International Journal of Medical, Medicine and Health Sciences
ISSN: 2517-9969
Vol:6, No:12, 2012

3D Digitalization of the Human Body for Use in Orthotics and Prosthetics

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***Abstract*—**The motivation of this work was to find a suitable 3D scanner for human body parts digitalization in the field of prosthetics and orthotics. The main project objective is to compare the three hand-held portable scanners (two optical and one laser) and two optical tripod scanners. The comparison was made with respect of scanning detail, simplicity of operation and ability to scan directly on the human body. Testing was carried out on a plaster cast of the upper limb and directly on a few volunteers. The objective monitored parameters were time of digitizing and post-processing of 3D data and resulting visual data quality. Subjectively, it was considered level of usage and handling of the scanner. The new tripod was developed to improve the face scanning conditions. The results provide an overview of the suitability of different types of scanners.

***Keywords*—**3D digitization, prosthetics and orthotics, human body digitization.

I. Introduction

OPTICAL digitization of real objects become standard tool in the various branches e.g. mechanical engineering, quality control, forensic science, archeology and medicine, especially in the area of prostheses and orthoses production. 3D scanners are available in different versions and for different purposes. The motivation of this work is to find a most versatile scanner that would meet the requirements for digitization of the human body parts.

The presented research, unlike other works, does not compare scanning systems in terms of accuracy. Most optical and laser scanners reach precision in the order of tenths of millimeters, which is sufficient for the human body scanning. Most tests focused on the accuracy of the 3D scanners were performed on castings or RP models. The evaluation of scanning accuracy directly on the patient encounters the problem of reference geometry.

Similarly, as Gibson et al. [1] presents the requirements for the medical use of RP models (Speed, Cost, Accuracy, Materials, Ease of use) it is possible to specify the basic requirements for digitizing technology for use in prosthetics and orthotics. The scanning speed, the ability to scan the details (e.g. wrinkles), ease of handling and ease of the scanner use can be classified among the most important. The speed of digitization process is on the first place. In the case of scanning the face or the body parts directly on the patient the digitization time is very crucial. Unlike the Computer Tomography, patient usually sits. Tissues are digitized in their natural shape and position [2] [3]. The head may also be supported, and the patient is trying not to move with the head and mimic muscles. A special case can be scanning of very young children. Children cannot control as adults and thus the head movement occurs in the process of scanning. Most scanners are not designed to scan living objects and it is assumed that the digitized object will not move. But during the scanning of live objects always some move occurs, albeit very small.

An important capability of the scanner is the reproduction of details, such as skin texture, especially in case of plaster casts of the human body. This allows producing more realistic prostheses using rapid prototyping technology e.g. in case of upper limb prosthesis or facial prosthesis.

The latter requirement is ease of use of the scanner, which means easy operation and handling, but also software and data processing. In the area of prosthetic devices manufacturing digitization is performed by trained personnel, but not a specialist.

The area of digitization in face scanning scenario was addressed by Boehnen and Flyn [4]. They presented a method for empirical accuracy analysis, and applied it to several scanners such as Qlonerator (3DMD), Vivid 910 (Konica Minolta), general-purpose FastTrack (Polhemus) and two scanners from anonymous vendor. Scanners have been tested on ten castings of the human face made from molds created by 3D printing technology of 3D Systems Thermojet. Deviations of the physical model from the original STL data were measured by tactile scanner Roland PIX-30. Subsequently, about 60 scans were captured, which were compared by means of absolute accuracy.

Problems with the face scanning and improvement of the scanning process´ parameters were also discussed by Bianchi et al [5]. The team deals with the optimization of digitizing parameters of laser scanner Cyberware head and face colour 3D Scanner 3030RGB (Cyberware Monterey, CA). A geometry including color information was scanned during 17 seconds of scanning time. Scans were processed in the RapidForm software (Inus Technologies, 2004). The author discusses the scanning conditions such as: suitable scanning distance, cosmetic treatment of skin and hair reduction in

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relation to the avoidance of artifacts. The loss of scan quality caused by significant motion is also discussed.

