO. Avoiding microfissures that may occur in the CORA is extremely important for the success of the operation and the patient's quick and proper recovery. (Tomofix, 2022)

The input variables that will be taken into account will therefore be the type of HTO which will be variable V1 which, as previously presented, has three levels of variation, the correction angulation which will be variable V2 also with three levels of variation and respectively V3 - the position of the CORA in relation to the lateral cortex of the tibia with three levels of variation (figure 4).

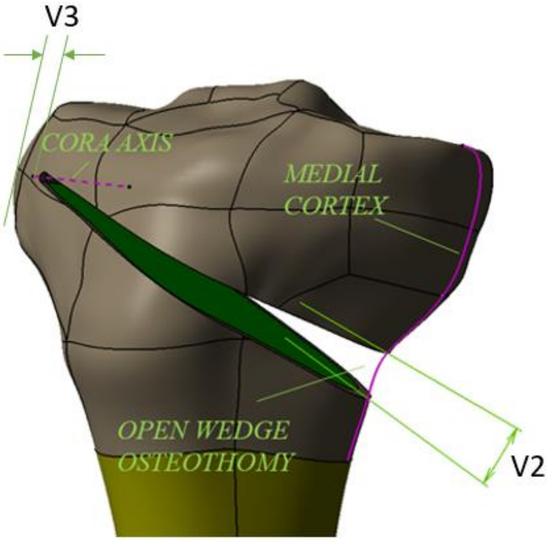

Figure 4. CWHTO (Cofaru, 2013)

The input variables and their levels are presented in Table 1.

Table 1. The main influence on the variables

Variables	V1	V2	V3
Type	Osteotomy	Correction Angle	Position on lateral cortical
Unit	-	[grade]	[mm]
Level 1	Monoplanar OWHTO-MOWHTO	6	8
Level 2	CWHTO	10	10
Level 3	Biplanar OWHTO-BOWHTO	14	12

The three levels of variation for the three variables were chosen considering surgical practice, previous research and clinical studies. Thus, for the variable V1 the three types of HTO are most used, for which values between 30 mm and 50 mm are recommended. (Elson and colab, 2015), (Yang and colab., 2018) For CORA positioning the recommended value ranges are 8-12 mm resulting in 3 values for V2. (Kwun and colab., 2017) The correction angles for which HTO is suitable range up to 14°. Therefore, the chosen values (6,10,14) correctly cover the range of variations in terms of the response function under study, i.e. the Von Mises Stress.

An experimental program was designed using the DOE Taguchi method to plan the sets of values for which the static analyses will be performed. The design of the experimental matrix was done using Minitab 18 software resulting in an orthogonal matrix of type L9 (3^3) with the combinations of variables and levels of variation shown in Table 2.

Table 2. The Taguchi orthogonal array L9(3^3) –for the input variables

	OSTEOTOMY	CORRECTION ANGLE	POSITION
		[grade]	[mm]
1	MOWHTO	6	8
2	MOWHTO	10	10
3	MOWHTO	14	12
4	CWHTO	6	10
5	CWHTO	10	12
6	CWHTO	14	8
7	BOWHTO	6	12
8	BOWHTO	10	8
9	BOWHTO	14	10

The comparative study of the three types of HTO was carried out by determining the Von Mises equivalent stress states in CORA for the parameter combinations in Table 2.

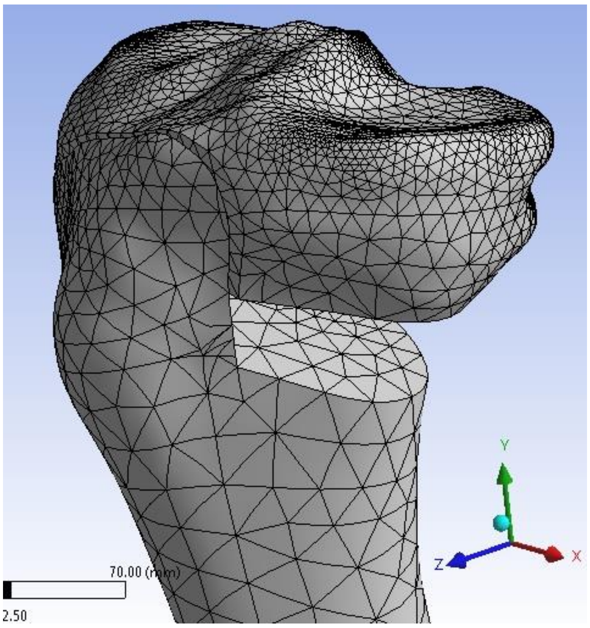

Figure 5. Mashed model (Cofaru, 2013)

