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Hand

Accuracy of Three-dimensional Scan Technology and Its Possible Function in the Field of Hand Surgery

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Background: Three-dimensional (3D) technology has become a standard manufacturing element in many industries and has gained significant interest in plastic surgery. The 3D scans are widely used for patient communication, virtual surgery planning, and intraoperative tool manufacturing, providing a more comprehensive view of procedures and their outcomes compared with 2D visualization.
Methods: We evaluated the performance of six commercially available 3D scanners by acquiring 3D models of a human hand and a 3D-printed replica of a human hand. We performed objective comparisons between the 3D models of the replica using color mapping techniques. Moreover, we compared the results of the human hand 3D scans.
Results: We achieved the highest precision with the Artec Space Spider 3D scanner (Artec 3D) when scanning the 3D-printed replica. The SD was ±0.05 mm, and the scan did not have major defects that needed manual correction. On the human hand scan, we achieved the best results using the Artec Eva (Artec 3D), the resulting scan was an accurate digital representation of the scanned human hand.
Conclusions: In our study, the Artec Space Spider 3D scanner demonstrated superior precision when scanning a 3D-printed replica, deviating only slightly from the original data, making it an optimal choice for nonmoving objects such as casts or medical instruments. For scanning human hands, the Artec Eva 3D scanner exhibited the highest performance, offering accuracy comparable to the Artec Space Spider, but with the added benefit of being able to scan larger objects. *(Plast Reconstr Surg Glob Open 2024; 12:e5745; doi: 10.1097/GOX.0000000000005745; Published online 23 April 2024.)*

INTRODUCTION

In recent years, three-dimensional (3D) technology has undergone tremendous improvement and has become a standard and well-integrated set of tools in many industries. Numerous studies evaluating the value of 3D technology in plastic surgery have been published in recent years.[1,2] In the field of plastic surgery, 3D scanning has gained significant interest and is often part of the daily clinical routine, particularly in aesthetic surgery. 3D scans are widely used, starting with patient scans to aid communication and explanation of procedures to the patient, and continuing through virtual surgery planning and additive manufacturing of tools for intraoperative use. Two-dimensional (2D) visualization provides only a single perspective and can make it difficult to fully assess the outcome of a procedure. By providing a more comprehensive view of the procedure and its outcome, 3D models used in conjunction with 3D planning tools can overcome these limitations.[3]

The initial stage of generating 3D models involves data acquisition. Radiology departments worldwide have been using programs capable of reconstructing 3D images from computerized tomography (CT) and magnetic resonance imaging (MRI) scans for a considerable time. Another crucial consideration in utilizing conventional MRIs or CT scans for the generation of 3D reconstructions lies in the significant material heterogeneity observed within the human hand. The presence of varying densities and water

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content levels poses a challenge in precisely delineating structural boundaries, necessitating consistent manual adjustments to these 3D representations. However, CT and MRI scans are not the sole sources of data for 3D models, and there are several available devices and options for acquiring 3D data, with many being excellent if used for their specific purpose.

3D scanning has a wide range of applications, including casts, jigs, implants, and prosthetics. This field has been increasingly researched and studied in recent years. The most recent research in 3D technology is aimed at augmented reality and virtual reality, which could be used in a variety of settings such as operative planning, patient education, teaching, and communication.[1,4,5] In the field of medicine, 3D scanners have found use, for instance, in outcome evaluation of rhinoplasty or maxillofacial surgery.[6–9] Recent investigations have explored the application of 3D technology in fabricating patient-specific guides and instruments for corrective osteotomies, demonstrating encouraging advancements in surgical outcomes and enhanced patient-related outcome measures.[10,11] In addition to personalized surgical guides and instruments, a diverse range of custom-designed, 3D-printed implants, tailored specifically to individual patient anatomy, have exhibited promising results.[12–14]

To capture the shape of an object in 3D, different types of scanning technologies can be used. Some of the most common ones are structured light scanning, laser scanning, and photogrammetry.

Structured light scanning involves a projector and a camera that project and capture a pattern of light (usually blue or infrared) on the object. The shape of the object is then calculated by triangulating the 3D coordinates of each point on its surface.

Laser scanning involves a laser beam and a sensor that scan the object line by line. The distance between the laser on the surface and the sensor is then calculated by the time difference or angular position of the reflected laser beam.

