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Optimization of Prosthodontic Computer-Aided Designed Models: A Virtual Evaluation of Mesh Quality Reduction Using Open Source Software

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Abstract

Purpose: Mesh optimization reduces the texture quality of 3D models in order to reduce storage file size and computational load on a personal computer. This study aims to explore mesh optimization using open source (free) software in the context of prosthodontic application.
Materials and Methods: An auricular prosthesis, a complete denture, and anterior and posterior crowns were constructed using conventional methods and laser scanned to create computerized 3D meshes. The meshes were optimized independently by four computer-aided design software (Meshmixer, Meshlab, Blender, and SculptGL) to 100%, 90%, 75%, 50%, and 25% levels of original file size. Upon optimization, the following parameters were virtually evaluated and compared; mesh vertices, file size, mesh surface area (SA), mesh volume (V), interpoint discrepancies (geometric similarity based on virtual point overlapping), and spatial similarity (volumetric similarity based on shape overlapping). The influence of software and optimization on surface area and volume of each prosthesis was evaluated independently using multiple linear regression.
Results: There were clear observable differences in vertices, file size, surface area, and volume. The choice of software significantly influenced the overall virtual parameters of auricular prosthesis [SA: $F(4,15) = 12.93$, $R^2 = 0.67$, $p < 0.001$. V: $F(4,15) = 9.33$, $R^2 = 0.64$, $p < 0.001$] and complete denture [SA: $F(4,15) = 10.81$, $R^2 = 0.67$, $p < 0.001$. V: $F(4,15) = 3.50$, $R^2 = 0.34$, $p = 0.030$] across optimization levels. Interpoint discrepancies were however limited to <0.1mm and volumetric similarity was $>97\%$.
Conclusion: Open-source mesh optimization of smaller dental prostheses in this study produced minimal loss of geometric and volumetric details. SculptGL models were most influenced by the amount of optimization performed.

Dentistry has seen a rapid boom in digitization over the last decade[1] with prosthodontics at the heart of it.[2,3] However, while many companies have set industry standards in digital prosthetic rehabilitation, the cost of procuring such devices and services deter many clinicians from embracing digital prosthetic dentistry.[4] Furthermore, there is a widespread stigma that computer-aided design and graphical work require 'professional' computer setups.[5] In reality, as computer components are getting better (and relatively cheaper) with passing years, certain modifications made at the initial stages of digitization can in practice allow for practitioners to perform computer-aided designs from their personal computers.[4] A recent systematic review[1] suggested that while clinicians rely on various expensive services for their computer-aided design and manufacturing workflows there are various tools available and somewhat unexplored by dental professionals which can perform the same functions without costing much, if anything. The aforementioned modifications and tools need to be briefly elaborated in order to highlight their relevance to this study.

A 'mesh' in respect to digital prosthodontics is the 3D virtual model which geometrically mimics the physical subject or object and can be used in computer-aided design and manufacturing.[6] Mesh such as these are made up of vertices which connect to give the 3D model its shape and features. Ideally, the more vertices that are present within the model, the greater the details of the prosthesis; the enhanced detail comes at the cost of increased file size and computer processing power.[7] When a 3D model contains the maximum possible details, the mesh is considered to be in full resolution.[8] Larger virtual prostheses such as complete dentures and detailed extraoral maxillofacial prostheses in full resolution would inherently require greater computer storage. Additionally, the high computational power required to work on such models may not be present on the average clinician's computer and only serve as an added deterrent to adopting a digital workflow.[9] This issue has challenged information-technology developers and engineers for decades aiming to efficiently utilize computer storage space and minimize computer power requirements per task. This led to the development of 'mesh optimization' in an attempt to bring computer aided designs to the consumer level and at a lower cost.[10] Mesh optimization is the art of reducing the size of the mesh in order to allow the virtual 3D model to render with lesser computational power.[11]

There are various community[12] and project[13] driven software tools which carry out computer-aided designing for free. Such tools are often freely licensed and labelled as "free and open source software" (FOSS) or simply "open source."[14] As demonstrated in the past, such software are quite capable of carrying out prosthodontic treatment planning and have been proposed as accurate alternatives.[9,15] Some of these open source software have mesh optimization as a built-in feature. Therefore, use of open source software to optimize prosthodontic models could potentially lower the computational requirements and make prosthodontic computer-aided design more accessible to a clinician at no added costs. However, it is imperative to explore whether such open source solutions can retain the dimensional accuracy of commonly provisioned prostheses after optimization. Therefore, this study aims to evaluate the parametric differences produced by digital prostheses after being optimized using open source and free software.

