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Optimization of 3D scanner parameters used to develop prosthetic hands of amputee patients

Ampute hastalarin protez ellerinin geliştirilmesinde kullanılan 3B tarayıcı parametrelerinin optimizasyonu

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Abstract

Especially for amputees, the design of a tailor-made prosthesis requires anthropometric data collection. This process is quite demanding and time-consuming when using conventional methods like a tape measure. Instead, 3D scanning technologies, which have come into our lives with the boosting of digital technology, enable anthropometric data to be acquired rapidly and precisely. Nevertheless, so many parameter settings are presented to users that grasping them takes a long time with this technology. Among these parameters, which depend on surrounding conditions or software, texture capture color, pattern type, mesh density, and clean-up can be considered the most commonly encountered software parameters. The effects of these parameters in generating the most appropriate computer-aided design (CAD) model remain uncertain. Besides, users typically gain experience by trying diverse variations in these parameters over time. Therefore, this study scrutinized the parameters of the least defective CAD model created for ultimate patient comfort in prosthesis design. 3D models of the plaster cast obtained from an amputated hand were made by changing the parameters in various combinations using a 3D scanner based on structural light scanning technology. The variety and quantities of defects occurring on the models were determined, and skewness, one of the mesh analysis methods, was calculated. As a result, the least defect and best mesh distributions were achieved with black texture capture, the scanning angle with a 10-degree increment, the focus pattern, 75% mesh density, and high clean-up. This study is anticipated to contribute to 3D scanner users producing models practically and precisely.

Keywords: Amputated hand, 3D scanning and modeling, 3D scanner parameters, Mesh analysis, Prosthetic hand design.

Öz

Kişiye özel protez tasarlamak özellikle ampute kişiler için antropometrik verilerin alınmasını gerektirir. Bu süreç mezura gibi konvansiyonel yöntemlerle gerçekleştirildiğinde oldukça zaman alıcı ve zahmetlidir. Bunun yerine dijital teknolojinin ivme kazanmasıyla ile hayatımıza giren 3B tarama teknolojileri antropometrik verilerin hızlı ve hassas bir şekilde alınmasını sağmaktadır. Yine de bu teknoloji ile kullanıcılara o kadar çok parameter ayarı sunulmuştur ki bunları kavramak zaman alıcıdır. Çevre koşullarına veya yazılıma bağlı olan bu parametreler arasında doku yakalama rengi, desen çeşidi, ağ yoğunluğu ve kusurları temizleme en sık karşılaşılan yazılım parametreleri olarak sayılabilir. Bu parametrelerin en uygun bilgisayar destekli tasarım (CAD) modeli oluşturmada etkileri ise henüz belirsizliğini korumaktadır. Bunun yanında kullanıcılar genellikle bu parametrelerdeki çeşitli varyasyonları zaman içerisinde deneyerek tecrübe kazanmaktadır. Bu sebeple, bu çalışma protez tasarımında hasta konforunu maksimize etmek için meydana getirilen en az kusurlu CAD modelinin parametrelerini araştırmıştır. Ampute bir kişinin elinden alınan alçı kalıbı, yapısal ışık tarama teknolojisini dayanan 3B'lu tarayıcı vasıtasıyla çeşitli kombinasyonlarda parametreler değiştirilerek 3B'lu modelleri oluşturulmuştur. Modeller üzerinde oluşan kusur türleri ve miktarları belirlenerek mesh analizi yöntemlerinden birisi olan skewness hesaplanmıştır. Sonuç olarak siyah renk doku, 10 derecelik tarama açısı, odak desen tipi, %75 ağ yoğunluğu ve yüksek temizleme ile en az kusurlu ve en iyi mesh dağılımları elde edilmiştir. Bu çalışma sayesinde 3B tarama kullanıcılarının daha pratik ve hassas modeller üretmesine katkı sağlayacağı düşünülmektedir.

Anahtar kelimeler: Ampute el, 3B tarama ve modelleme, 3B tarayıcı parametreleri, Mesh analizi, Protez el tasarımı.