Photogrammetry involves taking multiple photographs of the object from different angles and positions. The photographs are then processed by a software that matches and overlays common features and reconstructs a 3D model of the object based on the 2D pictures.[15,16]

The use of 3D scanners in hand surgery remains limited, most likely because their full potential is not being realized in the field of surgery. However, there exist numerous potential and beneficial applications for 3D scanners, particularly when combined with 3D printing, in the context of personalized medicine. These applications may include personalized casts, progress monitoring of hand function, and the creation and fitting of bionic prostheses. To guarantee accurate and dependable results, scanning small and nonstationary objects such as fingers necessitates careful consideration of the scanning setup and data collecting method.

Previous studies have assessed the accuracy of a variety of 3D scanners for facial scanning and their efficacy in plastic surgery. The cost of 3D scanners specifically designed for medical use can vary widely and often exceeds US $10,000.[7,17–19] Among these studies, Rudy et al[20] conducted research to compare the precision and cost of the iPhone X scanner (Apple, Inc, Cupertino, Calif.) with other commonly used scanners. The study determined that the iPhone X scanner provides a valid and accurate alternative to other scanners at a significantly lower price point.[20]

The objective of our study was to assess the feasibility and accuracy of 3D scanners for potential applications in hand surgery. The human hand presents a challenging object for 3D scanning due to its complex anatomy and fine details, which are not comparable to those of other body parts that have been scanned and described previously.

Takeaways

Question: Can you successfully create a useful three-dimensional (3D) scan of a human hand?

Findings: 3D scanning a human hand poses many challenges, and no scanner is commercially available for that purpose yet. We obtained the best results using the Artec Eva scanner.

Meaning: Although it is complicated, 3D scanning a hand is possible with current scanners on the market. A 3D scan can facilitate the production of personalized casts, guides, or other medical devices that need to be specifically fitted to a patient's needs.

METHODS

Our study involved a comparison of various 3D scanners available on the market, with a wide range of prices, to assess their precision and efficacy in hand surgery. Supplemental Digital Content 1 provides an overview of the scanners analyzed in the study, along with their fundamental characteristics (**See figure, Supplemental Digital Content 1, http://links.lww.com/PRSGO/D158**).

The Scanners

We included all the scanners that were accessible within our university setting, including those in other departments and faculties, without the need to engage external companies.

Keyence VL-550 (Keyence Corporation, Osaka, Japan)

The Keyence VL series is an optical 3D coordinate measuring device with 360 degrees scanning capability that can measure targets in 3D from multiple directions. For fully automatic recognition and scanning of the measurement target, the motorized turntable travels in multiple directions. By scanning the surface of the object and recording the reflected light, the high-magnification lens can collect up to 16 million data points, enabling for the acquisition of exact data on small targets and complicated structures that many ordinary scanners cannot measure.[21]

Creaform HandySCAN 700 Elite (Creaform, Inc, Lévis, Quebec, Canada)

The Creaform HandySCAN 700 Elite is a portable 3D scanner that uses a laser grid and a single dot to capture the shape and texture of an object. It works by projecting laser patterns onto the object and capturing them with two cameras. It then uses triangulation and photogrammetry to calculate the 3D coordinates of each point on the object.[22] The scanner is connected to a computer where VXelements software processes the data and generates a 3D mesh in real time. The model requires reference points, which are affixed to the object before scanning

Artec Eva (Artec 3D, Luxembourg City, Luxembourg)

The Artec Eva 3D scanner captures high-resolution 3D images of objects using white light. It is a structured light scanner that emits a pattern of structured light onto the object being scanned, consisting of a sequence of parallel lines or grids. The light pattern is distorted and reflected back to the scanner's cameras as it strikes the object's surface. The scanner's cameras take multiple photographs of the reflected light pattern from various angles. The scanner's software can rebuild the 3D shape of the object using these photographs by triangulating the location of each point where the light pattern meets with the object's surface. The software then stitches these individual points together to form a comprehensive 3D model of the object. The Artec Eva 3D scanner can scan objects with great accuracy and detail while also capturing the texture and color of the object being scanned at up to 16 frames per second.[23] This makes it a useful tool in a variety of areas, including product design, manufacturing, and healthcare.

Artec Space Spider (Artec 3D)

The Artec Space Spider is the smaller and more accurate version of the Artec Eva, due to its technical differences it is intended for smaller scans. The Artec Space Spider uses a blue LED light source for 3D data acquisition, whereas the Artec Eva uses a flashbulb. It has a 3D point accuracy of up to 0.05 mm, whilst the Artec Eva has a 3D point accuracy of up to 0.1 mm. The Artec Space Spider has a working distance of 0.2–0.3 m, whereas the Artec Eva has a working distance of 0.4–1 m.[23]

Apple iPhone 12 (Apple, Inc, Cupertino, Calif.)