Materials and methods

An auricular prosthesis, a complete denture, a ceramic crown for upper central incisor and a ceramic crown for upper 1st molar were fabricated conventionally by a team of prosthodontists. The prostheses were scanned using a laser scanner (NextEngine Inc, Santa Monica) and exported as standard tessellation language files. The scanned model files were created in full resolution and were used for all the software tested within this study.

Meshmixer v3.5 (Autodesk Inc, America) was considered as the standard software (control) based on its recent contributions within prosthetic dentistry.[4,16,17] The open

Table 1 Property parameters of the CAD based prostheses at full resolution

	Vertices	File size (Kb)	Mesh surface area (mm^2)	Mesh volume (mm^3)	Hausdorff's distance (mm)	Dice similarity coefficient
Auricular prosthesis	122486	11962	11663.066406	14679.401367	0.000000	1.000000
Complete denture	57943	5659	11345.215820	5684.477051	0.000000	1.000000
Central incisor crown	38970	3806	250.185226	272.871826	0.000000	1.000000
1st Molar crown	33343	3257	381.639587	472.627075	0.000000	1.000000

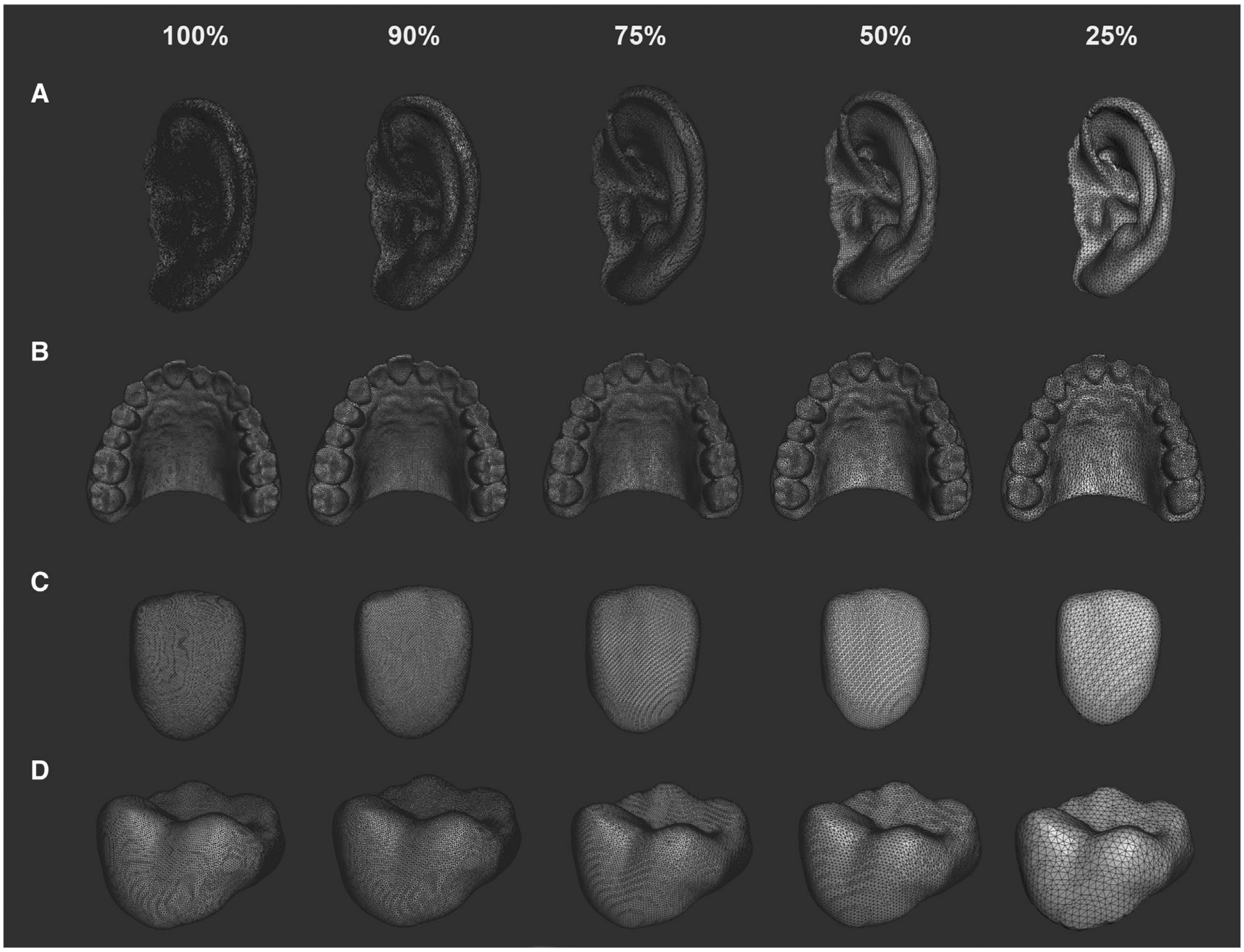

Figure 1 Wireframe demonstrating the amount of vertices reduction at each level of optimization.

source solutions chosen for evaluation were Meshlab v2020.03 (National Research Council, Italy),[13,17] Blender v2.82 (The Blender foundation, Netherlands)[9,12] and the internet-based optimization tool SculptGL v1.0 (Stephane Ginier, Canada; https://stephaneginier.com).[18] The software were selected based on previously mentioned research within the medical and prosthetic rehabilitation space.