Comparison of three measurement techniques for digitization in area of craniofacial malformations and cranio-maxillo-facial surgery is discussed by Ozsoy et al [6]. In the article three methods are compared: manual anthropometry, 2D photogrammetry and computer-aided 3D digitizer. The faces of the subjects were photographed with high-resolution digital camera (Canon Powershot G5; Canon Inc, Tokyo, Japan). For 3D digitizing was used MicroScribe G2X digitizer (Immersion Corp., San Jose, CA, USA) with Surfcam Velocity software (Surfware Inc., CA, USA). A total number of 35 female and 35 male volunteer adults were included to the study.

Another approach of 3D digitization involves scanning of plaster casts of the human body, such as upper limb and facial areas. The digitization of rigid objects allows to remove motion artifacts and thus to obtain very detailed descriptions of the geometry up to the level of wrinkles. The pilot research about suitable technologies that may be used for capturing, creating, and producing of fine textures and wrinkles was presented by Eggbeer et al [7].

II. Technical Specification of 3D Scanners

The tests were performed with four scanners: ATOS I (GOM, Germany), zSnapper (Vialux, Germany), Artec MH (ARTEC Group) and ZScanner 700 (Zcorporation, USA). The later experiment was extended by a new scanner ATOS TripleScan (GOM, Germany). Table I presents brief overview of the basic parameters of tested scanners.

Individual scanners differ from each other in a wide range of parameters, among the fundamentals and most important which should be considered from the orthotics and prosthetics point of view the following may be included:

Accuracy - indicates the deviation (error), which arise during determination of the points´ position in the space i.e. the difference between the real and measured values (eg, ± 0,05mm).

Resolution - specifies the smallest possible distance in space which is able to be measured.

Mobility - the possibility of a portable scanner setup and the necessary equipment (stand/tripod, computer, etc).

Range - Minimum and maximum scanning distance and size of the scanned area.

Preparation time and scanning time - the time of preparation involves 3D scanner setup, its calibration and preparation of the scanned object. The scanning time includes taking individual snapshots and basic data preparation.

Ease of use - Includes object preparation, the scanning procedure itself and post-processing of the scanned data (merging and modification).

The versatility - the 3D scanners´ ability to adapt to a wide range of subjects (size, shape, material type) and scanning conditions (environment, lighting, movement of the object).

Price - the cost of hardware and software for the creation of 3D model.

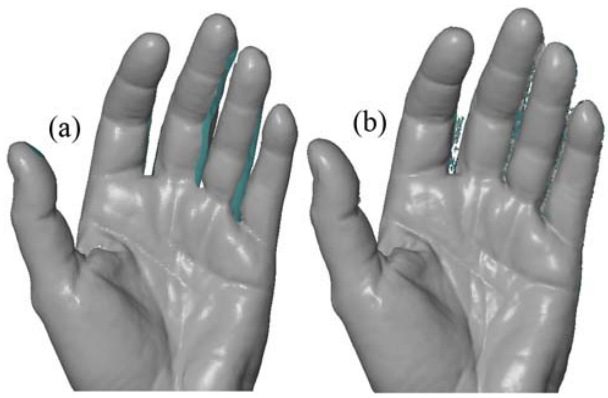
TABLE I
COMPARISON OF BASIC PARAMETERS

3D Scanner	Artec MH	ATOS I	zSnapper portable	ZScanner 700
Principle	Optical	Optical	Optical	Laser
Type	Mobile	Stationary	Mobile	Mobile
Sensor resolution	500 000 points	800 000 points	300 000/80 000 points (tripod/hand)	N / A
Accuracy	0,1 mm	0,05 mm	0,02 - 0,05 mm	0,05 mm
Resolution	0,5 mm	0,12 - 1,00 mm	0,04/0,30 mm (tripod/hand)	0,1 mm
Output format	OBJ, STL, WRML, ASCII, AOP, CSV	STL	ASCII, AOP	STL, RAW
Scanning speed	15 fps, i.e. 0,07 s/snapshot	0,8 s/snapshot	0,022/0,2 s/snapshot (tripod/hand)	18 000 points/s
Price (EUR)	10 800	46 000	32 700	38 500

Generally two approaches to obtain 3D surface data can be used in the field of orthotics and prosthetics. The first approach is to obtain 3D data from the manufactured plaster cast (CASE I). The second approach is to scan different parts of the body directly on the patient (Case II).