Scandy Pro App (Scandy, LLC, New Orleans, La.)

The TrueDepth camera system, which consists of a dot projector, an infrared camera, and a flood illuminator, is what powers the iPhone 3D scanner and is used for the facial identification method "Face ID." This system is made to take a multiple-depth map of an object and turn it into a 3D model. Although employing a 3D scanner, a pattern of infrared dots is projected onto the object to be scanned, and the infrared camera records the pattern as it reflects back. Following processing, a depth map of the object's surface is produced to calculate the geometry. Internal (within the app) calculations are utilized to create a 3D model of the object after the depth map has been produced.[24]

Polycam App (Polycam, Inc, Calif., Ky.)

Polycam works by using either your device's LiDAR sensor, if available, or camera to capture images of an object or space. For our purposes, it was used in combination with the iPhone 12 camera. It then uploads the images to a server computer vision and machine learning algorithms are used to reconstruct a 3D mesh from the images.[25]

STUDY PROTOCOL

We conducted a comparative study using the aforementioned scanners to evaluate their performance in potential clinical applications. The study involved scanning a human hand and a 3D-printed hand replica. All scans were conducted using the same hand, which was positioned in the standard anatomical position with the fingers slightly separated. The inclusion of the 3D-printed hand model allowed us to determine the importance of immobilization and whether scan quality improved significantly when scanning a nonmoving hand. Figures 1 and 2 are a schematic representation of our study protocol, Figure 1 representing the objective test using a 3D-printed model and Figure 2 the test on a human hand.

The quality of scans obtained, especially using handheld scanners, was found to be dependent on the user's level of expertise and improved with training. A comparison of the number of scans required to obtain a high-quality and usable scan was not performed due to the presence of several uncontrollable variables. These variables included the lighting conditions of the room, software crashes, the model of the iPhone used, and user dexterity. Instead of comparing the number of attempts required, we selected the best scans obtained from each individual scanner for comparison. None of the scanners required more than 5 attempts to obtain a usable scan.

POSTPROCESSING

Most industrial scanners, such as the Keyence VL-550, the HandySCAN 700, and all Artec products, are equipped with their own postprocessing software. Although some iPhone apps also allow for postprocessing to a certain degree within the app, we opted for a computer-based postprocessing software available at our institute, Meshmixer by Autodesk. Artec products come with their own software, Artec Studio, which allows for fast postprocessing due to its high level of automation and produces high-quality scans. To create the cross-sections used for comparison we used the CAD, software inventor, also by Autodesk. (**See figure, Supplemental Digital Content 2**, which depicts an example of a model created by the scanner and then by the postprocessing software. In cases of larger defects, these were manually corrected, **http://links.lww.com/PRSGO/D159**.)

MEASUREMENT/ANALYSIS

To compare the quality of 3D scans produced by the aforementioned scanners, we first printed a 3D model of a scanned hand. (**See figure, Supplemental Digital Content 3**, which displays hands used for initial scan and 3D-printed model of the same, **http://links.lww.com/PRSGO/D160**.)

This hand was then scanned using, in our opinion, the most accurate scanner available to us, the Keyence VL-550. This scanner was specifically designed for