Previous studies[4,19] on digital prosthetic rehabilitation indicated large effect sizes (>1.0) in their studies owing to highly accurate computer-generated parametric values and negligible human intervention.[20] Thus, for this study, 20 progressive optimization levels (effect size = 1.0, $\alpha = 0.05$ and power = 0.90) were distributed among the 4 software for each prosthesis[21] (100%, 90%, 75%, 50%, and 25% of full resolution).

The prostheses were loaded into each software individually and optimized using their native settings. After the mesh were loaded into the respective software, the following sequence of commands were used to optimize the files.

1. Meshmixer; select > select all > edit > reduce > select percentage > accept.
2. Meshlab; filters > remeshing, simplification and reconstruction > quadratic edge collapse decimation > select percentage > apply.
3. Blender; modifier properties > add modifier > decimate > select percentage ratio > apply.
4. SculptGL; topology > voxel remeshing (quads) > select percentage resolution > remesh.

(The software indicated the following resolutions for a full resolution mesh: 202 for auricular prosthesis, 131 for complete denture, 105 for incisor, and 97 for molars. Percentage reductions were calculated and applied based on triangle count.)

The full resolution files were opened and saved without modification using each software independently (100%). Optimization was then done on the full resolution models at 90%, 75%, 50%, and 25% resulting in 5 levels of optimization for each prosthesis per software.

The parameters for evaluation were (1) total vertices, (2) computer file size, (3) mesh surface area (in mm^2), (4) mesh volume (in mm^3), (5) interpoint discrepancies by Hausdorff's distance (in mm), and (6) spatial similarity by Dice Similarity Coefficient. Vertice, file size, surface area, and volume were

