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GEOMETRIC ACCURACY ANALYSIS IN MESH-TO-SOLID CONVERSION FOR 3D ANATOMICAL MODELS THROUGH TAGUCHI METHODOLOGY

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Highlights:

- A methodology was developed for the processing of meshes of 3D surface models for mesh-to-solid conversion.
- The smooth factor had the greatest impact, followed by remesh, while polygon reduction was less significantly relevant.
- Statistical analysis showed that different conversion techniques produced geometrical differences.
- Deviations in both the methodology and the techniques employed result in a minimum loss of geometric information.

Abstract:

Three-dimensional reconstruction of anatomical models from clinical data faces challenges in maintaining geometric fidelity during the conversion of surface models to parametric solids. Mesh processing techniques, such as smoothing, remeshing, and polygon reduction, aim to optimize mesh quality but can lead to loss of geometric information. A methodology was developed to process 3D surface meshes and convert them into solids from both faceted and organic geometries. The impact of different processing parameters on mesh topology and post-conversion geometry was evaluated using the Taguchi methodology with an L16 orthogonal design, analyzing three factors: smooth factor, remesh, and polygon reduction percentage. The smooth factor had the most significant influence ($p < 0.01$), followed by remesh ($p < 0.05$), while polygon reduction was not statistically significant ($p > 0.05$). Conversion techniques produced significant differences ($p = 0.0012$), with faceted geometries yielding results closer to the target. Geometric deviation analysis using bidirectional Hausdorff distance demonstrated sub-millimetric discrepancies in all cases. Faceted models showed RMS values between 0.067 and 0.183 mm while organic models ranged from 0.076 to 0.225 mm with minimal deviation. Volumetric analysis revealed moderate reductions averaging $4.53 \pm 2.88\%$ for faceted and $4.98 \pm 3.07\%$ for organic geometries without volumetric expansion. Despite slightly higher sensitivity in organic models, deviations remained within acceptable tolerances for anatomical reconstruction and computational biomechanics, indicating preserved morphological fidelity after processing.

Keywords: 3D modeling, geometric analysis, mesh analysis, mesh conversion, taguchi methodology.

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1. Introduction

Three-dimensional reconstruction of anatomical models from clinical data presents fundamental challenges related to geometric fidelity during the transition from polygonal surface model representations to parametric solids (Drakopoulos et al., 2024). The conversion of three-dimensional models from surface models to solid is a fundamental process in various applications, including biomechanical engineering, additive manufacturing, structural analysis, and computer-aided design (CAD). Specifically, three-dimensional anatomical models derived from medical imaging, such as computed tomography (CT) or magnetic resonance imaging (MRI),

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are frequently generated as surface meshes in STL or OBJ formats. However, these representations lack a defined volume, necessary topological properties, and may undergo geometric alterations during refinement processes, which are needed for an adequate analysis (Remondino & El-Hakim, 2006; Shirshin et al., 2021).

There are mainly two techniques for converting meshes to solids: faceted and organic geometry. Faceted geometry constructs solid bodies while maintaining the flat polygon structure that defines the original mesh. On the other hand, organic geometry generates smooth surfaces through interpolation or envelopes adapted to curved shapes, making it especially suitable for complex biological morphologies. The choice between these techniques has a significant impact on the geometric accuracy of the final model, as well as its compatibility with CAD/CAM software and finite element analysis (FEA) (Nava-Alcantar et al., 2025; Park et al., 2019; Wang et al., 2022).

Mesh processing techniques such as smoothing, reducing, and remeshing are usually applied to optimize mesh quality and reduce computational complexity. However, these procedures can induce a loss of geometrical information whose magnitude and effects are not yet fully characterized (Chin et al., 2021; Keast et al., 2023; Veneziano et al., 2018; Zhou et al., 2024). The geometric accuracy of the conversion process directly influences surface area measurements, which serve as quantitative indicators of topological fidelity. These measurements allow for the detection of deformations and irregularities in the geometry. It is very sensitive to changes in the local topography, such as bumps, depressions, and roughness, and is frequently used to compare models after processing (Gharehtappeh & Peng, 2021; Kim et al., 2019). Comparative studies show that differences between reverse-engineered solid models generated by different solid modeling workflows deliberately influence the models when mesh processing methods are applied (Gargallo-Peiró et al., 2014; Wakjira et al., 2024). Accuracy in these metrics is essential for applications in FEA and personalized ergonomic device design, where geometric discrepancies have minimal tolerances. Changes in model parameters can severely affect models if the process is not performed correctly and robustly (Campen et al., 2015).

The objective of this work is to analyze the changes in the morphology of 3D anatomical models induced by mesh processing and mesh-to-solid conversion through of different processing techniques, to quantify the associated topological alterations, and to determine the existence of statistically significant differences between the different groups of models, using a design of experiments to test different configurations of the parameters that most influence this phenomenon.