The established steps were followed to perform the FEM analysis. The geometric models realized in previous research were used, models realized using the CATIA V5R20 program. (Cofaru and colab., 2022)

The models were then mashed considering the actual bone structure of the tibia (Figure 5).

Figure 6 presents constraints and loads applied on the discretized model. These have been placed on the two faces of the osteotomy wedge because the area of interest for our response function is their respective CORA intersection. Thus, both modelled bone entities, cortical and cancellous, were found to be homogeneous, isotropic and linearly elastic. The Young's modulus for the tibia was 17 GPa for the cortical bone, 5 GPa for the cancellous bone, and the Poisson's ratio was 0.33. (Lou and colab., 2013), (Lou and colab., 2015), (Hoffler and colab., 2000)

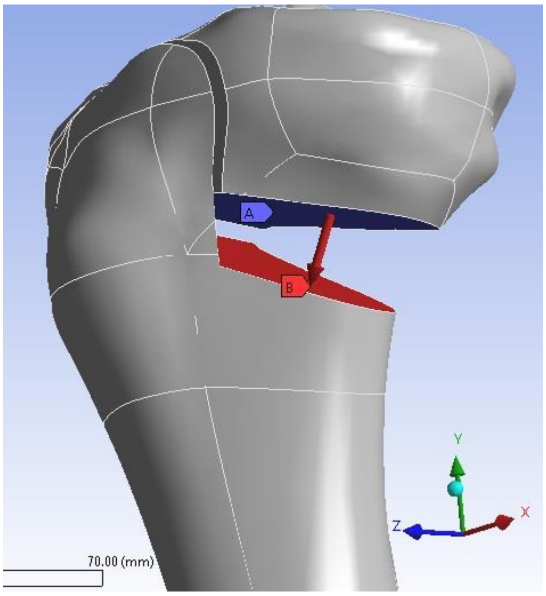

Figure 6. Placing constraints and loads

Since the static analyses aimed at the intraoperative creation of the osteotomy wedge, the value of the applied force was 175 N. The value was chosen considering the existing values in the literature ranging between 120-200 N. (Yang and colab., 2018)

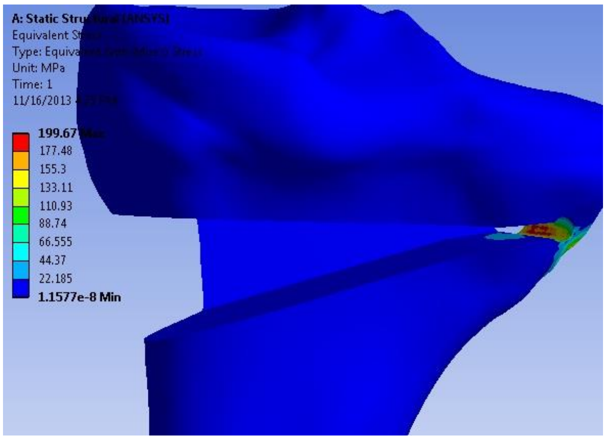

Figure 7. BOWHTO equivalent stress distribution (Cofaru, 2013)

Figure 7 presents the Von Mises equivalent stress distribution for BOWHTO with a correction angle of 14 degrees and a 10 mm positioning of the CORA with respect to the lateral cortex using the ANSYS program.

It can be noticed the existence of the maximum value for the Von Mises Equivalent Stress in the internal area of the CORA hinge. This highlights the importance of the correct positioning of the CORA regarding the lateral cortex of the tibia, which in this case has materialized by the variable V2.

The FEM analysis was run for all the combinations presented in Table 2 and the results are presented in the next chapter.

3 RESULTS AND DISCUSSIONS

The results were then collected in the same way as for the initial planning of the combinations of input variable levels.