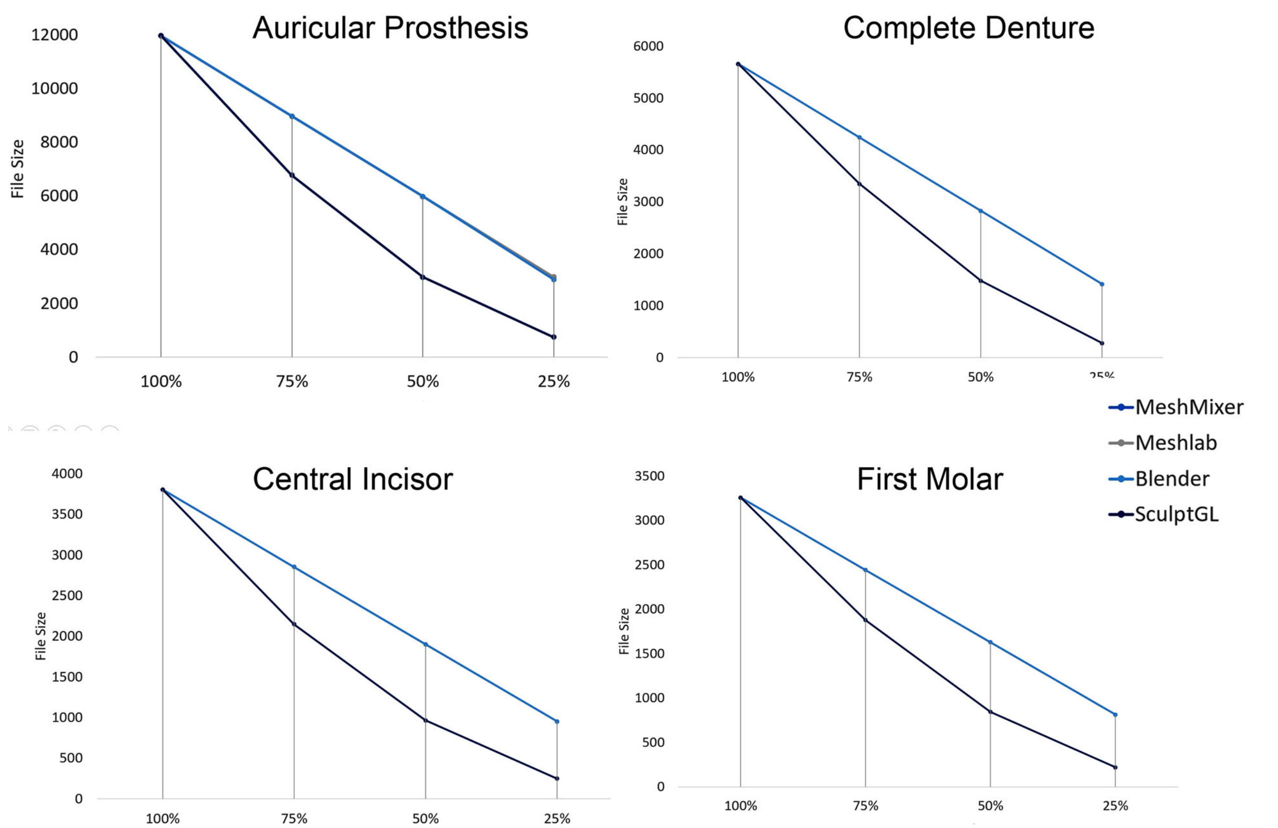

Figure 2 File size reduction across optimization levels.

measured following previous research[17] using the 'compute geometry' feature found within Meshlab. Hausdorff's distance (HD) measured the inter-point discrepancies between two similar objects after converting the 3D models into 50,000 points and determining how many points did not align. Dice Similarity Coefficient (DSC) measured the volumetric spatial overlap between two similarly shaped objects and produced a coefficient of how similar the two shapes were to one another. Both Hausdorff's distance and Dice similarity were first proposed in the medical field for evaluations by Egger et al[22] and later adapted for craniofacial analyses[15] followed by maxillofacial prosthetic applications[4,17] using the open source software Cloudcompare (Girardeau-Montaut; Telecom ParisTech).[23] Therefore, this study also used the same software and methods to evaluate Hausdorff's distance and Dice similarity.

The data was evaluated using a statistical software (SPSS v26.0; IBM Corporation, USA). A multiple linear regression model was developed to predict the influence of the optimization on the software selection that may have dictated changes in surface area and volume.

Results

The property parameters of the scanned meshes at full resolution have been mentioned in Table 1. The 3D models saved at 100% for all 4 software demonstrated no change in parameters when compared to full resolution. The vertices present at 100, 90, 75, 50, and 25 percentage upon optimization have been displayed in Figure 1 using virtual wireframe analysis.

Meshmixer, Meshlab and Blender saw a reduction in file size and vertices of similar proportions while SculptGL saw a reduction of approximately 25% more vertices and file size for every stage of optimization. This was seen throughout the study with all the prostheses as demonstrated in Figure 2.

The trend in virtual area and volume (Fig 3) suggested SculptGL to undergo the greatest overall parametric changes when compared to the other software for all prostheses. When compared to Meshmixer, SculptGL demonstrated the greatest mean surface area change for auricular prosthesis (−16.67%) and greatest mean volume change for complete denture (+3.78%). Meshlab and Blender (compared to Meshmixer) followed similar trends in area (<1.3%) and volume (<1.2%) variations.

Significant regression equations were found for all prostheses in surface area influence prediction. Auricular prosthesis [$F(4,15) = 12.93$, $R^2 = 0.72$, $p < 0.001$] and complete denture [$F(4,15) = 10.81$, $R^2 = 0.67$, $p < 0.001$] showed the greatest overall significance indicating strong influence between software and optimization levels. In both instances, SculptGL influenced the significant changes [(auricular prosthesis: $t = -5.76$, $\beta = -2055.03$, $p < 0.001$); (complete denture: $t = -5.08$, $\beta = 192.84$, $p < 0.001$)]. Level of optimization showed