2. Methods

2.1. Mesh-to-solid conversion methodology

A methodology was developed for the processing of meshes of 3D surface models oriented to the conversion of mesh-to-solid, generated by faceted and organic geometry, as shown in Figure 1.

A CT scan of a human lower limb (a 30-year-old adult male) was used to create the three-dimensional tibial model; the tibia was selected due to its simple geometry. The surface modeling technique was used to generate a three-dimensional model from a CT scan using 3D Slicer software (version 5.6.1, The Slicer Community, Boston, Massachusetts, USA).

Subsequently, a post-processing process was carried out in Autodesk® Meshmixer (version 3.5, Autodesk® Inc., San Rafael, California, USA); the ‘smooth mesh’ tool was used to smooth the surfaces, and the ‘reduce’ function was applied to simplify the mesh. Finally, the retopology tool in Autodesk® Maya (version 2024, Autodesk® Inc., San Rafael, California, USA) was used to convert the triangular mesh into a clean quadrilateral mesh. Retopology was selected as a remesh technique because this process optimizes a high polygon count, irregular surface, and unoptimized structure mesh into a more manageable model.

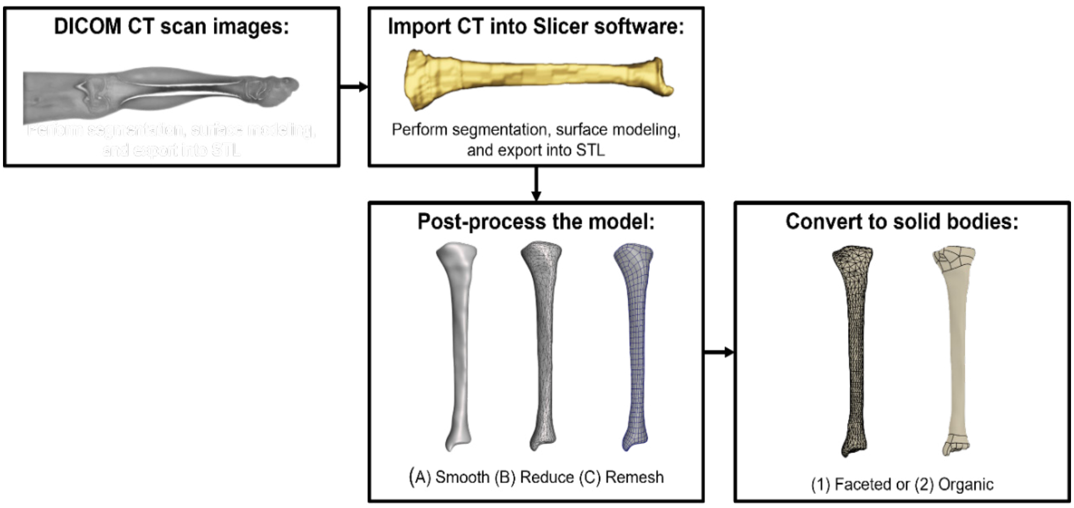

Figure 1: Mesh optimization for the mesh-to-solid methodology.

Autodesk® Fusion 360 (version 2.0, Autodesk® Inc., San Rafael, California, USA) and the 'convert mesh' tool were used to transform the mesh model into a solid body, applying parametric geometric operations. Two types of geometry were used: faceted (flat surfaces for angular shapes) and organic (soft and natural shapes). A high conversion parameter was selected for converting to organic geometry, resulting in a solid body that matches the shape of the mesh body. The prismatic geometry technique was not considered because this mesh conversion method is only used for prismatic shapes.

2.2. Design of experiments

The Taguchi methodology was used as a design of experiments (DOE) applying an orthogonal arrangement L16 corresponding to a design with three factors, each with four levels. The Taguchi methodology was chosen as an experimental design due to its ability to evaluate the individual effect of each factor and its relative contribution to the optimization of the response variable. The L16 orthogonal array was selected because it enables a structured evaluation of four factors, each at four levels, while preserving orthogonality. This arrangement allows for the independent estimation of main effects. It provides enough resolution to identify the most influential parameters while still being feasible for experimentation.

The factors considered were the tools previously utilized for processing its mesh. The levels assigned to each factor were: (A) smooth factors of (1) 4.0, (2) 12.0, (3) 24.0, (4) 36.0 were considered, being a low, medium, high and very high smooth factor respectively; for (B) Remesh, using the retopology technique to remeshing the models, the values of (1) 1000, (2) ,000, (3) 5000, and (4) 7000 faces were selected; and for the (C) percentage of reduced polygons, values of (1) 10%, (2) 50, (3) 70% and (4) 90% were taken. With these parameters and using Autodesk® Meshmixer software, sixteen different models were generated according to the combinations defined in the DOE. Subsequently, using Autodesk® Fusion 360, the conversion from mesh-to-solid was carried out using both faceted and organic geometry, obtaining a total of thirty-two solid models (sixteen faceted and sixteen organic) are shown in Figure 2.