1 Introduction

3D scanners convert the shape and surface geometry of any material into the digital environment. These devices can be classified into three categories based on their technology: optical, laser, and ultrasonic scanners [1]. These technologies capable of non-contact measurements employ time-of-flight, structured light, laser triangulation, and high-frequency sound wave techniques. 3D ultrasounds produce images of infants' soft tissues, organs, and other anatomical features using high-frequency sound waves and advanced imaging software [2]. Optical scanners measure the distortion of the pattern light on the object by striking structured light onto the object with the help of a projection [3]. The system requires at least two cameras to perform these measurements. The scanning outputs are obtained using the location of each point in the coordinate plane, called "point cloud" [4]. Then, consecutive images taken by scanning the entire area of the object are combined with the software. In laser scanners, an infrared laser pulse is sent to the object. A part of this pulse returns to the scanner, and the distance is calculated according to the time of flight of the pulse [5]. Similar to optical scanning, the point cloud is generated based on coordinates. These two scanning techniques provide different applications based on the goal. Laser scanners are less accurate, cannot capture color scanning, and are more expensive [6]. On the other hand, they scan faster and give better results in places such as shiny/dark surfaces and sharp corners [7]. In addition, these scanning systems can be produced as handheld, tripod-mounted, and desktop [8]. Handheld devices offer advantages like ease of use, light weight, and portability. Although they can potentially be used in hard-to-reach locations, their accuracy is not as high as that of a

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tripod-mounted system. Nevertheless, 3D scanners offer great opportunities in various fields, including health, industry, architecture, civil engineering, and the automobile [9].

Applications for 3D scanners in the healthcare industry include the design of medical devices, the creation of prototypes, manufacturing orthotics and prosthetics customized to patients, dental applications, plastic and aesthetic surgery, and manufacturing cranial implants [10],[11]. Especially in producing subject-specific prostheses, scans from the patient's missing limb are processed in 3D to create modeling and prototypes. To meet the patient's demands, this model is produced using various production processes, including 3D printing technology [12]. In a study by Herbst et al., a prosthesis was developed by scanning from the unaffected hand of an amputee [13]. In another study, Seo et al. created a human mimetic forearm using 3D scans of an amputee [14]. Even though this topic has been the focus of numerous research studies, 3D scanning-one of the initial phases of prosthesis development-presents several challenges.

Although 3D scanning devices are an indispensable technology in modeling processes, users may encounter challenges in obtaining high-accuracy scans or the quality of the measured data [15]. The level of detail can be impacted by a wide range of variables, including the surface characteristics of the object to be scanned, ambient light, and the acquisition device's performance, such as accuracy and resolution. In particular, devices based on the optical scanning method are highly sensitive to ambient light intensity; however, the use of adjustable lighting can address this issue. In addition, a variety of specialized sprays available on the market may coat an object to mattify its surface and reduce glare in cases when the object's surface is not appropriate for scanning. On the other hand, the proper choice of scanning parameters directly influences the scanning quality and depends on the user's experience. This is primarily due to the numerous technical factors, each of which has an impact on the scans. The user must make numerous attempts to obtain the optimal scan, which is laborious and time-consuming.

The impact of various factors on laser scanning, including ambient light, angle, filters, distance, and white balance, was investigated by Gerbino et al. [16]. By computing the error, they were able to compare how accurate these parameters were to the measurement. However, they did not carry out the study for optical scanning equipment and indicated that more investigation was required to completely reveal the effects of parameters. In addition, the distance of the camera to the object, scanning angle, and device calibration process are a few examples of factors that might be dependent on the surrounding conditions. Kaushik et al. optimized some of these parameters using the heuristic GA-ANN technique [17]. Nevertheless, depending on the software and the number of scans, many different factors also have a direct impact on the model in addition to these. Types of textures and patterns, mesh density, cleaning techniques, and finalization processes are some examples of these parameters. The effects of these parameters on scanning outcomes have not yet been completely determined.

Moreover, a completely convenient prosthesis is required in amputee hand designs to maximize patient comfort and reduce complaints. Thus, one of the most crucial and initial steps is to take a profoundly accurate scan and optimize the best model. The objective of this study is to investigate the impacts of the 3D scanner parameters, whose effects are unclear, on the model during the amputee hand design process.

2 Material and methods

A tripod-mounted optical scanner (3D3 Solutions HDI Advance R1, LMI Technologies Inc., BC, Canada) with structured light was used. The properties of the 3D scanning device are given in Table 1.

Table 1. Detailing the specific properties of the scanner.

Properties	HDI Advance
Camera	Dual cameras with 1.3 megapixel 12.5 mm lenses
Color Scanning	Non
Number of points per Scan	2.6 Million
Resolution	50μm
Scanning Speed	1.3 seconds/scan
Point to Point Distance	0.1 mm
Operating distance	From 0.4 m to 5 m
Available File Formats	PLY, OBJ, STL, ASC, 3D3

According to Paxton et al., for these scanners to produce the best results, the object must remain stationary [15]. Additionally, it has been suggested that the best technique to capture very accurate 3D scanning measurements of the subject is to obtain the patient's limb as a plaster model and scan it in this manner [18]. Sodium alginate served as the primary material for molding. The plaster model created from the amputee's hand is shown in Figure 1.