An important element of experimental planning using Taguchi method is that the two important output variables that characterize the research, the Signal factor (the response function or output variable) and the disturbing factors Noise, which are generally uncontrollable variables, are optimized together by the so-called S/N - ratio. The higher this ratio is, the better it is, and the joint, cumulative evaluation of signal and noise gives greater robustness to the research.

The Taguchi method allows an efficient calculation of the average effects of the variables on the response magnitudes, allowing several restrictive conditions to be met.

The results obtained from the FEM analysis are shown in table 3. where, in addition to the actual values of the response functions, the Signal/Noise ratios are also shown, a characteristic result of the Taguchi method.

Depending on the criteria to be optimized, three approaches of S/N ratio are established: "smaller is better", "nominal is better" and "larger is better". Since in our research we aim to minimize the response function values we will choose for optimization, the criterion "smaller is better".

Table 3. The result of the Taguchi orthogonal array L9(3^3) – the input and output variables

	INPUT VARIABLES			OUTUT VARIABLES	
	V1	V2	V3	VON MISES STRESS	S/N RATIO
		[^{o}]	[mm]	[MPa]	
1	MOWHTO	6	8	122.254	-41.7453
2	MOWHTO	10	10	112.832	-41.0486
3	MOWHTO	14	12	135.258	-42.6233
4	CWHTO	6	10	61.315	-35.7513
5	CWHTO	10	12	66.100	-36.4040
6	CWHTO	14	8	352.218	-50.9362
7	BOWHTO	6	12	42.594	-32.5870
8	BOWHTO	10	8	193.840	-45.7489
9	BOWHTO	14	10	199.670	-46.0063

Table 4 shows the mean response values of the S/N ratios analysing the effect of the three input variables on the Equivalent Von Mises Stress response function.

Table 4 Response Table for signal to noise ratio (S/N) for the Equivalent Von Mises Stress

Level	OSTEOTOMY	CORRECTION ANGLE	POSITION
	-	[grade]	[mm]
1	-41.81	**-36.69**	-46.14
2	**-41.03**	-41.07	-40.94
3	-41.45	-46.52	**-37.20**
Delta	**0.78**	**9.83**	**8.94**
Rank	**3**	**1**	**2**

It results from the table which are the optimal levels of the influence factors for which the highest S/N ratio and consequently the lowest Von Mises equivalent stress is obtained. These are: OSTEOTOMY level 2 i.e. CWHTO (S/N=-41.03), for CORRECTION ANGLE level 1 with a value of 6 degrees (S/N=5.6383) and for POSITION level 3 with the value of 12 mm (S/N=10.5112). On the last two lines of the table there are two Delta and Rank measures reflecting the impact that the input variables have on the output variable and which variable has the greatest impact on the response. Delta represents the difference between the highest and the lowest response value and the rank indicates that the greatest influence on the Von Mises equivalent stress is CORECTION ANGLE followed by POSITION.

These influences and dependencies are even more suggestive plotted in figures 8 and 9. Figure 8 shows the average effects of the influencing factors on the S/N ratio and Figure 9 the same average effects on the mean value.

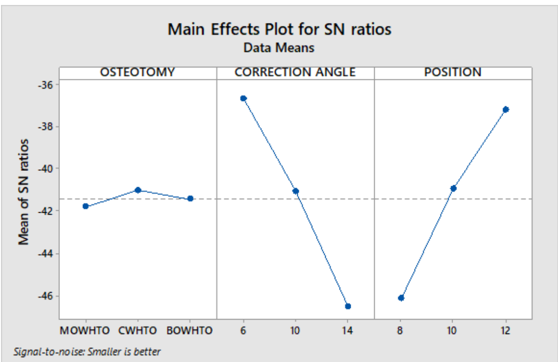

Figure 8. The main effect plot for S/N ratio

The importance of CORRECTION ANGLE and POSITION is emphasized for which in both graphs a very steep slope between the levels of influence of these factors is noticeable.