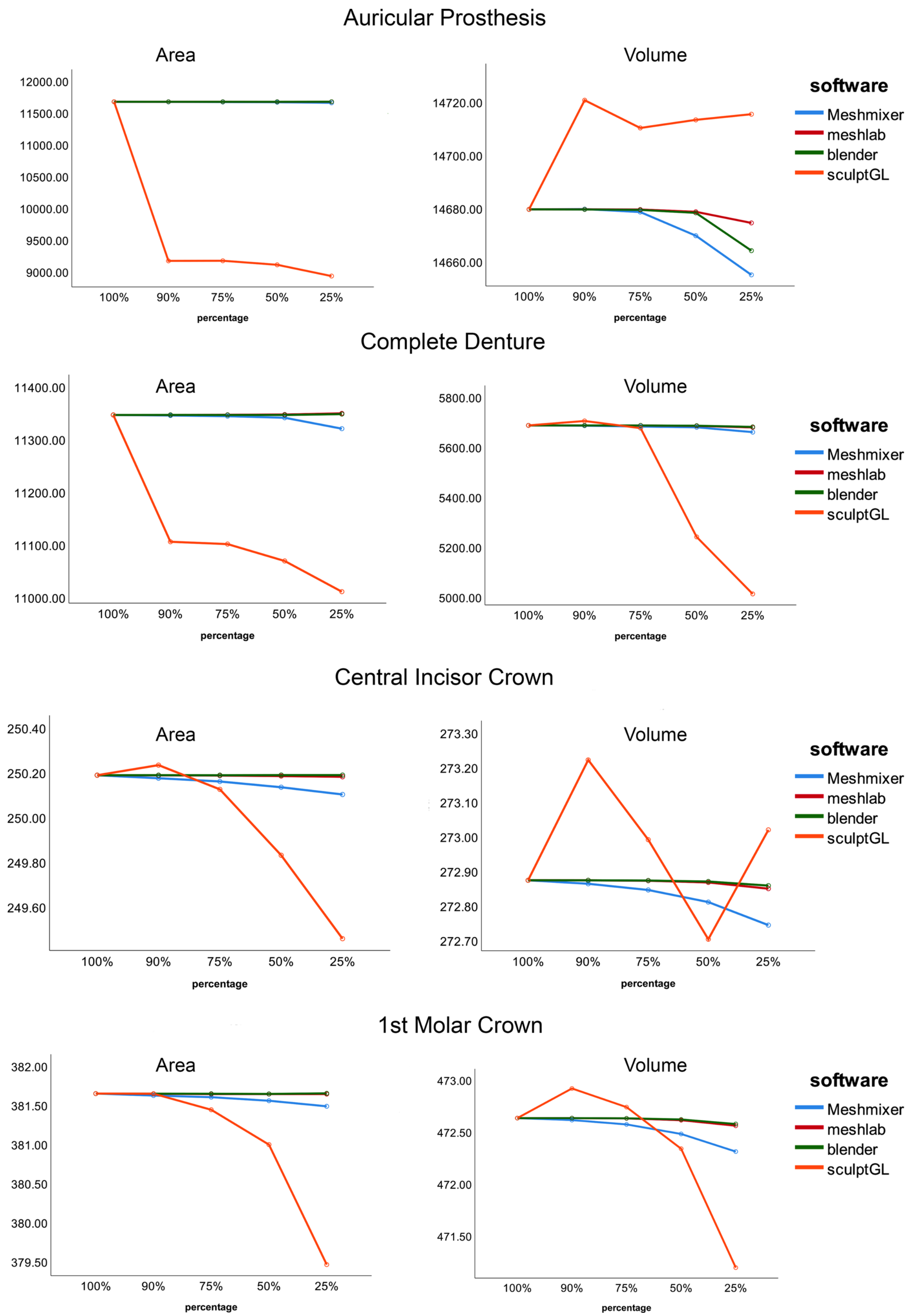

Figure 3 Area and volume trends (y-axis) across different optimization levels (x-axis).

Table 2 Influence of software selection and level of optimization on the surface area of prosthodontic models

Independent variables		Mean ± SD	Zero-order r[a]	β-Coefficient (t-stat)	*p*-Value*,[b]
Auricular prosthesis					
Software	Meshmixer	11654.84 ± 8.95	-	-	-
	Meshlab	11662.76 ± 0.27	0.29	6.73 (0.02)	0.985
	Blender	11662.97 ± 0.44	0.29	6.91 (0.02)	0.985
	SculptGL	9711.24 ± 1305.18	−0.87	−2055.03 (−5.76)	<0.001*
Level of optimization (%)		-	0.16	6.20 (1.34)	0.200
Overall		R = 0.88, Adj. R^2 = 0.72, Std. er = 564.56, F (4,15) = 12.93, $p < 0.001$			
Complete denture					
Independent variables		Mean ± SD	Zero-order r[a]	β-Coefficient (t-stat)	p-value*,[b]
Software	Meshmixer	11336.81 ± 11.96	-	-	-
	Meshlab	11346.19 ± 1.37	0.29	7.71 (0.20)	0.842
	Blender	11345.64 ± 0.84	0.29	7.72 (0.19)	0.851
	SculptGL	11155.70 ± 142.00	−0.84	−192.84 (−5.08)	<0.001*
Level of optimization (%)		-	0.20	0.49 (1.58)	0.136
Overall		R = 0.86, Adj. R^2 = 0.67, Std. er = 60.06, F (4,15) = 10.81, $p < 0.001$			
Central Incisor					
Independent variables		Mean ± SD	Zero-order r[a]	β-Coefficient (t-stat)	*p*-value*,[b]
Software	Meshmixer	250.14 ± 0.04	-	-	-
	Meshlab	250.18 ± 0.01	0.21	0.03 (0.37)	0.720
	Blender	250.19 ± 0.00	0.22	0.04 (0.41)	0.691
	SculptGL	249.90 ± 0.33	−0.52	−0.19 (−2.06)	0.057
Level of optimization (%)		-	0.46	0.03 (2.49)	0.025*
Overall		R = 0.70, Adj. R^2 = 0.35, Std. er = 0.14, F (4,15) = 3.61, $p = 0.030$			
1st Molar					
Independent variables		Mean ± SD	Zero-order r[a]	β-Coefficient (t-stat)	*p*-Value*,[b]
Software	Meshmixer	381.56 ± 0.07	-	-	-
	Meshlab	381.64 ± 0.01	0.20	0.06 (0.23)	0.819
	Blender	381.64 ± 0.00	0.20	0.06 (0.24)	0.810
	SculptGL	380.88 ± 0.99	−5.23	−0.55 (−2.10)	0.055
Level of optimization (%)		-	0.43	0.10 (2.24)	0.041*
Overall		R = 0.68, Adj. R^2 = 0.31, Std. er = 0.41, F (4,15) = 3.16, $p = 0.045$			