2.3. Geometric measurements of the models

Once the models were converted to solids, MeshLab® software (version 2025.07, Visual Computing Lab – ISTI-CNR, Pisa, Italy) was used to obtain the metrics considered in the analysis. The values of 'mesh surface area' (mm²) are shown in Table 1.

As a nominal reference for comparison with the models generated from Taguchi's experimental array, the geometry obtained directly from the segmentation of raw images was used, without applying any mesh processing and preserving the segmented geometry as faithfully as possible to the tomography. Under this assumption, it was considered that the value of the 'mesh surface area' represents the real dimensions of the tibia, with a value of 446.27 mm².

Table 1: Response variable measures.

A	B	C	Faceted (mm^2)	Organic (mm^2)
1	1	1	422.53	411.70
1	2	2	431.14	429.28
1	3	3	432.74	428.87
1	4	4	431.97	428.88
2	1	2	414.24	403.05
2	2	1	421.68	418.71
2	3	4	421.58	420.17
2	4	3	423.16	422.19
3	1	3	403.17	394.78
3	2	4	408.18	405.94
3	3	1	410.51	408.79
3	4	2	410.71	409.23
4	1	4	389.57	382.09
4	2	3	396.69	395.09
4	3	2	397.28	397.28
4	4	1	398.88	398.48

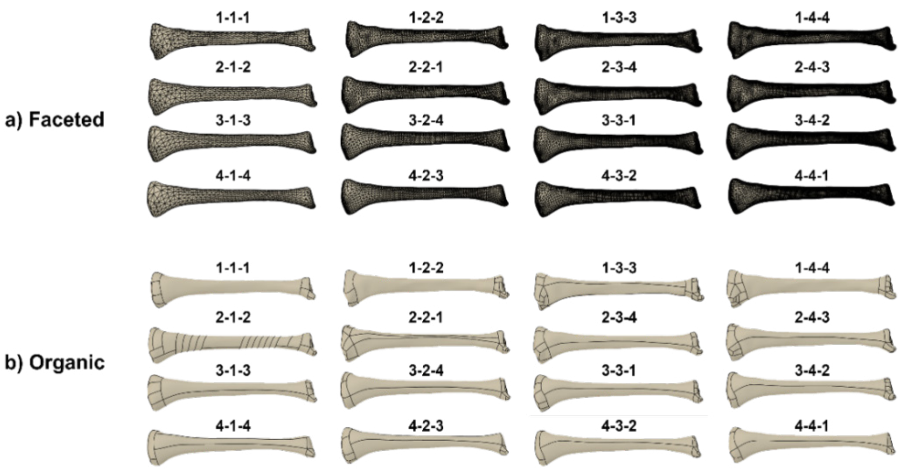

Figure 2: Models obtained from the DOE mesh-to-solid methodology. a) Faceted models. b) Organic models.

Additionally, to validate the geometric changes of the models and analyse their deviations, the Hausdorff distance technique was used, which measures the distance between two compact subsets of a metric space (Aspert et al., 2002; Cignoni et al., 1998), as well as the volumetric deviation to quantify the difference in the dimensions between different 3D models (Eisert, 2006; Tubic et al., 2003).

3. Results

To evaluate the significance of the factors analyzed on the response variables, a Signal-to-Noise ratio (S/N) analysis was carried out under the criterion of 'nominal is better'. This criterion is commonly applied when looking for a feature to be as close as possible to an ideal target value, minimizing quality loss due to deviation. In this case, a value close to the ideal value is considered to indicate a minimal change in the morphology of the model. RStudio® software (version 2024.12 / Posit®, Boston, Massachusetts, USA) was used to perform the statistical analysis of the data.

3.1. Descriptive statistics

A descriptive statistical analysis was performed for both groups of models to quantify the deviation of the geometric metrics from the original geometry, as shown in Figure 3. In terms of 'mesh surface area', faceted models presented an average of 413.38±13.70 mm², while organic models reached 409.66±14.16 mm². Both values show a significant reduction compared to the original value, that is 446.27 mm², with deviations of 7.40% and 8.20%, respectively, being the difference between the two methods compared to the loss of surface.

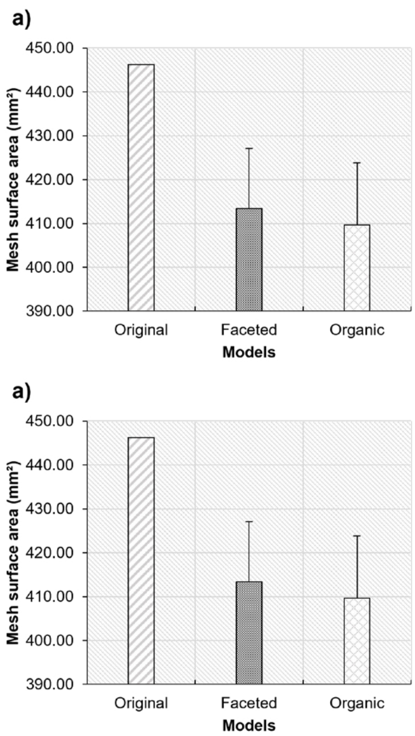

Figure 3: Descriptive statistical measures of mesh surface area.