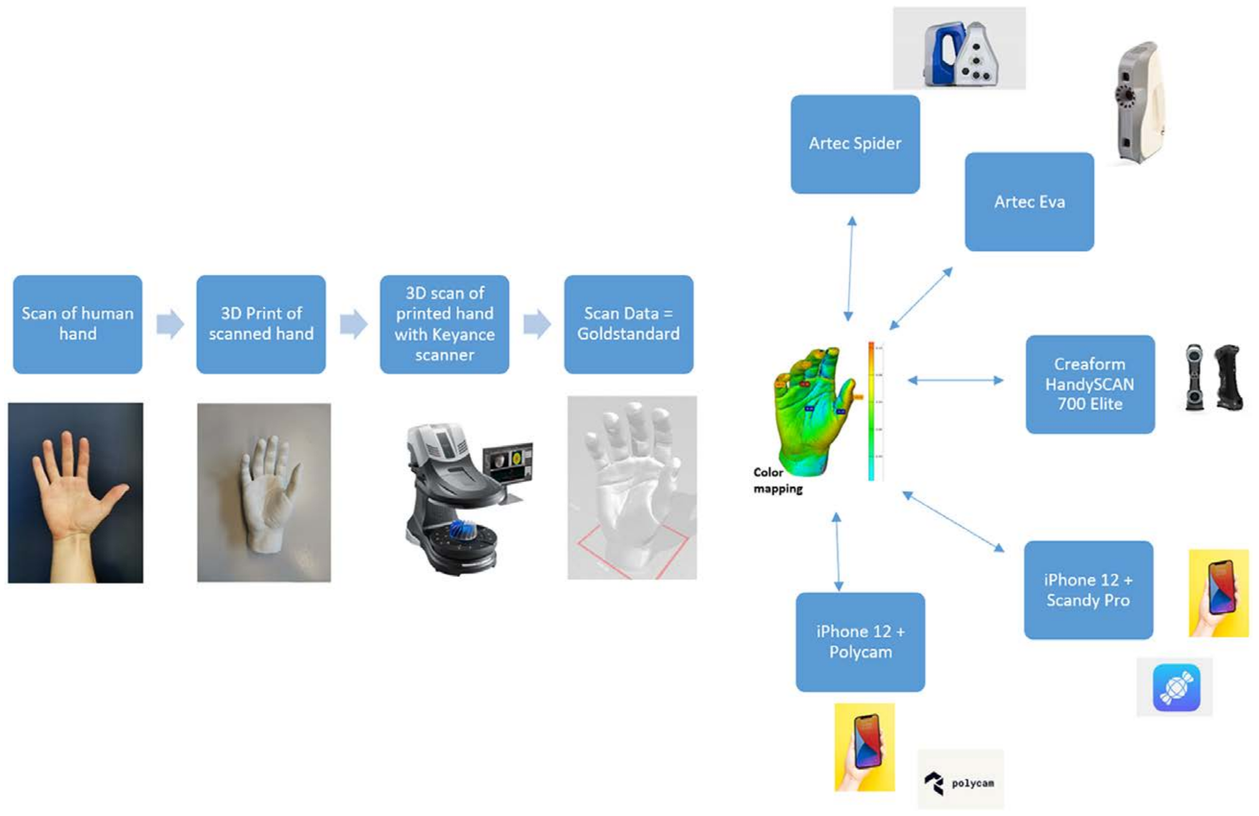

Fig. 1. Schematic representation of the comparative analysis of scans of the 3D-printed model.