*Significant at <0.05.
[a] Estimated by Pearson's correlation.
[b] Multiple linear regression with dummy variable estimate. Meshmixer considered software reference variable (n = 20).
SD, Standard Deviation; Adj. R^2, Adjusted R Square; Std. er, Standard error of estimate.

Table 3 Influence of software selection and level of optimization on the volume of prosthodontic models

Independent variables		Mean ± SD	Zero-order r[a]	β-Coefficient (t-stat)	*p*-Value*,[b]
Auricular prosthesis					
Software	Meshmixer	14672.31 ± 10.66	-	-	-
	Meshlab	14678.18 ± 2.20	–0.18	5.87 (0.89)	0.387
	Blender	14675.99 ± 6.69	–0.26	3.67 (0.56)	0.585
	SculptGL	14707.62 ± 16.22	0.83	35.31 (5.36)	<0.001
Level of optimization (%)		-	0.12	0.08 (0.89)	0.389
Overall		R = 0.85, Adj. R^2 = 0.64, Std. er = 10.41, F (4,15) = 9.33, $p < 0.001$			
Complete denture					
Independent variables		Mean ± SD	Zero-order r[a]	β-Coefficient (t-stat)	*p*-value*,[b]
Software	Meshmixer	5676.37 ± 10.97	-	-	-
	Meshlab	5682.45 ± 3.39	0.19	6.08 (0.07)	0.947
	Blender	5683.00 ± 2.60	0.19	6.08 (0.07)	0.942
	SculptGL	5461.77 ± 318.60	–0.55	–214.60 (–2.39)	0.031*
Level of optimization (%)		-	0.42	2.63 (2.26)	0.039*
Overall		R = 0.70, Adj. R^2 = 0.34, Std. er = 142.24, F (4,15) = 3.50, $p < 0.05$			
Central incisor					
Independent variables		Mean ± SD	Zero-order r[a]	β-Coefficient (t-stat)	*p*-value*,[b]
Software	Meshmixer	272.82 ± 0.05	-	-	-
	Meshlab	272.86 ± 0.01	–0.09	0.04 (0.63)	0.541
	Blender	272.87 ± 0.01	–0.07	0.04 (0.67)	0.509
	SculptGL	272.96 ± 0.19	0.46	0.13 (2.16)	0.048*
Level of optimization (%)		-	0.25	0.00 (1.13)	0.277
Overall		R = 0.54, Adj. R^2 = 0.10, Std. er = 0.10, F (4,15) = 1.57, $p = 0.233$			
1st Molar					
Independent variables		Mean ± SD	Zero-order r[a]	β-Coefficient (t-stat)	*p*-value*,[b]
Software	Meshmixer	472.52 ± 0.13	-	-	-
	Meshlab	472.60 ± 0.03	0.14	0.09 (0.47)	0.645
	Blender	472.61 ± 0.02	0.16	0.10 (0.51)	0.617
	SculptGL	472.36 ± 0.69	–0.29	–0.16 (–0.83)	0.418
Level of optimization (%)		-	0.54	0.01 (2.64)	0.018*
Overall		R = 0.62, Adj. R^2 = 0.22, Std. er = 0.30, F (4,15) = 2.33, $p = 0.103$			

*Significant at <0.05.

[a] Estimated by Pearson's correlation.

[b] Multiple linear regression with dummy variable estimate. Meshmixer considered software reference variable (n = 20).

SD, Standard Deviation; Adj. R^2, Adjusted R Square; Std. er, Standard error of estimate.