Figure 1(a): Hands of the amputee. (b): Scanning of the plaster model. (c): Plaster model of the partial hand amputee.

The scanner was calibrated using a calibration grid board (12Wx9H*7mm) before beginning the scanning procedure. With a total of 157 scans, calibration coverage of 74.8%, reprojection error of 536.72 μm, and error deviation of ±14.4 μm were accomplished. Generally, the acceptable calibration coverage is preferred to exceed 60% in the scanning device. The plaster model was scanned from every angle using a 360-degree rotating table, which was also calibrated. To eliminate discrepancies within scans, all were conducted in a sealed area with no windows, and the ambient light was consistently low. In addition, the distances and angles of the tripod carrying the 3D scanner relative to the scanned objects were maintained consistently throughout all scans.

Mesh density, scanning angles and numbers, pattern forms, texture color, and clean-up properties were determined as variables. The quantity of elements the scanner generates per unit area in a mesh is known as the mesh density. Although the model may be created precisely with high mesh numbers, this causes enormous file sizes and, thus, long analysis times. Although this number may be adjusted by the user between 0 and 100, we decided to use three different density levels for this study: 25%, 50%, and 75%. The scanning angle is a variable that indicates how often it acquires an image around the object. Though reducing this degree is necessary for accurately producing each detail on the model, it may complicate the process of merging all the scans. Pattern form determines the type of pattern to be reflected on the object. The software allows five pattern forms: focus, white, black, phase, and none. The most commonly used are white and focus, which are preferred to capture fine details. Texture color provides a different texture image using a projector with an identified brightness. Four color options are available for the projector: light grey, dark grey, black, and white. The clean-up is used to remove unwanted elements derived from the scan automatically. There are four levels to choose from: none, relaxed, high, and extreme. The decision must be made based on the level of detail in the object. The Flexscan3D PRO software (Polyga, BC, Canada) aligned and merged the scan images acquired using the specified parameters. The finalization process was performed through the software and the 3D model was exported as STL.

To assess quality and defects, the 3D models were imported into the Geomagic Studio (v.12, 3D Systems, Rock Hill, SC, US) software. The mesh doctor operator was utilized to analyze the results of highly creased edges, spikes, small components, small tunnels, and small holes. Each edge has a crease value associated with it, which is used to indicate how sharp that edge will be. An excessively high value is not desirable and is regarded as a defect [19]. Spikes represent a combination of unwanted points on the model. The cameras detect foreign objects, such as dust, around the part during scanning, creating small components that arise independently of the model. Small tunnels, another type of defect, are the gaps between the structures in the model. It usually occurs between compartments separated from each other by thin structures. Small holes occur when the point cloud cannot be created in certain regions as a result of any artifact during scanning. All these variables associated with the image directly influence the quality of the model.

Furthermore, the models' mesh quality was evaluated using the skewness scale. Skewness, which shows the deviation between the ideal and actual cell sizes, is one of the most crucial metrics for determining mesh quality. The skewness has a number between 0 and 1, and a value closer to one indicates lower quality. Because they lead to inadequate accuracy inside the interpolated zones, highly skewed cells are not desired. The calculation method is given in Equation 1. The distribution of skewness according to the elements was illustrated using the MeshProcess application.

$$Skewness = max\left(\frac{\theta_{max} - 90}{180 - 90}, \frac{90 - \theta_{min}}{90}\right) \tag{1}$$

3 Results

Defect analysis in scans performed with different parameters is shown in Table 2.

Table 2. Analysis results of defects based on texture capture colours and scanning angles.