3.2. S/N and ANOVA analysis

The analysis of the S/N ratio for the faceted models, as shown in Figure 4a and detailed in Table 2, indicates that the 'smooth factor' dominates with 90.52% of the variability (F-value = 129.35, p-value = 1×10^{-5}), followed by 'remesh' with 7.44% (F-value = 10.63, p-value = 0.0082). The 'percentage of reduced polygons' count is significantly lower at 0.64% (F-value = 0.92, p-value = 0.4874). The low residual error of 1.40% suggests the model fits well.

Table 2: ANOVA for S/N ratio of faceted models.

Factor	Df	Sum Sq	Mean Sq	F-value	p-value	Contribution (%)
Smooth factor	3	219.32	73.10	129.35	1×10^{-5}	90.52
Remesh	3	18.03	6.01	10.63	0.0082	7.44
% Reduced polygons	3	1.55	0.52	0.91	0.4874	0.64
Residuals	6	3.39	0.57	-	-	1.40

In the analysis of means, showed in Figure 4b and detailed in Table 3, the 'smooth factor' accounts for 92.74% of the variation (F-value = 1,494.37, p-value = 1×10^{-7}), 'remesh' contributes 7.05% (F-value = 113.55, p-value = 1×10^{-5}), and the 'percentage of reduced polygons' remains statistically insignificant at 0.09% (F-value = 1.43, p-value = 0.3242). The residual error is minimal at 0.12%.

Table 3: ANOVA for means of faceted models.

Factor	Df	Sum Sq	Mean Sq	F-value	p-value	Contribution (%)
Smooth factor	3	2609.38	869.79	1494.37	1×10^{-7}	92.74
Remesh	3	198.27	66.09	113.55	1×10^{-5}	7.05
% Reduced polygons	3	2.49	0.83	1.43	0.3242	0.09
Residuals	6	3.49	0.58	-	-	0.12

Similarly, in the organic models, the 'smooth factor' remains the predominant factor, contributing 74.38% (F-value = 56.88, p-value = 8×10^{-5}) to the variability of the S/N ratio, as shown in Figure 5a and detailed in Table 4. In comparison, the 'remesh' factor is the second most relevant factor with an approximate contribution of 21.98% (F-value = 16.81, p-value = 0.0025).

Table 4: ANOVA for S/N ratio of organic models.

Factor	Df	Sum Sq	Mean Sq	F-value	p-value	Contribution (%)
Smooth factor	3	151.99	50.66	56.88	0.0001	74.38
Remesh	3	44.91	14.97	16.81	0.0025	21.98
% Reduced polygons	3	2.10	0.70	0.79	0.5441	1.03
Residuals	6	5.34	0.89	-	-	2.62

In contrast, the variable 'percentage of reduced polygons' has no significant impact on the response variable since its marginal contribution is 1.03% (F-value = 0.79, p-value = 0.5441). The analysis of means, shown in