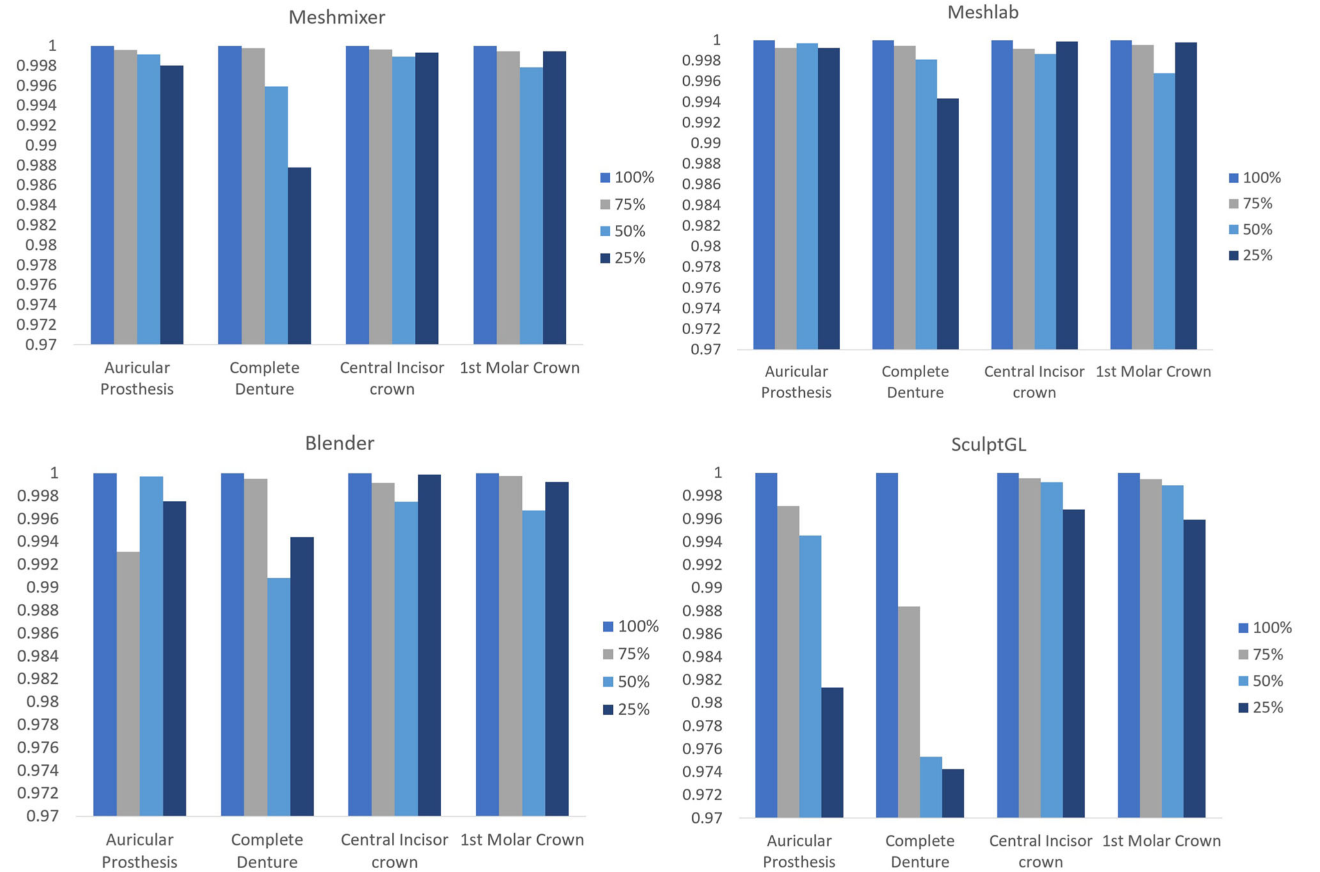

Figure 4 Dice similarity coefficient distribution across all software.

significance for surface area changes in central incisor ($t = 2.49$, $p = 0.025$) and 1st molar ($t = 2.24$, $p = 0.041$). The findings have been presented in Table 2.

Significant regression equations for volume were found in auricular prosthesis [$F(4,15) = 9.33$, $R^2 = 0.64$, $p < 0.001$] and complete denture [$F(4,15) = 3.61$, $R^2 = 0.34$, $p < 0.001$]. SculptGL demonstrated significant volumetric changes ($t = 5.36$, $\beta = 35.31$, $p < 0.001$) following optimization. Both SculptGL($t = -2.39$, $\beta = -214.60$, $p = 0.03$) and level of optimization ($t = 2.26$, $\beta = 2.63$, $p = 0.039$) influenced complete denture volume. SculptGL significantly ($t = 2.16$, $p = 0.048$) influenced optimized central incisor volume without significantly affecting the overall regression model [$F(4,15) = 1.57$, $R^2 = 0.10$, $p = 0.233$]. Details have been presented in Table 3.