Texture Capture	Number of Scans	Scanning Angle (°)	Highly Creased Edges	Spikes	Small Components	Small Tunnels	Small Holes	Total Defects
Black	4	90	50	5618	8	1	3	5680
	6	60	21	1644	5	0	3	1673
	8	45	30	1448	6	1	2	1487
	12	30	73	1379	9	0	4	1465
	18	20	63	1314	13	0	3	1393
	24	15	125	2200	22	1	3	2351
	36	10	4	183	28	0	72	287
White	4	90	26	1090	6	0	1	1123
	6	60	25	1156	6	0	6	1193
	8	45	18	1079	6	0	7	1110
	12	30	31	1057	10	0	4	1102
	18	20	56	1443	12	0	4	1515
	24	15	119	2057	16	0	4	2196
	36	10	35	1816	14	1	2	1868
Dark Grey	4	90	124	4882	19	4	0	5029
	6	60	15	1424	2	0	2	1443
	8	45	11	1283	2	0	3	1299
	12	30	20	1195	3	1	4	1223
	18	20	22	772	7	0	3	804
	24	15	38	822	5	0	2	867
	36	10	150	3509	33	3	0	3695
Light Grey	4	90	82	4115	13	2	3	4215
	6	60	8	1160	3	0	5	1176
	8	45	14	2593	3	0	3	2613
	12	30	42	1940	14	0	9	2005
	18	20	146	3459	20	1	5	3631
	24	15	609	10527	92	26	1	11255
	36	10	811	11085	122	16	0	12034

In this table, in addition to the scan capture colors, the scanning angles were added and their effect on the results was observed. According to this table, the least defect was obtained for scanning at a 10° angle in black color. The most defects occurred at angles of 10° and 15° in light gray. It is determined from the high number of errors that the 90-degree scanning angle is not sufficient to create a model in all scanning colors. On the other hand, as the number of scans increased, the number of errors tended to decrease in black and dark grey, while white and light grey increased. Scans obtained from white and light grey colors were impacted by the plaster model's whiteness, and it showed that the scan's defects were more abundant.

The defects that emerged from different patterns, meshes, and cleaning parameters on the model are given in Table 3. Focus and white patterns don't differ from one another; however, the focus was shown to have fewer defects. As the mesh density decreased, the number of defects decreased. A similar notable drop in the number of defects occurred when cleaning parameters were raised.To assess the mesh quality, skewness distributions based on the elements were computed and presented in Figure 2. Given that a skewness of approximately 0.5 is acceptable, the meshing appears to be adequate based on the dark blue, cyan, and green elements according to the color scale. These colors predominate over other colors in all models. However, considering that the mesh numbers are, on average, 1.46 million per model, the number of elements in other colors is also considerable. Therefore, the color distribution's histogram was computed and is shown in the same picture. Approximately 68% ± 1 acceptable skewness value was achieved in all models. These histogram results showed that the scan completed with a 5% mesh density had a much lower element number than the other cases.

Finally, Table 4 provides the results of the scanning durations based on scanning angles. Accordingly, scanning at a 10-degree angle required around 6.6 times as much time as scanning at a 90-degree angle.

Table 3. Defect numbers of pattern, mesh and cleaning tools according to different parameters.

Parameters		Highly Creased Edges	Spikes	Small Components	Small Tunnels	Small Holes
Pattern	Focus	2	2336	2	0	2
	White	2	2412	3	0	2
Mesh Density	75%	13	1065	1	0	2
	50%	8	565	0	0	5
	25%	2	126	0	0	3
	5%	0	5	0	0	0
Clean-up	None	447	28932	343	37	0
	Relaxed	130	12059	67	5	2
	High	52	2052	11	0	6
	Extreme	37	1737	12	0	5