III. Case I - Digitization of Plaster Casts

Plaster casts can be made by conventional methods with fast curing silicone, in which the required portion of the patient's body is imprinted. It may be, for example a stump to create a prosthesis bed or part of a healthy limb if the aim is to produce the custom prosthesis of a missing limb with the same proportions, shape and detail accurately reproducing the original limb.



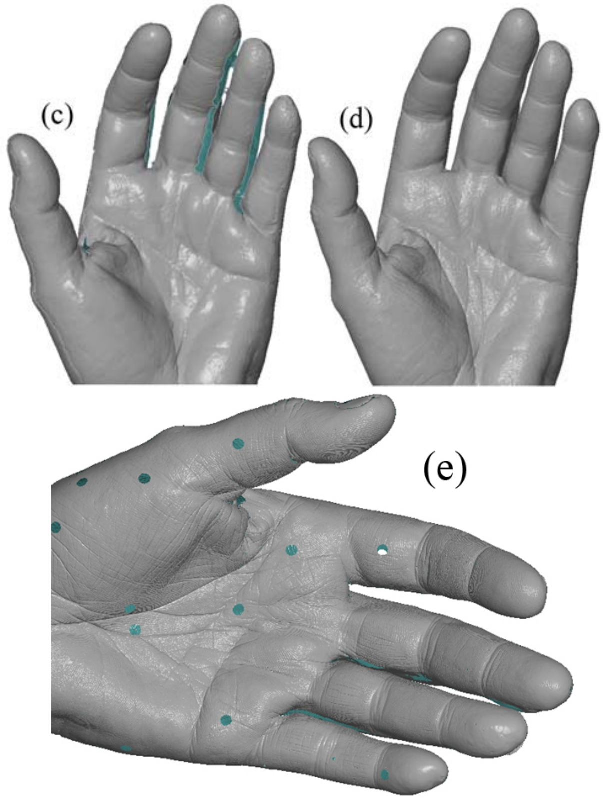


Fig. 1 3D data of upper limb plaster cast (a) Zscanner 700, (b) Artec MH, (c) zSnapper, (d) ATOS I, (e) ATOS TripleScan

Silicone imprint is then used as a mold for production of the plaster copies of the limb or body part. The technology of casting into silicone molds achieves a high level of copy precision of surface detail, wrinkles and ridges. It is thus possible to consider the 3D digitization possibilities with a focus on surface details.

Scanning was performed by a trained operator in a standard manner. In the case of hand-held scanners a tripod or other aids were not used. ATOS I was placed on a stand. ATOS Triple Scan was placed on a lift and scanning was performed with the use of an automated rotary table. For comparison, only the base Post-processing was performed on all scans, which consisted of a point cloud polygonization. It should be noted, that the data quality of the Zscanner and Artec MH scanners can depend on hardware of connected laptop especially on installed memory.

TABLE II
PARAMETERS OF STL DATA

	Triangles	Digitization [min]	Post-processing [min]	Visual Quality 1(best) -5
Artec MH	781946	4	5	3
ATOS I	1 874 210	10	4	2
zSnapper	403581	6	1	4
ZScanner	143579	8	2	5
ATOS TripleScan	6 091 631	12	5	1

The test results are presented in Table II. Fig. 1(b) shows that the Artec MH Scanner generated wrong polygons between the fingers, while the zSnapper scanner showed (Fig. 1c) poor connection of the palm and dorsal hand parts. On the ATOS I (Fig. 1d) there are no errors in these areas, but the space between the fingers was also not possible to scan. Generally, the reproduction of details using the tested hand scanners is very similar. The major qualitative difference is apparent in the comparison with the ATOS TripleScan scanner (Fig. 2).