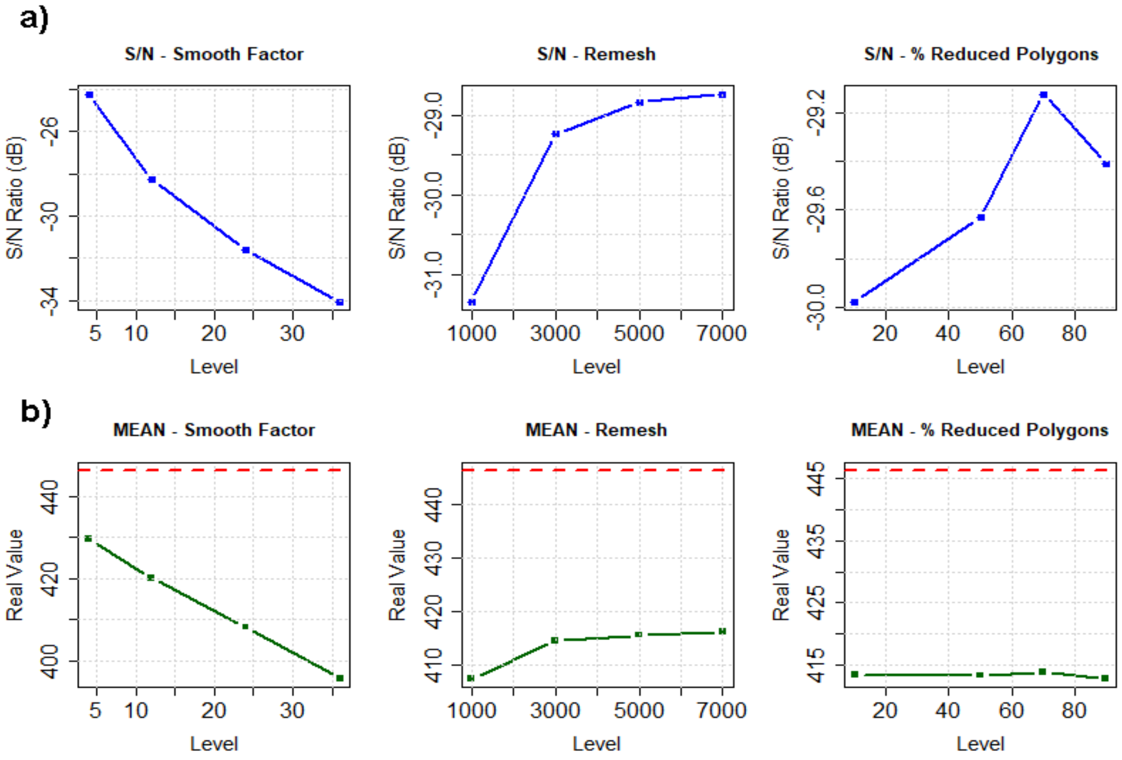

Figure 4: Main effects graphs for faceted models. a) S/N ratio "nominal is better". b) Means.

Figure 5b and detailed in Table 5, indicates that the 'smooth factor' remains the most influential, accounting for 74.59% of the variation ($F = 338.21$, $p = 1\times10^{-8}$). 'remesh' contributes 24.90% ($F = 112.91$, $p = 1\times10^{-5}$), while the 'percentage of reduced polygons' is statistically insignificant at 0.07% ($F = 0.33$, $p = 0.81$). The residual error is minimal at 0.44%.

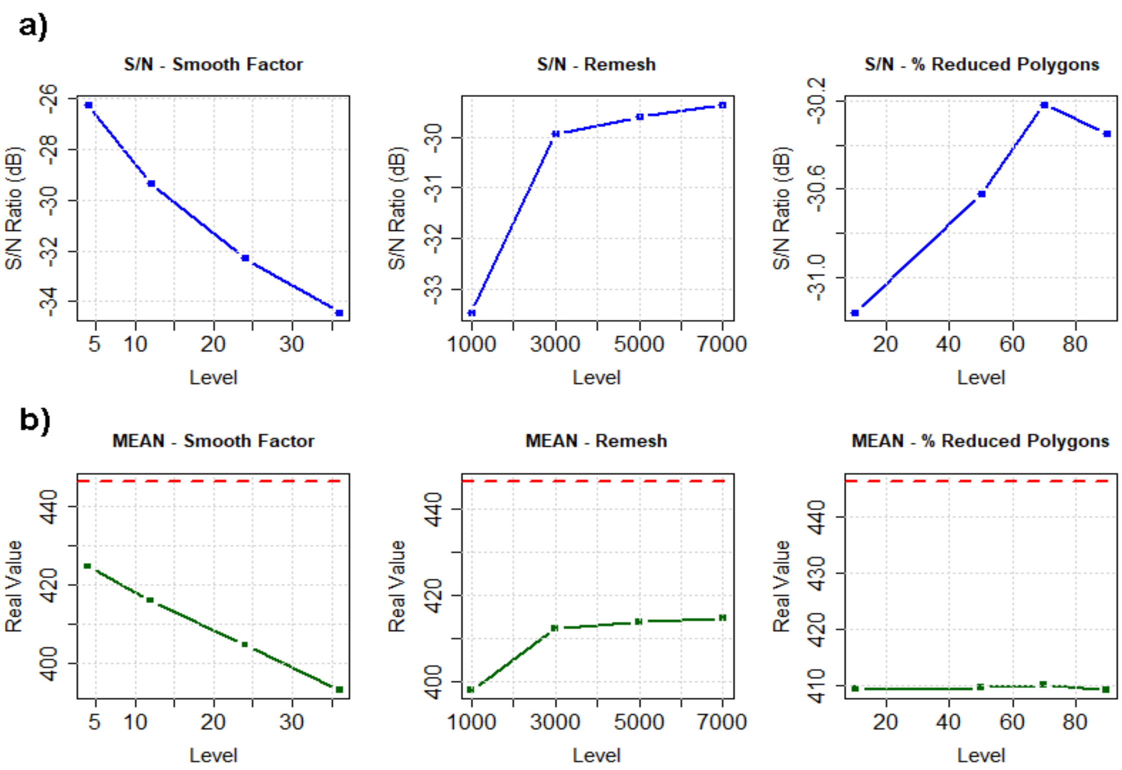

Figure 5: Main effects graphs for organic models. a) S/N ratio "nominal is better". b) Means.