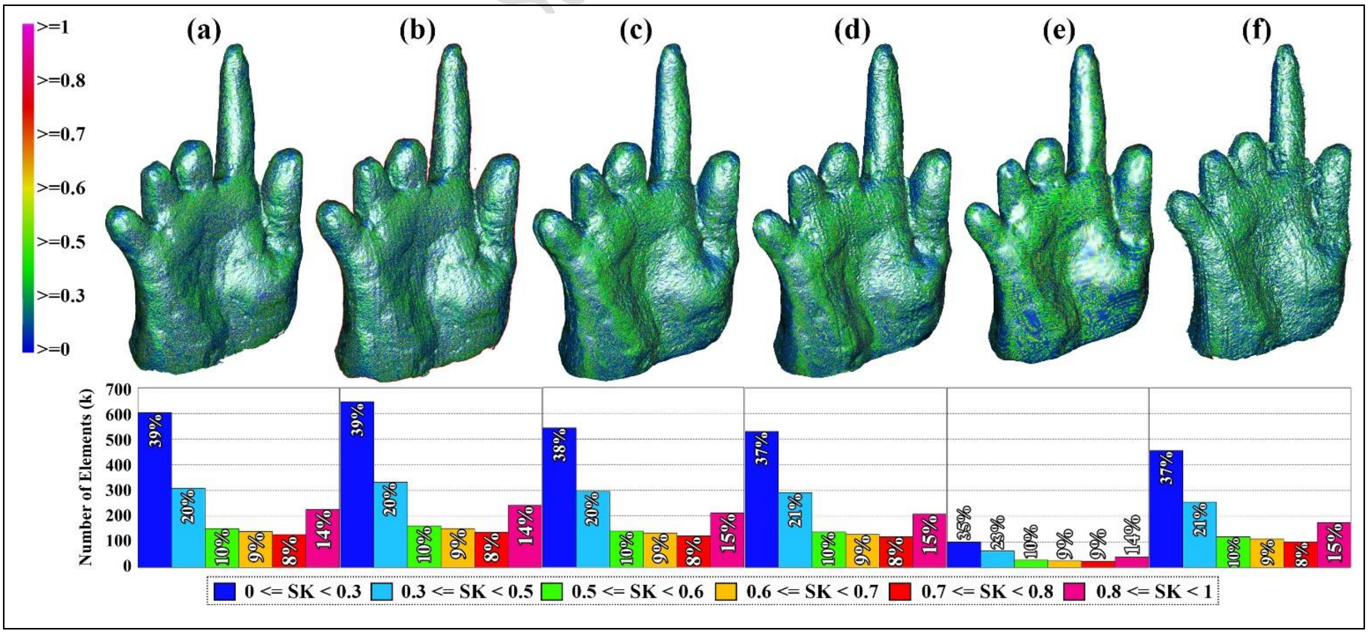

Figure 2. Mesh distribution and histogram of elements of the amputee hand model according to the skewness scale.
(a): Black texture capture. (b): White texture capture. (c): Dark gray texture capture. (d): Light gray texture capture. (e): 5% mesh density. (f): Clean-up is not activated.

Table 4. Total scanning times according to scanning angles.

Scanning Angle (°)	Scanning Time (s)
90	80
60	106
45	135
30	209
20	263
15	352
10	530

4 Discussion & Conclusions

Building a 3D model is one of the most complicated aspects of reverse engineering, prosthesis design, and customized material manufacturing [20]. Obtaining the anthropometric data of an amputee with high precision to design the most comfortable prosthesis is both time-consuming and requires expertise [21]. Structured light scanning technology, among the state-of-the-art, is gaining traction in numerous applications as solution to this concern [22]. Although 3D scanning technology streamlines this procedure, it can also present significant challenges for users, especially regarding the acquisition of a high-quality model. Numerous factors, including the scanning instrument, software options, number of scans, and surroundings, influence the achievement of an appropriate model. This is the reason why the study investigated the mesh quality and defects in the 3D model constructed from scans with various parameters.

Isa et al. sought to minimize deviations and identify types of defects in CAD models by enhancing the calibration and configuration of scanner positions in their custom laser scanning system [23]. However, they scanned the models without doing any mesh analysis. They concluded from their study that various mesh software should be employed to assess CAD models. Korosec et al. concentrated on the parameters of scanning distance and scanning angle and observed that deviation climbed when angle values exceeded 55° [24]. This study had a similar conclusion, with more defects being created by increased angle. In the study by Pathak and Singh who evaluated the laser scanning angle and distance, a highly precise model can only be obtained if the angle value is less than 50 degrees [25], A comparable result has been achieved using structured light scanning, even though its operation differs from laser scanning. In this study, scanning angles less than 45 degrees were confirmed to be the best for obtaining low defect rates, albeit this fluctuates depending on other factors. Although obtaining a more detailed model from all sides is possible when the scanning angles are low, combining these scans in software becomes challenging. Song et al. performed optimization of calibration parameters for low-cost 3D scanners and camera-projector systems [26]. The mean calibration error was calculated using specific patterns (usually cross patterns) arranged on a flat reference grid. However, this study only focused on calibration parameters. In addition, there are studies that optimize 3D scanner parameters based on algorithms. In one of them, Braun et al. optimized external parameters, such as light intensity and camera position, using Particle Swarm Optimization (PSO) [27]. The PSO algorithm has been demonstrated to be an effective tool for finding optimal parameter combinations that increase accuracy and reduce error rates. In another study, 3D laser scanning parameters were determined to ensure the precision of the tooth model surface [28]. This research demonstrates that metaheuristic methods, including genetic algorithms and PSO, are effective for optimizing the extrinsic parameters of 3D scanners. The comparison of all these studies is given in Table 5. This research distinguishes out among the others in the literature because it optimizes intrinsic parameters using measurements of mesh quality and defects as the basis for optimization.

Table 5. Comparison of previous studies.