According to both the diagrams presented above and Table 4, the angle of correction and the position of the CORA in respect to the lateral cortex are more important than the type of osteotomy. The "Delta" values for these variables (V2 and V3) are about ten times higher than for the HTO type variable (V1). For this variable even if in the case of the main effect plot for Means (figure 9) there is some variation in the case of the main effect plot for S/N ratio the graph is nearly a horizontal line, hence the type of HTO does not have a considerable significance in terms of the state of the stresses in the CORA.

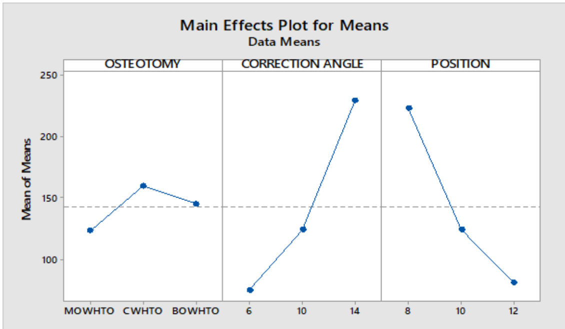

Figure 9. The main effect plot for Means

Comparing the influences of the other two variables V2 and respectively V3 they are close with a more important effect for "Correction Angle". For this variable in the case of the main effect plot for S/N ratio (figure 8) the slope of the graph line is steep and almost linear between the three levels of variation. For the variable "Position" in the same figure there is a slight change of slope with a slightly steeper slope between 8 and 10 mm.

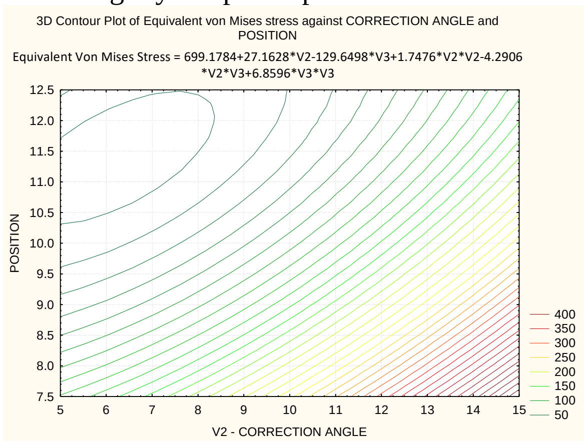

Figure 10. 3D Contour Plot of Equivalent von Mises stress against CORRECTION ANGLE and POSITION

Considering the importance of variables 2 and 3 we consider that it is important to establish certain dependencies between them, dependencies useful for surgeons in the geometric planning of HTO.

These dependencies were realized in the format of a 2nd rank regression equation and a nomogram expressing 3D Contour Plot of Equivalent von Mises stress against CORRECTION ANGLE and POSITION (figure 10). Both the regression equation and the nomogram were realized using STATISTICA 12 software.

4 CONCLUDING REMARKS

The study presented in this article is an original contribution on the geometric planning of a surgical intervention widely used to treat osteoarthritis of the knee, namely HTO. It is an interdisciplinary approach in which specific engineering research methods were used, i.e. Finite element Method or Design of Experiment using Taguchi Method. It allowed an optimization of the geometric planning of the HTO procedure considering the type of HTO, the angle of correction and the position of the CORA in correspondence to the lateral cortex of the tibia, the response function being the von Mises Equivalent in CORA. The optimal combination of the levels of variation of these variables was established, namely CWHTO, correction angle 6 degrees and Position 12 mm.

Although CWHTO was optimal for the osteotomy type, taking into account the very slight difference in effect compared to OWHTO type, we can conclude that the latter type of HTO can be selected in the surgical strategy taking into account the advantages it has, and which have also been presented in the paper. For these two variables the influence is significant on the response function. The 2nd rank regression equation as well as the realized nomogram are considered to have a very high practical utility for the choice of the optimal values in the geometric planning of HTO.

5 REFERENCES

Alagha R., (2009) - PhD Thesis, Iași.

Amendola, A., Bonasia, D.E., (2009) Results of high tibial osteotomy: Review of the literature. Int. Orthop., 34, pp. 155–160.

Amis, A.A., (2012) *Biomechanics of high tibial osteotomy*, Knee Surg. Sports Traumatol. Arthrosc., 21, pp. 197–205.