Hausdorff's distance analyses determined that all software produced <0.1 mm of discrepancies at every level of optimization, regardless of the prosthesis. Figure 4 demonstrates the Dice similarity coefficient summary of all 4 prostheses. Findings indicate all 4-software experienced varying amounts of inaccuracies in spatial overlap when optimizing complete dentures with the least changes observed for central incisor and 1st molar. However, overall similarities were >97% for all prostheses and optimization levels.

Discussion

This study aimed to evaluate the optimization efficiency of various open source software solutions for 4 different types of prostheses. Level of optimization influenced software outputs for both surface area [$F(4,15) = 12.93$, $p < 0.001$] and volume [$F(4,15) = 9.33$, $p < 0.001$] for larger prostheses and primarily for SculptGL based outputs. However, overall interpoint discrepancies (HD) were within 0.1mm across all measurements and prostheses. For reference, previous literature suggested discrepancies should be <0.20-0.50 mm [24] with certain studies finding a discrepancy of 0.80-5.00 mm also clinically acceptable.[4,17] Furthermore, the overall volumetric spatial similarity (Dice similarity) was found to be >97% (0.97) which exceeded the minimum acceptable threshold of 70% (0.70).[25] The findings of HD and Dice Similarity indicate near identical shape similarity to the full resolution models while differences in surface area and volume indicate a possible loss of anatomical details and contour. This can be seen in Figure 1.

Majority of the differences were found for SculptGL and could be attributed to the loss of project volunteers and subsequently limited software updates to refine the optimization algorithm.[18] This issue is persistent among the majority of the open source systems which stop being supported by their developers after certain periods of time.[26] Internet-based tools such as these have the advantage of being user friendly, minimalist, passively updated and readily available subject to proper internet connectivity.[27] For the prosthodontist, this translates to a readily available internet-based software which does not require any installations, can perform basic design functions and is self-maintained, i.e., does not require periodic updates on the user's end. Such tools do come with disadvantages such as lack of security over the internet and performance issues arising when multiple users access the program at once (globally shared resources).[27]

Additionally, as current findings suggest, the optimized files from SculptGL were 25% smaller than the other open source systems, which can greatly benefit storage of larger volumes of patient data. However, Figure 3 suggest that the software's mesh optimization process thoroughly reduced anatomical grooves in larger prostheses to drastically decrease the surface area while increasing the overall volume of the prosthesis. On the other hand, usage of Blender and Meshlab provided consistent results in this study. Furthermore, the two software provide a wide range of additional refined tools and functionalities and are also supported by some of the largest online communities at present times.[12] The clinician can find multiple free online resources (for example, Reddit, Discord, YouTube, GitHub, etc.) that can assist even in uncommon prosthetic designs.[9] Proprietary software providers generally do not disclose educational resources, provide prompt support services or cater to less common requests.[14]

The ear is the most anatomically detailed organ in prosthodontics and has therefore had the greatest differences in virtual surface area and volumetric parameters.[4,28] This issue was also present for complete dentures, which too hold very minute anatomical details which could be lost during mesh optimization. Higher levels of optimization can also substantially influence prosthetic parameters. While the differences appear minor, it should be noted that overreduction of vertices during optimization results in sharper mesh contours and are ultimately projected onto the 3D printed prostheses themselves having several clinical implications. Minute sharp internal angles result in poor marginal fit of printed crowns on their abutments,[29] while sharp angles within dentures may lead to traumatic ulcerations.[30] This also creates issues for extraoral prostheses which are later converted to silicone. Sharp angles may result in uneven force distribution and uneven exposure to weather, leading to premature mechanical and color degradation.[31,32] Similar to past findings, this issue was virtually more noticeable for larger prostheses like auricle and denture.[33]

This study was limited by several factors. The dataset was limited to four types of prostheses and clinical variables within each prosthesis were not considered. It was not deemed necessary to reevaluate the same prostheses as the workflow from scanning to optimization was computer-driven and therefore had negligible likelihood of variations or errors. The lack of repeated/additional measures however prevented multifactorial analyses of variance for the current dataset. The influence of software selection was evaluated using a dummy variable regression model considering Meshmixer as control and therefore dictated the values of the other software. The regression model was also inclusive of outliers produced by SculptGL and therefore could have influenced overall results. In depth statistical analyses of optimization levels were also not carried out. Therefore, additional studies should be performed to evaluate the influence of optimization on a greater number of scanned prostheses with clinical variations. Further studies can be carried out to evaluate the percentage of optimization appropriate for different prostheses.

Conclusion

Current study suggested open source solutions were capable of optimizing smaller dental prostheses without greatly influencing dimensional parameters. The larger prostheses showed greater and varying loss in parameters upon optimization within SculptGL.

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