Studies	Scanner Modality	Parameters	3D Modality	Method
Isa et al. [23]	Laser	Scanner position, orientation and calibration	Point Cloud	Comparing error using Coordinate measurement machines (CMM)
Korosec et al. [24]	Laser	Distance and impact angle of the laser beam	NURBS	Surface morphology (considering slope and surface curvature)
Pathak and Singh [25]	Laser	Scanning angle and distance of the laser beam	Deviation measure with Inspect Plus software	Algorithm-based (Modified PSO (MPSO))
Song et al. [26]	Single Camera	Calibration	Calibration targets	The mean calibration error
Braun et al. [27]	Optical	Scanning angles and offsets	Point Cloud	PSO algorithm
Kaushik and Garg [28]	Laser	Scanning angle and distance, Light Intensity	Point Cloud	Genetic Algorithm and Mean square error (MSE)
This Study	Optical	Scanning angle, texture capture, pattern, mesh density, clean-up	Meshing (Skewness)	Types and numbers of defects

Furthermore, when the time spent according to scanning angles is analyzed in line with Table 4, there is a time difference of around four times between 10 and 45 degrees. The scanning time increases exponentially for scans at angles less than 10 degrees. The results of this analysis showed that, on average, the details of the models produced at 10 degrees were rather excellent, and that, at the same degree, the black texture capture had the fewest defects.

According to a study that evaluated how defects in the number of patterns and encoding parameters during the calibration process affected structured light scanning, it was declared that the use of various filtering techniques in creating point clouds had a positive effect on the results [29]. Our study utilized two distinct types of patterns, and the results were similar for both. Yet, earlier research has concentrated more on mistakes made during the scanning device's calibration procedure. The study employed a commercial scanner that calibrates the scanned grid board by measuring deviations via Flexscan3D software. Furthermore, this study is not concerned with deviations because the manual for this commercial product specifies deviations and accuracy. Rather, the impact of the software's settings on the CAD model that was generated was scrutinized.

In CAD models, spike defects were the most frequently encountered among defect types. The use of a rough plaster mold structure is a primary cause of this occurrence. The scanner, which can produce point clusters at 0.1mm intervals, detected the irregularities on the plaster along the entire surface [30]. The software can overcome this matter by increasing the clean-up parameter values. Although the number of spikes greatly decreased when clean-up was set to extreme, some artifacts could still be detected in the CAD. On the other hand, when clean-up was disabled, high distortions were detected in the CAD model, as illustrated in Figure 2(f). Therefore, setting this option to high resulted in the best performance. In addition, CAD models shouldn't contain small holes, components, or tunnels [31]. This is due to the fact that these defects force the structures that belong in a solid structure to be depicted as surfaces, which requires a lot of time on the part of users to modify. Aside from that, using software to fix these defects might lead to deviations from the model's fidelity [32]. Consequently, for these defect varieties, the light gray texture had the poorest performance.

The mesh analysis of CAD models revealed that textures with black and white had the best skewness values. Skewness is one of the most often used techniques for evaluating mesh metrics. Asymmetric deformations may be observed on the mesh surface. For instance, an abundance of detail on one side of the human hand coupled with a deficiency of detail on the other side results in positive or negative skewness. In addition, the interior angles of each triangle are expected to be regular and close. When optimal mesh quality is unattainable, real-world mesh deformations occur, leading to diminished visual quality, potential errors in the production process, inaccuracies during model slicing for 3D printing, and ultimately resulting in prostheses that do not adequately conform to the patient's limb due to reduced model precision [33]. Even though the color distributions of the models in Figure 2 are comparable to each other, the distribution of the colors dark blue and cyan was predominantly apparent in these textures with around 1.5 million elements. The histogram distribution additionally illustrates the aforementioned result. It is evident from other models that the mesh quality has declined as the distribution of green and different colors has changed comparatively. Furthermore, it has been denoted that the CAD model can be rendered with less detail as the mesh density decreases [34]. Therefore, the number of elements descending in the histogram in Figure 2(e) corresponds to the mesh analysis of the model produced with 5% mesh density. Reducing the number of elements eases the computation burden and ends up in a CAD model with less detail. This means that optimization of this parameter is required. Thus, regarding the number of defects generated, 75% mesh density showed satisfactory performance in this experiment. A mesh distribution above this number has been demonstrated to increase the processing burden and result in redundant data. Conversely, it has shown that when it builds up below this threshold, fewer elements are present, and specific details are vanished.