The results showed that hand scanners are not able to capture skin textures. Nevertheless they are suitable for fast and easy obtaining the basic geometry of a plaster cast.

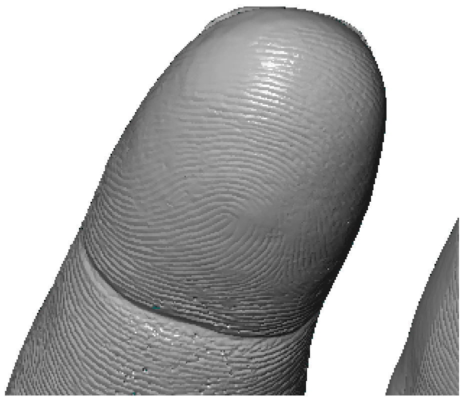


Fig. 2 Detail of 3D data of a plaster finger, digitized by ATOS TripleScan

IV. Case II - Body 3D Digitalization

Direct scanning of the patients brings the benefits of speed and contactless capture which significantly increases the patient comfort during the digitization and also saves time and material in comparison to the production of casting.

Realized tests were focused on practical use during operation. Since the deviations of direct scanning of the human body may be in the order of tenths to one millimeter, which is still sufficient for the production of prostheses and orthoses, the primary parameters are the scanners' handling (ease of use) and scanning time.

When running the 3D scanners´ test various body parts were digitized directly on the patient, while following parameters were considered:

Digitization - time needed for preparation and scanning.

Post-processing - time for basic data processing in the scanner software (repair of the 3D scanning data has not been investigated because it can be implemented in a number of software tools with varying quality).

Number of Snapshots - necessary scanning positions to capture a whole object.

Number of Triangles - resulting size of the polygonal mesh.

Visual Quality - appearance of the resulting data considering further processing with Rapid Prototyping, Reverse Engineering, CAD/CAM tools.

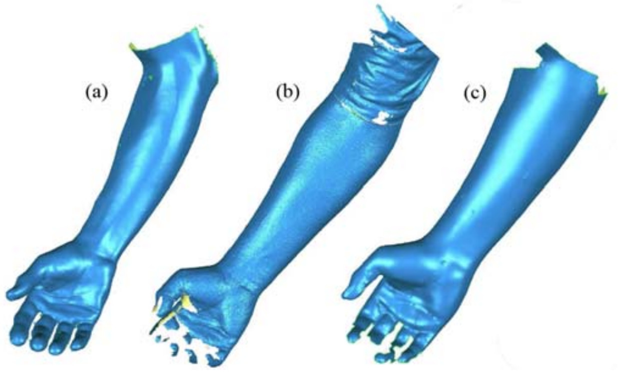


Fig. 3 Upper limb scanning results1 (a) Artec MH, (b) ATOS I, (c) zSnapper

The upper limb was scanned in a loose position on a flat surface. Scanning was performed only from one direction to obtain the inside geometry of the arm for the considered design of the orthosis used for fixation of the wrist position.

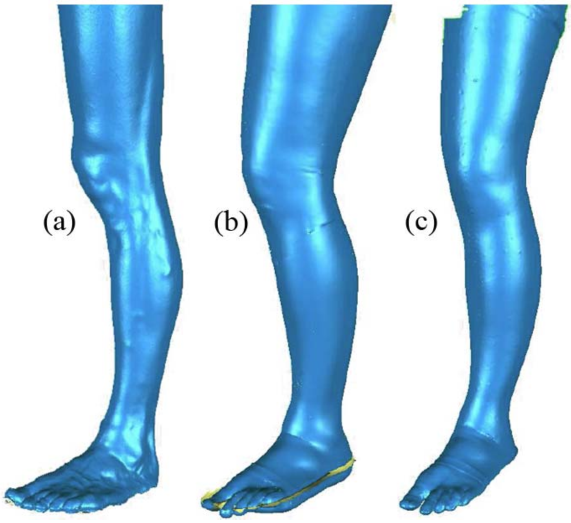


Fig. 4 Lower limb scanning results (a) Artec MH, (b) ATOS I, (c) zSnapper

The lower limb was scanned in a relaxed position when standing on the other leg. While scanning, the patient was leaning on parallel bars. To ensure the same conditions stocking was used.