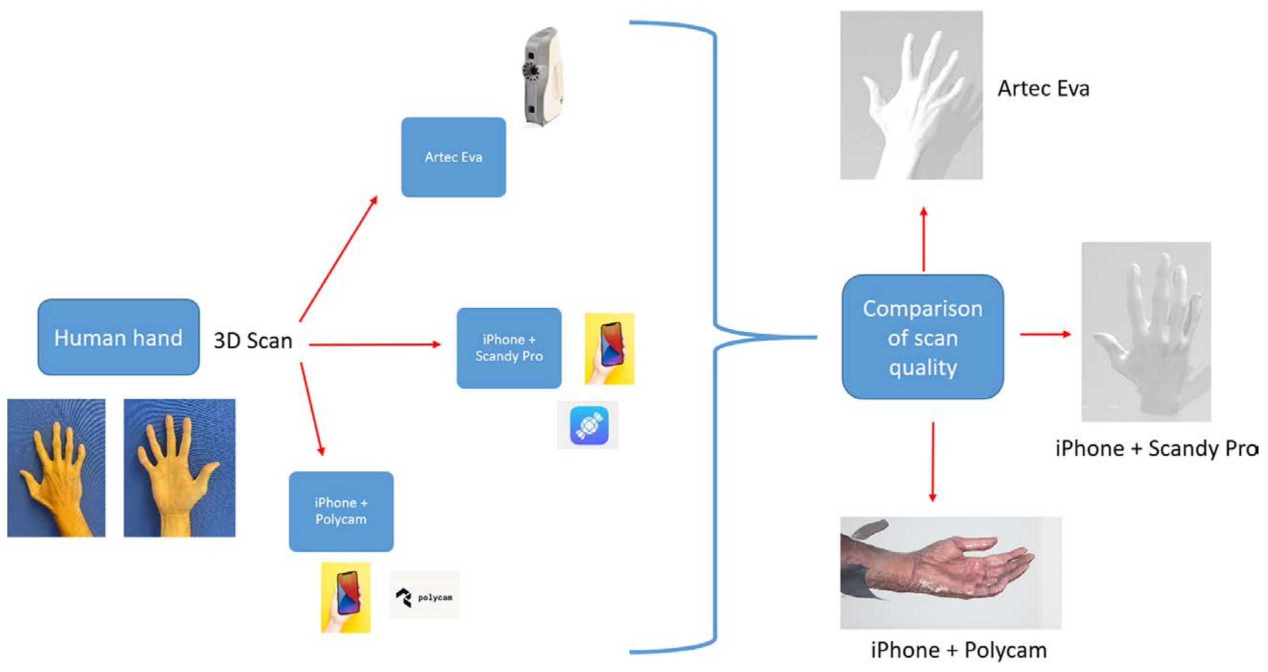

Fig. 2. Schematic representation of the comparative analysis of scans of the human hand.

scanning manufacturing parts and therefore fit the purpose of setting the gold standard. The 3D scan data from this initial scan (using the Keyence scanner) of the 3D-printed hand were used as a gold standard against which all other scanners were compared. All scans were performed on the same 3D-printed model hand to ensure

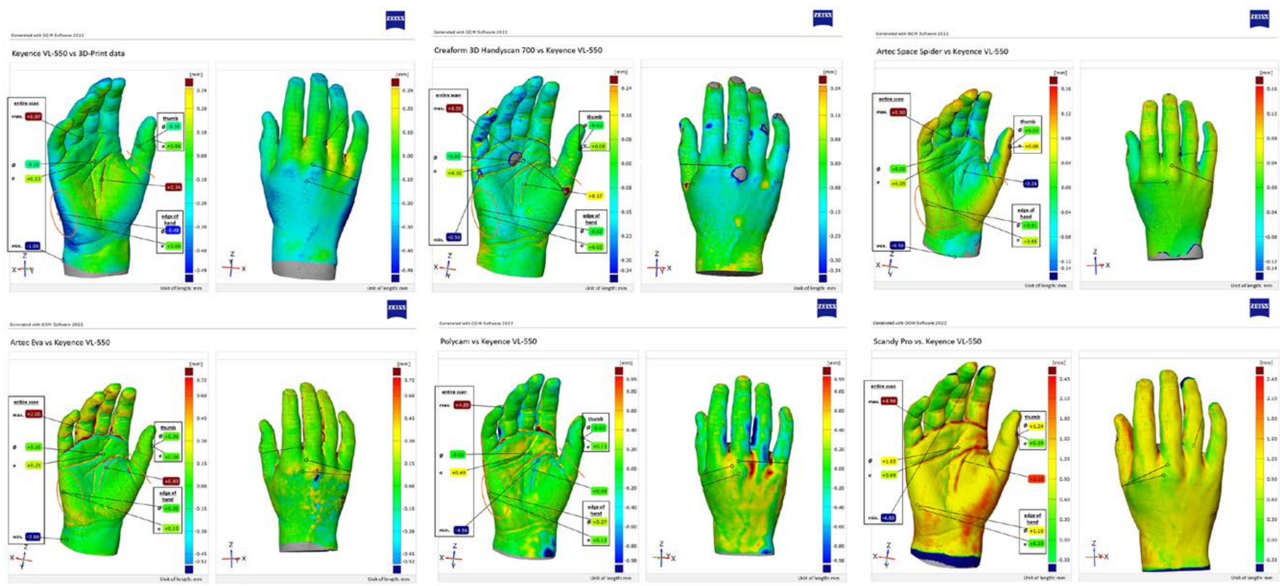

Fig. 3. Comparison of scans with deviation displayed as a color map.