Consequently, determining CAD defect types and mesh-based analysis was performed to optimize scanner parameters, which are quite laborious and time-consuming for users, and the best results were obtained with black texture, scanning angle in 10-degree increments, focus pattern, 75% mesh density, and high clean-up. In contrast to earlier research, this software-based study aims to close this gap in the literature and make it easier to produce extremely precise models for prosthetic designs. Nevertheless, other significant external factors remained out of the study's scope, including the object's distance, angle, and surrounding light intensity. Besides the intrinsic factors examined in this research, scanner type, object surface characteristics, and user experiences might significantly influence scans. Future research may be able to produce more accurate results by combining the intrinsic and extrinsic factors analysis.

On the other hand, there are some limitations related to this study. It was not possible to do statistical analysis since the data were only acquired from a single amputee patient. This was because it was challenging to find participants for the research. In addition, amputee hand models reconstructed with the least defects and the best mesh quality were not produced by 3D printing. However, in future studies, the fabrication of prosthetic hand models with minimal surface errors can be achieved by using the GOA-PID controller algorithm [35]. This approach enables the evaluation of fabrication procedures and the usability of manufactured prostheses in real-world conditions.

5 Author contribution declaration

In the scope of this study, the contribution of Samet Çıklaçandır was in the literature review, the material and methods of the study, experimental results, the evaluation of the obtained results, and the preparation of the article.

6 Ethics committee approval and conflict of interest statement

This study was approved by the Ethics Committee of Izmir Kâtip Çelebi University Science and Engineering Research on February 2025 with the decision number 18. There is no conflict of interest with any person/institution in the article prepared.

7 References

[1] Verykokou S, Ioannidis C. "An overview on image-based and scanner-based 3D modeling technologies". *Sensors*, 23(2), 596, 2023.

[2] Dawood Y, Buijtendijk MFJ, Shah H, Smit JA, Jacobs K, Hagoort J, Oostra RJ, Bourne T, van den Hoff MJB, de Bakker BS. "Imaging fetal anatomy". *Seminars in Cell & Developmental Biology*, 131, 78-92, 2022.

[3] Bourouina T, Fujita H, Reyne G, Motamedi ME. *Optical Scanning*. Editor: Motamedi ME. Micro-Opto-Electro-Mechanical Systems, 323-367, Washington, USA, SPIE Press, 2005.

[4] Wojciechowski J, Suszynski M. "Optical scanner assisted robotic assembly". *Assembly Automation*, 37(4), 434-441, 2017.

[5] Ebrahim MAB. "3D laser scanners' techniques overview". *International Journal of Science and Research*, 4(10), 323-331, 2015.

[6] Marshall GF, Stutz GE. *Handbook of Optical and Laser Scanning*. 2nd ed. Florida, USA, Taylor & Francis, 2012.

[7] Bailey-Brændgaard M, Enevoldsen PW. Accuracy and Reliability of 3D Scanning Spatial Data when Capturing Limb Morphology for Use within Prosthetics and Orthotics: A Scoping Review. Bachelor Thesis, Jönköping University, Sweden, 2022.

[8] Logozzo S, Valigi MC, Canella G. "Advances in optomechatronics: An automated tilt-rotational 3D scanner for high-quality reconstructions". *Photonics*, 5(4), 42, 2018.

[9] Haleem A, Javaid M. "3D scanning applications in medical field: a literature-based review". *Clinical Epidemiology and Global Health*, 7(2), 199-210, 2019.

[10] Grazioso S, Selvaggio M, Di Gironimo G. "Design and development of a novel body scanning system for healthcare applications". *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 12, 611-620, 2018.

[11] Taneva E, Kusnoto B, Evans CA. "3D scanning, imaging, and printing in orthodontics". *Issues in Contemporary Orthodontics*, 148(5), 862-7, 2015.

[12] Barrios-Muriel J, Romero-Sánchez F, Alonso-Sánchez FJ, Salgado DR. "Advances in orthotic and prosthetic manufacturing: A technology review". *Materials*, 13(2), 295, 2020.

[13] Herbst Y, Polinsky S, Fischer A, Medan Y, Schneor R, Kahn J, Wolf A. "Scan-Driven fully-automated pipeline for a personalized, 3D printed low-cost prosthetic hand". *IEEE 17th International Conference on Automation Science and Engineering (CASE)*, Lyon, France, 23-27 August 2021.

[14] Seo M, Kim H, Choi Y. "Human mimetic forearm mechanism towards bionic arm". *International Conference on Rehabilitation Robotics (ICORR)*, London, UK, 17-20 July 2017.