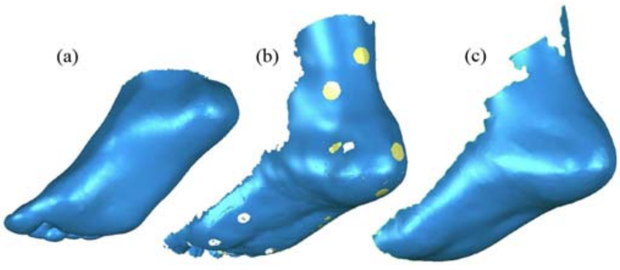


Fig. 5 Foot scanning results (a) Artec MH, (b) ATOS I, (c) zSnapper

During the digitization of the foot the patient was standing on the opposite foot while the scanned leg was bent at the knee and placed in a stable position on a chair.

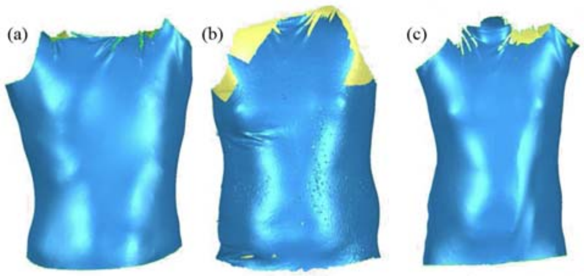


Fig. 6 Body scanning results (a) Artec MH, (b) ATOS I, (c) zSnapper

The patient´s hull was captured in a standing position. The patient had his hands folded in a stable position on his head and was leaning on his back on a slim board. To improve the conditions of scanning the patient was dressed in a stretch-fit t-shirt.

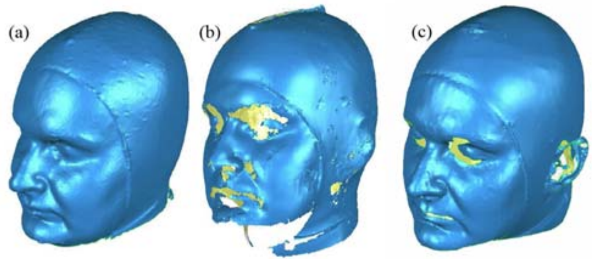


Fig. 7 Head scanning results (a) Artec MH, (b) ATOS I, (c) zSnapper

The patient's head was scanned in a stable sitting position in a chair. Since all of the scanners have problems capturing hair, a flexible thin cap was used to cover the hair.

Figures 3-7 shows the comparison of the scanning results of the individual body parts. Time of scanning, data processing and the resulting size of the polygonal mesh are shown in Table III.

Initial tests showed that the laser scanner is not suitable for scanning of living objects. The ZScanner 700 has problems with the composition of the scans even at a slight movement of the scanned object; therefore it was not possible to capture the face and head. Moreover the time of data post-processing from the laser scanner was too long. Therefore, the laser scanner was excluded from other operational tests and evaluation.

The operational tests were conducted at the ING Corporation workplace during a period of several months. To ensure the comparability of the results in terms of level of control of individual scanners, the measurements on patients were conducted by experienced operators. It should be taken into consideration that while scanning on live patients (figurants) the same, exact conditions cannot be ensured (e.g. same level of movement).