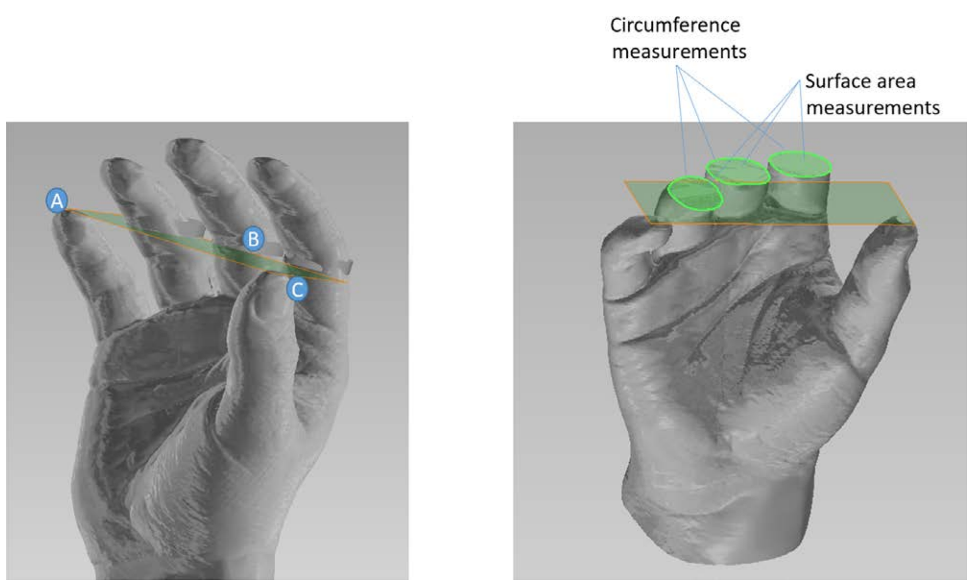

Fig. 4. Cross-section through fixed marker points visible on all scans.

an objective comparison. The reason for 3D printing the hand first was to overcome the challenge of objectively comparing scans, a real human hand would have moved between scans. The most common method for objectively comparing scans is through color map analysis.[6,26] To visualize the 3D scan data, the GOM Inspect software was used. This software generates a color map, also known as a surface comparison, which serves as a guide throughout the analysis. The software can evaluate two sets of 3D data and compare them to provide the surface deviation between the two scans. This deviation is then displayed as a color map, with green areas indicating perfect overlap and red or blue areas indicating positive or negative deviations, respectively. The range of the color scales were individually adjusted, and only serve the purpose of visually pointing out differences; the actual quantifiable deviation is only visible through the data (Fig. 3).

Additionally, we established defined locations on the model hand that were visible on all scans, and drew a horizontal plane from the tip of the thumb (C), through the palmar fold of the proximal interphalangeal joint of the middle finger (B), to the tip of the little finger (A) (Fig. 4). We used Inventor by Autodesk software to create a cross-section at this location. This line of sectioning was applied to all scans and enabled us to measure the circumference of the fingers. These measurements were then compared (Fig. 5). These circumference measurements provide an

Comparison (target)	Scanner (actual)	Index finger		Middle finger		Ring finger		Deviation from Keyence Vl–550			
		Circumference (mm)	Surface area (mm ²)	Circumference (mm)	Surface area (mm ²)	Circumference (mm)	Surface area (mm ²)	Average circumference (mm)	Standard deviation (σ) (mm)	Average surface area (mm²)	Standard deviation (σ) (mm)
Print-data	Keyence	62.369	307.487	65.416	334.652	68.633	348.691	65.47	/	330.28	/
Keyence VL - 550	Creaform3D HandySacan 700	61.475	296.873	64.639	328.068	67.715	341.925	64.61	1.06	322.29	10.04
	Artec Space Spider	62.643	309.219	65.841	339.128	69.763	358.585	66.08	0.88	335.64	7.78
	Artec Eva	62.679	309.716	66.076	341.355	68.757	351.759	65.84	0.52	334.28	5.45
	Polycam Smartphone-App	62.168	304.187	68.548	357.138	66.534	325.328	65.75	2.67	328.88	23.05
	Scandy Pro Smartphone-App	73.005	73.005	75.16	439.962	80.137	469.69	76.10	13.05	469.69	200.89

Fig. 5. Measurements of cross-sectional data (circumference and surface area).

immense additional value as they offer an objective measure of scan quality, specifically including the interdigital area.

Due to the dynamic nature of the human hand, it is impossible to use the abovementioned color mapping technique to compare 3D scans of live hands. For this technique to work, the hands would have to maintain identical positions for all scans. Any difference in position, even slight, would seem as a scanning error in the final comparison, even though it may simply be due to a different finger position.

In addition to color coding and comparing the scans of the 3D-printed model, we also performed scans of a live hand using all scanners that were suitable for performing a full hand scan. These scans were subjectively compared for quality and usability in future projects. (**See figure, Supplemental Digital Content 4**, which displays human hand scans, **http://links.lww.com/PRSGO/D161**.) Approval of the local ethics committee was obtained (Official file reference number: BO-EK-163042023).

RESULTS

All of the studied scanners provided usable 3D scans. However, not all of them were ideal for the intended application of scanning hands. Although the overall length and size of the hand were acceptable for all scanners, a more detailed examination of the scans revealed significant variation in surface and finger diameters and accuracy of the interdigital area.