[15] Paxton NC, Nightingale RC, Woodruff MA. "Capturing patient anatomy for designing and manufacturing personalized prostheses". *Current Opinion in Biotechnology*, 73, 282-289, 2022.

[16] Kaushik A, Punia U, Garg RK, Yadav M, Vashistha R, Rathee M, Sahdev RK, Chhabra D. "Optimization of process parameters for scanning human face using hand-held scanner". *Research Square*, 2022. https://doi.org/10.21203/rs.3.rs-2051093/v1

[17] Gerbino S, Del Giudice DM, Staiano G, Lanzotti A, Martorelli M. "On the influence of scanning factors on the laser scanner-based 3D inspection process". *The International Journal of Advanced Manufacturing Technology*, 84, 1787-1799, 2016.

[18] Paterson AMJ, Bibb RJ, Campbell RI. "A review of existing anatomical data capture methods to support the mass customisation of wrist splints". *Virtual and Physical Prototyping*, 5(4), 201-207, 2010.

[19] Affatato S, Valigi MC, Logozzo S. "Wear distribution detection of knee joint prostheses by means of 3D optical scanners". *Materials*, 10(4), 364, 2017.

[20] Çelebioğlu K, Kaplan A. "Development and implementation of a methodology for reverse engineering design of Francis turbine runners". *Pamukkale University Journal of Engineering Sciences*, 25(4), 430-439, 2019.

[21] Stančić I, Musić J, Zanchi V. "Improved structured light 3D scanner with application to anthropometric parameter estimation". *Measurement*, 46(1), 716-726, 2013.

[22] Ma L, Xu T, Lin J. "Validation of a three-dimensional facial scanning system based on structured light techniques". *Computer Methods and Programs in Biomedicine*, 94(3), 290-298, 2009.

[23] Isa MA, Lazoglu I. "Design and analysis of a 3D laser scanner". *Measurement*, 111, 122-133, 2017.

[24] Korosec M, Duhovnik J, Vukasinovic N. "Identification and optimization of key process parameters in noncontact laser scanning for reverse engineering". *Computer-Aided Design*, 42(8), 744-748, 2010.

[25] Pathak VK, Singh AK. "Optimization of morphological process parameters in contactless laser scanning system using modified particle swarm algorithm". *Measurement*, 109, 27-35, 2017.

[26] Song LM, Chen CM, Chen Z, Xi JT, Yu YG. "Essential parameter calibration for the 3D scanner with only single camera and projector". *Optoelectronics Letters*, 9(2), 143-147, 2013.

[27] Braun J, Lima J, Pereira AI, Rocha C, Costa P. "Searching the optimal parameters of a 3D scanner through particle swarm optimization". *International Conference on Optimization, Learning Algorithms and Applications*, Bragança, Portugal, 19-21 July 2021.

[28] Kaushik A, Garg RK. "Searching the optimal parameters of a 3D scanner in surface reconstruction of a dental model using central composite design coupled with metaheuristic algorithms". *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 18(10), 7401-7411, 2024.

[29] Eiríksson ER, Wilm J, Pedersen DB, Aanæs H. "Precision and accuracy parameters in structured light 3-D scanning". *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 5, 7-15, 2016.

[30] Buffa R, Mereu E, Lussu P, Succa V, Pisanu T, Buffa F, Marini E. "A new, effective and low-cost three-dimensional approach for the estimation of upper-limb volüme". *Sensors*, 15(6), 12342-12357, 2015.

[31] Helle RH, Lemu HG. "A case study on use of 3D scanning for reverse engineering and quality control". *Materials Today: Proceedings*, 45, 5255-5262, 2021.

[32] Önçağ AÇ, Tekcan Ç, Özden H. "Assessment and application of modeling mechanic parts with reverse engineering". *Pamukkale University Journal of Engineering Sciences*, 24(1), 43-49, 2017.

[33] Sorgente T, Biasotti S, Manzini G, Spagnuolo M. "A survey of indicators for mesh quality assessment". *Computer Graphics Forum*, 42(2), 461-483, 2023.

[34] Guo J, Ding F, Jia X, Yan DM. "Automatic and high-quality surface mesh generation for CAD models". *Computer-Aided Design*, 109, 49-59, 2019.

[35] Okur S, Altan A. "Grasshopper optimization algorithm-based adaptive control of extruder pendulum system in 3D printer". *IEEE Innovations in Intelligent Systems and Applications Conference (ASYU)*, Elazig, Türkiye, 06-08 October 2021.