Table 5: ANOVA for means of organic models.

Factor	Df	Sum Sq	Mean Sq	F-value	p-value	Contribution (%)
Smooth factor	3	2243.13	747.71	338.21	1×10^{-8}	74.59
Remesh	3	748.88	249.63	112.91	1×10^{-5}	24.90
% Reduced polygons	3	2.16	0.72	0.33	0.3242	0.07
Residuals	6	13.26	2.21	-	-	0.44

For both mesh-to-solid conversion methods, the 'smooth factor' is the most critical parameter, as it controls the mesh surface and significantly alters the mesh topology, potentially causing substantial loss of geometry as the 'smooth factor' increases. 'Remesh' has a secondary but important effect due to the remeshing technique (retopology), which reconstructs the model mesh from a triangular to a cleaner quadratic mesh, although with some geometric loss. Finally, the 'percentage of reduced polygons' does not significantly influence the results in any of the analyses, indicating that reducing polygon count is unnecessary if remeshing techniques like retopology are used. According to the main effect graphs, the most optimal settings suggest a 'smooth factor' of 4.0, a 'remesh' that involves a count of 7000 or more polygons, and a 'percentage of reduced polygons' up to 70%, despite not being able to reach the objective value of the original geometry, which indicates that necessarily when processing the mesh there is geometric loss.

A Student's t-test was carried out for paired samples to compare the measurements of both groups of models and evaluate whether the observed difference is statistically significant. To do this, a Shapiro-Wilk normality test was performed to assess whether the data were normally distributed. The results showed that both groups follow a normal trend, with a p-value of 0.4129 for the faceted models and a p-value of 0.5089 for the organic models.

Once this was done, a p-value of 0.0012 was obtained from Student's t-test, demonstrating that there is a statistically significant difference between the two mesh-to-solid conversion techniques. Faceted geometry produces significantly higher values than Organic geometry. As shown in Figure 6, the graph compares two methods, faceted and organic, with the faceted method showing higher median values.

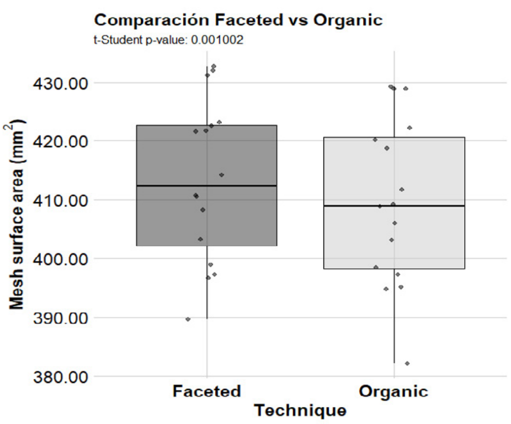

Figure 6: Comparison of mesh surface area by technique.

Despite this slight difference in the central trend, both distributions show a very similar dispersion and considerable overlap between their interquartile ranges, suggesting that there is no drastic difference in the resulting surface area between the two methods, although the faceted geometry data tend to be at marginally higher values.

3.3. Geometric deviation analysis

Geometric accuracy was evaluated through bidirectional Hausdorff distance analysis performed in MeshLab® after rigid registration using the iterative closest point (ICP) algorithm. Maximum deviation and root mean square (RMS) surface deviation were computed. Additionally, volumetric deviation was quantified as the relative percentage difference between the reference and processed meshes.

3.4. Volumetric deviation

Volumetric deviation was quantified as the relative percentage difference between each processed mesh and the reference volume (345.22 mm³). In all cases, both faceted and organic models exhibited a slight deviation, indicating consistent volumetric underestimation following mesh processing.

The faceted models presented a mean volumetric deviation of 4.53 ± 2.88%, with no cases of expansion with respect to the reference geometry. This shrinkage is associated with smoothing and remeshing processes that attenuate surface irregularities without generating significant structural distortion. Organic models showed a slightly higher mean deviation with a 4.98 ± 3.07%, also without volumetric overestimation. Its greater sensitivity is explained by the complexity of curvature, where small displacements of vertices in convex regions produce cumulative reductions in volume. The volumetric loss is moderate and consistent, resulting from controlled geometric regularization with no signs of deformation.

3.5. Hausdorff distance analysis

Bidirectional Hausdorff distance analysis showed that both faceted and organic models exhibit submillimeter deviations and high geometric fidelity from the originals.

In the faceted models, RMS values ranged from 0.067 mm to 0.183 mm, with averages of 0.104 mm (faceted to original) and 0.115 mm (original to faceted). Directional deviation was minimal at 0.01 mm. Maximum deviations remained below 0.45 mm, with no evidence of structural distortion. The alterations introduced by the faceting process are negligible and do not compromise subsequent biomechanical analyses.