TABLE III
RESULTS OF THE OPERATIONAL TESTS

		Artec MH	ATOS I	zSnapper
Upper Limb	Digitization (min)	4	1	19
	Post-processing (min)	4	5	8
	No. of Snapshots	355	3	12
	No. of Triangles	344 628	372 663	229 486
Lower Limb	Digitization (min)	4	8	25
	Post-processing (min)	8	22	31
	No. of Snapshots	500	17	35
	No. of Triangles	1 113 930	1 513 606	1 864 590
Foot	Digitization (min)	5	7	5
	Post-processing (min)	5	7	3
	No. of Snapshots	535	8	6
	No. of Triangles	990 160	464 768	159 896
Body	Digitization (min)	4	3	12
	Post-processing (min)	3	120	36
	No. of Snapshots	611	9	30
	No. of Triangles	1 808 400	4 908 122	2 546 944
Head	Digitization (min)	5	31	4
	Post-processing (min)	11	5	4
	No. of Snapshots	236	23	8
	No. of Triangles	1 956 384	2 591 893	244 753

The ATOS I Scanner is characterized by a high accuracy and resolution. It is suitable for very accurate scans of static castings. The mobility and versatility of the scanner is small; the preparation time for scanning is relatively long. It is beneficial for laboratories to use rather than with mobile applications in a clinical environment.

The ZSnapper portable is a mobile scanner with an excellent universal use in a clinical environment. It is characterized by a short preparation time, ease of use and high mobility. Nevertheless the accuracy of 3D scans does not reach the quality of the ATOS I scanner. The disadvantage of this scanner is the necessity of reference points. The scanner can be used without reference points, but post-processing time is long.

The Artec MH scanner appears to be ideal for application in a clinical environment. It has a short preparation time; it is easy to use and highly mobile. Another advantage is that it does not require reference points during capturing and has a high speed of scanning. The accuracy and resolution of the scanner is lower than other scanners, but still satisfactory.

V. CASE III - FACE DIGITALIZATION

A specific area is to digitize a patient's face for facial prosthesis production e.g. nose prosthesis or orbital prosthesis. For these purposes the standard procedure with plaster casts is currently most widely used, but the use of contactless production would result in a large increase of patient comfort. Consequently, the possibilities of face digitization on live patients were studied in detail.

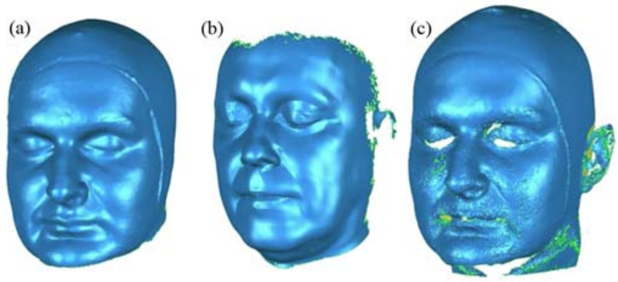


Fig. 8 Face scanning results (a) Artec MH, (b) ATOS I, (c) zSnapper

For more detailed tests, the ATOSI and ATOS TripleScan scanners were used which allows scanning with a greater detail as it is evident from the results of Case I and Fig. 8. One of the limitations of these scanners is their dimensions, which require a tripod/stand to ensure a stable position during scanning. When scanning the face the speed of scanning process itself is especially important, while the patient has to move as little as possible. To speed up the process of face digitization using the ATOS I scanner a special stand with a swinging arm was designed (Fig. 9). The stand allows a quick change of the scanner position in range of +-30° from the medial plane. And therefore less time is needed and a more accurate position is ensured during the face digitization.

Fig. 9 Stand with swinging arm for ATOS I

Another specific problem is the use of reference points when using industrial scanners. These points generally serve to ensure the alignment of individual snapshots against each other. In case of points (paper stickers) application on the patient´s skin, the point movement occurs due to breathing and movement of mimic muscles. This prevents the points use as a reference. For that reason, the scanning capabilities without the use of reference points were also tested.