Cofaru, I.,I. (2013) *Cercetări privind biomecanica deviațiilor axiale ale membrului inferior uman și dezvoltarea unor echipamente chirurgicale aferente* – PhD Thesis.

Cofaru, I.I., Oleksik, M., Cofaru, N.F., Branescu, A.H., Haşegan, A., Roman, M.D., Fleaca, S.R., Dobrotă, R.D. (2022) *A Computer-Assisted Approach Regarding the Optimization of the Geometrical Planning of Medial Opening Wedge High Tibial Osteotomy*. *Appl. Sci.*, *12,* 6636.

Cofaru, N.F., Oleksik, V., Cofaru, I.I., Simion, C.M., Roman, M.D., Lebada, I.C., Fleaca, S.R. (2022) *Geometrical Planning of the Medial Opening Wedge High Tibial Osteotomy — An Experimental Approach.* Appl. Sci., 12, 2475.

Cofaru, N.F., Cofaru, I.I., Brănescu, A.H., Avirgean, E. (2024) *A CAD-CAE modelling of the biomechanics of the biplanar medial opening wedge high tibial osteotomy*, Acta Technica Napocensis - Series: Applied Mathematics, Mechanics and Engineering [S.l.], v. 67, n. 1s, jan. 2024. ISSN 2393–2988.

Elson, D.W., Petheram, T.G., Dawson, M.J. (2015) *High reliability in digital planning of medial opening wedge high tibial osteotomy, using Miniaci's method*. Knee. Surg. Sports Traumatol. Arthrosc., 23, 2041–2048, doi:10.1007/s00167-014-2920-x.

Hoffler, C. E., Moore, K. E., Kozloff, K., Zysset, P. K., & Goldstein, S. A. (2000). *Age, gender, and bone lamellae elastic moduli.* Journal of Orthopaedic Research, 18(3), 432-437.

Insall J.N., Joseph D.M., Msika, C. (1984) *High tibial osteotomy for varus gonarthrosis.* A longterm follow-up study. J Bone Jt Surg Am; 66(7):1040–8.

Kwun, J.D., Kim, H.J., Park, J., Park, I. H., Kyung, H.S. (2017) *Open wedge high tibial osteotomy using three-dimensional printed models: Experimental analysis using porcine bone*. Knee, 24, pp. 16–22.

Lee, S.C., Jung, K.A., Nam, C.H., Jung, S.H., Hwang, S.H. (2010) *The short-term follow-up results of open wedge high tibial osteotomy with using an Aescula open wedge plate and an allogenic bone graft: the minimum 1-year follow-up results.* Clin Orthop Surg.;2(1): pp. 47–54.

Liu, X., Chen, Z.; Gao, Y.; Zhang, J.; Jin, Z. (2019) *High Tibial Osteotomy: Review of Techniques and Biomechanics.*, J. Health Eng.

Luo, C.A., Hua, S.Y., Lin, S.C.(2013) *Stress and stability comparison between different systems for high tibial osteotomies.*BMC Musculoskelet Disord.

Luo C.A., Lin S.C., Hwa S.Y., Chen C.M., Tseng C.S. (2015) *Biomechanical effects of plate area and locking screw on medial open tibial osteotomy.* Comput Methods Biomech Biomed Engin.

Pape, D., Dueck, K., Haag, M., Lorbach, O., Seil, R., Madry, H., (2013) *Wedge volume and osteotomy surface depend on surgical technique for high tibial osteotomy*, Knee Surg Sports Traumatol Arthrosc.

Staubli, A.E., De Simoni, C., Babst, R., Lobenhoffer, P., (2003) *TomoFix: a new LCP-concept for open wedge osteotomy of the medial proximal tibia--early results in 92 cases.* Injury.;34(Suppl 2):B pp. 55–62.

Tomofix Medial High Tibial Plate for Medial Tibial Osteotomy, accessed on 15 January 2022.

Yang, J.C., Chen, C.F., Luo, C.A., Chang, M.C., Lee, O.K., Huang, Y., Lin, S.C. (2018) *Clinical Experience Using a 3D-Printed Patient-Specific Instrument for Medial Opening Wedge High Tibial Osteotomy.* BioMed Res. Int., pp. 1–9, doi:10.1155/2018/9246529.