When comparing the color maps, it is important to note that not all values can be considered. The most significant values are the SDs of the entire scans and the SDs of the predefined points (thumb, edge of the hand, and thenar crease). Figure 6 shows the results, with the SDs (σ) highlighted. The first row compares the Keyence VL-550 against the original print data, which means it cannot be directly compared with the other scanner values because it only shows the capabilities of the 3D printer used. The next five rows compare the scan results of the individual scanners with those from the Keyence VL-550.

Comparison of those deviations showed a highly precise scan when using the Artec Space Spider with only 0.05 mm SD. The Creaform3D HandyScan with 0.1 mm followed these excellent results. The Artec Eva also showed excellent results with a SD of 0.21 mm. Following those come the iPhone scanners; the Polycam scan showed a SD of 0.48 mm and the ScandyPro 0.69 mm. When comparing the individual marked points on the scans, the results show smaller deviations in almost all scanners but with a similar ranking of precisions.

When comparing the cross sections, we obtained the best results from the Artec Eva and Artec Space Spider scanners with only 0.52 and 0.88 mm SD (Fig. 5). When calculating the surface area of the cross-sectioned fingers, similar results were obtained. The Artec Eva scans were within a 5.45 mm² SD, whereas the Artec Space Spider within 7.78 mm². The iPhone applications showed considerably weaker results comparing the surface area of the cross-sectioned fingers, with Polycam having a 2.67 mm² SD when comparing circumferences and the Scandy Pro 13.05 mm². The best results when looking at the human hand scans were obtained using the Artec Eva scanner, which showed excellent precision, especially in the interdigital areas where the iPhone applications had the most difficulty (**Supplemental Digital Content 4, http://links.lww.com/PRSGO/D161**).

DISCUSSION

We anticipate that the utilization of 3D scanning will continue to expand in significance within the medical industry, particularly within the confines of healthcare institutions, eventually becoming an integral component of the medical product manufacturing chain. Whether applied to human anatomical structures or physical objects such as casts, instruments, or implants, 3D scanning is poised to enhance its value.

Comparison (target)	Scanner (actual)	Default comparison range (mm)	Entire hand			Thumb	Edge of the hand	Thenar crease (mm)
			Min. (mm)	Max. (mm)	Standard deviation (σ) (mm)	Standard deviation (σ) (mm)	Standard deviation (σ) (mm)	
Print-data	Keyence	–1 ...+1	–1	0.97	0.13	0.06	0.06	0.36
Keyence	Creaform3D HandyScan 700	–0.5 ... +0.5	–0.5	0.5	0.1	0.08	0.05	0.17
	Artec Space Spider	–0.5 ... +0.5	–0.5	0.5	0.05	0.06	0.01	–0.26
	Artec Eva	–2 ...+2	–2	2	0.21	0.08	0.05	0.8
	Polycam Smartphone-App	–5 ...+5	–4.89	4.96	0.48	0.13	0.13	0.09
	Scandy Pro Smartphone-App	–5 ...+5	–4.8	4.98	0.69	0.39	0.23	2.16

Fig. 6. Data comparison from the color mapping.

A notable constraint of our study lies in the fact that objectively comparable scans were exclusively applicable to the model hand (object scanning), whereas the human hand's evaluation relied on subjective assessments. Additionally, we did not investigate processing time or the requisite number of trials for achieving a successful scan. Despite these limitations, we believe that this study provides a comprehensive overview of the suitability of various scanners for both hand and object scanning within a healthcare context.

The complexity of scanning hands lies in the intricate anatomy of the human hand. Scanning the palm and dorsum typically presents no difficulties; however, the long, thin, and closely positioned fingers are particularly challenging to capture accurately.

Regarding the color mapping in our study, we decided to compare all models with the data from the Keyence scanner. The scan data are not compared with the original printed CAD model because the printed model already has unknown deviations due to the usual shrinkage/contraction of the material. Instead, the scan data from the very accurate Keyence VL-550 scanning system is used as the target geometry, which has an advertised scan accuracy of ±10 μm.