In the organic models, the deviations were slightly larger due to their greater geometric complexity. RMS values ranged from 0.076 mm (original to organic) to 0.225 mm (organic to original), with averages of 0.122 mm and 0.136 mm depending on the direction of comparison, and an average deviation of 0.014 mm. Although they show greater sensitivity to processing, all deviations remain within acceptable tolerances for anatomical reconstruction and computational modeling. Together, both types of models maintain morphological integrity and geometric accuracy suitable for biomechanical applications.

Table 6: Comparison of both model groups.

Parameters	Faceted (mm)	Organic (mm)
Average RMS	0.104	0.122
Bidirectional increment	0.010	0.014
Maximum RMS	0.183	0.225
Maximum average	0.390	0.470

As shown in Table 6, when both datasets were evaluated together, faceted models show slightly lower deviation magnitudes than organic models, as expected due to their lower curvature complexity and sharper geometric transitions. Organic surfaces amplify small vertex relocations because curvature continuity increases sensitivity to smoothing and remeshing operations. When both datasets are evaluated together, faceted models show slightly lower deviation magnitudes than organic models, as expected due to their lower curvature complexity and sharper geometric transitions. Organic surfaces amplify small vertex relocations because curvature continuity increases sensitivity to smoothing and remeshing operations.

The Hausdorff average deviation maps shown in Figure 7 revealed a consistent spatial pattern across all configurations, with higher deviations localized in high-curvature epiphyseal regions and lower deviations along the diaphyseal shaft. No global distortion patterns were observed, indicating that mesh processing primarily affects curvature-sensitive areas rather than inducing structural displacement.

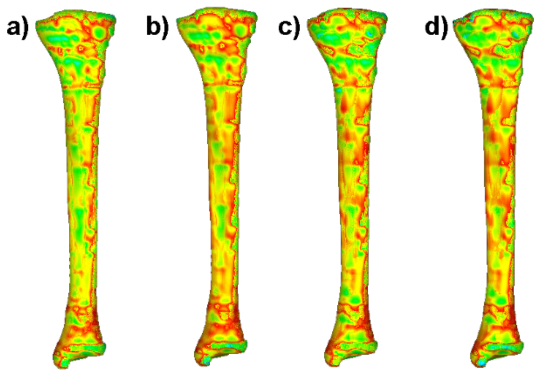

Figure 7: Hausdorff's average deviation maps. a) Faceted to original. b) Original to faceted. c) Organic to original. d) Original to organic.

4. Discussions

The objective of this work was to compare both techniques of conversion from mesh to solid and analyze their differences with respect to their original geometry, and to be able to quantify how much geometric loss exists when the mesh is processed to make it more manageable. The selected factors were chosen because they directly govern the geometric behavior of mesh processing operations and represent the parameters most commonly adjusted in biomedical modeling workflows. Specifically, smoothing intensity, mesh resolution, and remeshing constraints influence vertex displacement magnitude, curvature preservation, and surface regularization.

The results revealed an evident hierarchy in the influence of control parameters on mesh processing and mesh-to-solid conversion. The 'smooth factor' turns out to be the determining variable of the change in the topology of the mesh and the final result of the model, explaining between 74% and 92% of the variability of the surface area in both techniques, this is attributed to how the smoothing process alters the topology of the mesh by averaging the positions of the vertices, resulting in a contraction in the surface of the model (Bacciaglia et al., 2021; Vollmer et al., 1999). As the level of smoothing increases to improve surface continuity, dimensional accuracy is sacrificed in relation to the original geometry.

The parameter 'remesh' showed a secondary but significant influence. The transition from a triangular mesh to a quadratic mesh by retopology introduces an inherent geometric simplification, typical of the various remeshing techniques that could vary the influence of this factor on the geometry of the model (Montagnat et al., 2001; Rossoni et al., 2020). This also indicates that it is necessary to have a greater number of faces to have more geometric fidelity, although to validate this statement, it must be verified if there are statistically significant differences when using a face count beyond 5000.

A notable finding is the statistical irrelevance of the 'percentage of reduced polygons', this suggests that within the workflow studied, the initial density of the mesh is less critical than the subsequent reconstruction operations, and in practical terms, this implies that it is not necessary to implement this processing technique unless the reduction of file weight is sought to work with lighter files, but without compromising the final quality of the mesh, provided that appropriate processing techniques are applied. However, if this tool is used in a bad way, that is progressively reducing the polygons of a mesh more than it should, it can deform the model, damaging the topology of the mesh to the point of reaching a zero geometry, losing all model (Gharehtappeh & Peng, 2021; Ju, 2009; Nooruddin & Turk, 2003).