The maximum and minimum values on the color maps only provide a rough orientation indirectly. This is due to the existence of singularities in the triangle mesh, which means that the maximum and minimum are always close to the boundaries of the preset comparison range. Therefore, the comparison range was manually adjusted so that almost all areas of the scan are within this range. The cited study by Rudy et al[20] evaluated various 3D scanners by scanning the human face, which is a favorable surface for 3D scanning due to its less complex geometry. However, when attempting to scan the fingers, the thin and long tubular structure presented difficulties, resulting in artifacts that often required postprocessing to remove and reshape. The time required for capture and postprocessing was found to be user dependent. Increasing the number of scans by the same user resulted in decreased times. However, some scanners, such as the Artec Eva, were not readily available for daily use, limiting the number of times they could be utilized. With more experience, the processing time can be reduced. Furthermore, the quality of scans, particularly with more affordable scanners, was found to be more dependent on the user. Some scans with the iPhone 12 produced high-quality results, whereas others required more postprocessing to remove artifacts. Scanners at a higher price point were found to exhibit greater consistency in their scans.

The Clinical Application of 3D Scanning and Printing Is Still in Its Early Stages

It is important to keep in mind that 3D scanning is a time-consuming process, and although the functionalities of the postprocessing software are enormous, there are no known integrations for clinical applications. For example, to create a cast from a scanned arm or hand, the cast would still have to be manually designed. In the future, it is very possible that software will aid those processes and make 3D scanning and printing a much more dynamic process. Similarly, 3D printers have already made incredible leaps in quality and functionality but are still slow when it comes to actual printing times. The models we printed from our 3D scans took an average of 10 hours to print, and a full forearm cast can take up to 13 hours.

3D scanners are widely utilized in both industry and research. One major advantage for many medical applications is the ability to scan nonmoving parts. Stationary objects can be scanned with higher quality. For example, even slight shaking of a human hand during scanning with a precise scanner can cause loss of tracking. This is due to the scanner's ability to capture minute details such as finger creases, which are used for alignment during the scanning process. Movement or shaking can inhibit this alignment process. One solution we have encountered, in addition to attempting to immobilize the hand as much as possible, is to use less precise scanners. For instance, the Artec Space Spider scanner worked perfectly on a model hand but had almost no chance of fully tracking a live hand. In contrast, the Artec Eva scanner, with its point accuracy of 0.1 mm compared with the 0.05 mm accuracy of the Artec Space Spider, performed much better on our human test hand. That being said, the accuracy of the Artec Eva scanner was sufficient for its intended purpose of use.

Yang et al[27] undertook a novel approach to constructing a custom hand scanner. The group purpose-built a scanner comprising 50 8-megapixel cameras. The total material cost for their human hand scanner was 3650 euros, which is significantly lower than many of the scanners evaluated in our study. Final testing, which compared their scanner to the Artec Space Spider by scanning a 3D-printed prosthetic hand, revealed a mean absolute error between the two scans of 0.62 ± 0.28 mm. This demonstrates that high-precision 3D scanning is achievable at a lower cost. However, we estimate that most departments will opt for a prefabricated scanner due to time constraints and lack of expertise in assembling such a scanner.

We acknowledge that none of the scanners mentioned in this study were specifically built for the purpose of scanning hands. Some of the included scanners, such as the Creaform HandySCAN 700 Elite and the Keyence VL-550, were specifically designed for industrial use and are optimized to precisely scan components for industries such as the automotive industry. Therefore, scanning human body parts presented a challenge due to the scanners being used outside of their intended purpose. We included these scanners to provide a comprehensive overview of what is available on the market and to offer a valuable comparison of the capabilities of 3D scanning technologies, even if they are not yet optimized for medical use. Additionally, these scanners can be precisely and purposefully used to scan medical components such as casts, implants, or instruments.

One important advantage of photogrammetry, as demonstrated by some iPhone scanners (such as Polycam) and the Vectra camera by Canfield, is the provision of color structure. This is particularly suitable for applications such as wound management and dermatology. For our purposes, the focus was on geometric data. In the case of photogrammetry, these data are usually less precise due to the lower number of data points, which results in reduced accuracy.[28]

CONCLUSIONS

The most accurate scanner overall in our test was the Artec Space Spider when scanning the 3D-printed model, with minimal deviation from the original data (SD 0.05 mm). For the purpose of scanning a human hand, our results indicate that the Artec Eva scanner shows best accuracy. It allows for comparable precision to the Artec Space Spider with the advantage of being able to scan larger objects. It generates a high-resolution 3D scan with high accuracy and minimal postprocessing. However, we recognize that for other anatomical regions with simpler shapes, such as the face, a less complex option like the iPhone may suffice for most applications.

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DISCLOSURE

The authors have no financial interest to declare in relation to the content of this article.

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