On the other hand, both techniques resulted in a reduction of the mesh surface area, with operational differences between them. Student's t-test confirmed that there is a significant difference, where faceted models retain a higher average surface area compared to organic models with respect to the original value. This is due to the algorithmic processing performed by the mesh-to-solid technique by the organic method, as this technique tends to smooth the shape of the model with respect to the number of faces that can be generated, while the faceted technique maintains a more rigid and polygonal structure, which preserves the shape of the processed model without the need to interpolate it further. However, despite the statistical differences, the interquartile ranges overlap and show similar dispersion, suggesting that both techniques are valid, with no noticeable differences in practice, and the choice of conversion technique could depend more on aesthetic or functional requirements, such as FEA applications or product design.

The quantitative trends identified through the Taguchi design offer direct guidance for optimizing mesh processing parameters. The results showed that the optimal combination of parameters leads to a lower RMS deviation. However, this does not necessarily minimize volumetric loss, underscoring the importance of multi-objective evaluation. From a practical perspective, the findings indicate that moderate smoothing levels help maintain geometric fidelity while preventing excessive volumetric contraction. In contrast, organic geometries require more conservative parameter settings due to their higher sensitivity to curvature. Furthermore, a bidirectional RMS evaluation should be preferred over unidirectional metrics to effectively detect deviations between samples in relation to the target, and vice versa.

Certain methodological limitations were identified in the study. Although an optimal configuration was found based on the "nominal is better" criterion, there is evidence of an inherent limitation in both current mesh processing techniques and the conversion from mesh to solid geometry. Specifically, it is impossible to fully replicate the original geometry. The observed deviations suggest that both the methodology and the techniques employed result in a loss of geometric information, which must be addressed or regarded as a margin of error.

One important factor affecting the loss of geometric information is the resolution of the CT scan. This resolution impacts the segmentation of images during the geometry reconstruction process (Remondino & El-Hakim, 2006; Stelldinger et al., 2007). Additionally, when comparing the segmented images to actual measurements of the tibia, any assumptions made may introduce biases if precise geometric accuracy is prioritized. Finally, there are various techniques related to the methodology discussed, which may differ based on the software used and variations in parameters.

On the other hand, this study focuses on a single anatomical geometry, which limits the generalizability of the findings. Anatomical structures vary greatly in curvature, topology, and morphology, so the results cannot be applied universally. The tibia's combination of elongated diaphyseal regions and complex epiphyseal surfaces makes it a relevant case for evaluating mesh processing behaviour. The observed trends are significant for this specific geometry. However, these conclusions should not be extended to other bones or structures with different geometries. Future research should include various anatomical models to determine if the identified deviation patterns are consistent across different geometries. This would enhance the understanding of geometry-dependent sensitivity and broaden the applicability of the methodology.

It is important to acknowledge that such a geometry does not represent an absolute ground truth. CT-derived anatomical reconstructions inherently contain uncertainty arising from multiple sources, including voxel resolution limitations, segmentation threshold selection, interpolation procedures, and reconstruction artifacts. However, all comparative analyses were performed using the same reference dataset and identical imaging conditions. This ensures internal methodological consistency. While segmentation uncertainty may influence absolute geometric accuracy, it does not invalidate the relative comparisons between faceted and organic processing workflows. Future investigations incorporating higher-resolution imaging modalities, multi-threshold sensitivity analyses, or physical measurement validation would allow further quantification of segmentation induced uncertainty.

Finally, by applying a Taguchi methodology, the present study introduced a statistical framework for evaluating parameter influence on geometric accuracy. This structured approach enables identification of dominant factors and interaction effects rather than relying on heuristic parameter tuning.

5. Conclusions

The comparative analysis showed that the 'smooth factor' is the most influential variable in mesh processing and conversion to solids, since it dominates the variation of the surface area and causes geometric losses as the continuity of the surface increases. 'Remesh' has a secondary but significant effect, associated with the geometric simplification inherent in retopology processes, while the reduction of the 'percentage of polygons' is not relevant for the conservation of geometry and is only useful to reduce the size of the file. Both conversion techniques generate a decrease in surface area; Faceted models retain slightly higher values than organic models, although practical differences are limited, so the choice of method depends mainly on functional or application requirements. Finally, an intrinsic limitation of the workflow was identified, since the original geometry cannot be completely replicated, and the loss of information is conditioned by the processes employed.

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Author Contributions

Christian Enrique Nava-Alcantar: Conceptualization, formal analysis, methodology, investigation, and writing—original draft; Israel Miguel-Andrés: Supervision, visualization, and writing—review & editing; Jorge Armando Ramos-Frutos: Writing—review & editing, data curation; Didier Samayoa-Ochoa: Writing—review & editing, and technical data processing support; Javier Cruz-Salgado: Writing—review & editing; Agustín Vidal-Lesso: Writing—review & editing, visualization; Marco Antonio Martínez-Bocanegra: Writing—review & editing, and technical consistency review.

Conflicts of Interest

The authors declare no conflicts of interest. They confirm that they have no known financial interests or personal relationships that could have influenced the work presented in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors employed Grammarly to assist with translation, correct grammatical errors, and improve the overall quality of the language.

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