A. Face Digitization Using ATOS I

Using the ATOS I with combination of ATOS Professional

7.5 software, it is possible to digitize objects without reference points (Fig. 10 and 11). Individual snapshots are aligned automatically into common coordinate system by the built-in "Best Fit" function. For proper functionality of this feature, it is necessary to capture the object with a sufficient overlapping of digitized surface within individual snapshots. With this procedure it is possible to realize digitization with the use of one snapshot from the front (Fig. 10) or two snapshots from the sides with angle about 20deg. (Fig. 11) or three snapshots from the front and sides with angle about 30-40deg. The measurement parameters used for digitization of the face with the ATOS I are shown in Table IV.

TABLE IV
MEASUREMENT PARAMETERS

	ATOS I	ATOS Triple Scan
Measuring volume	500 mm	560 mm
Face to scanner distance	650 mm,	830 mm,
No. of shutter times	1	1
Shutter time	20 ms	20 ms
Scan detail option	More points	Fast scan

During the measurement, the figurant was sitting in a stable chair back to the wall and with the back of the head touching the wall to keep a stable position. As can be seen from the Fig. 10 one snapshot from the front is not usable. The areas on the sides of the nose contain no data. Therefore multiple snapshots need to be taken to obtain a complete face. This usually leads to problems with fast transportation of the scanner with a stand into a second position. In this case the use of the swinging arm stand was found to be very beneficial, especially in case of scanning young patients.

Fig. 10 ATOS I without reference points, 1 snapshot

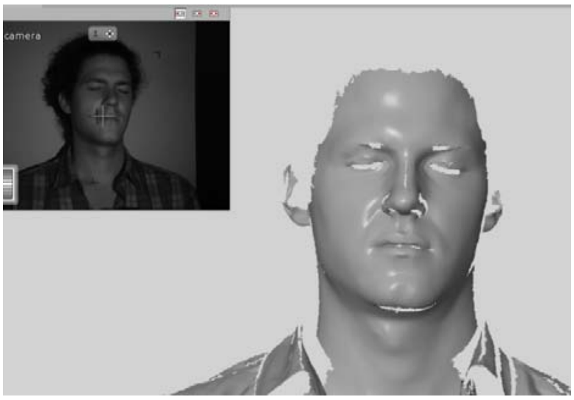


Fig. 11 ATOS I without reference points, 2 snapshots

The digitization with reference points placed directly on the patient´s face is not feasible as discussed earlier. Placing the reference points on another still object e.g. the wall behind the patient´s head is feasible, however if the patient moves his head during the snapshots, then the measuring is ruined. For this purpose a simple tool was invented (Fig. 12). It is a headband with soldered plastic rectangles on which the reference points (5mm round points) can be easily applied. The headband is light, flexible and easy to use for any size of head. The reference points on the headband moves with the patients head, and alignment errors do not occur.

Fig. 12 Headband with reference points

The scanning from three positions without reference points showed no significant improvement of scan quality; therefore relevant figures are not included. Also scanning with the reference points did not show significant visual improvement. In this case the biggest advantages were the lower demands on the “stillness” of the patient and almost no necessity to repeat measurements.

B. Face Digitization Using the ATOS TripleScan

The ATOS Triple scan was included because of the potentially better scanning parameters and lower requirements for object preparation. In comparison with the ATOS I, it has a much higher resolution (8Milion points) which could bring greater detail. Also it´s enhanced light source scanning at worse light conditions could capture more data within one snapshot. However during face scanning without reference points, it was found that only a single scan is possible to create. The alignment of multiple scans using the “best-fit” function was not successful. Hence the face scanning with the ATOS TripleScan proved to be feasible only with the use of reference points and with the application of the aforementioned headband. The headband must be shifted forward, just above the forehead. Capturing of more than 1 snapshot (Fig. 13) is then possible using this setup. The scan quality is thus comparable, as seen from the attached figures (Fig. 11 and Fig. 14), however the ATOS TripleScan´s result contains more points (40 000 vs. 25 000) and details.

The ATOS I show better results in the gap between the lips and also contains no holes around the eyebrows. It may also be due to lower resolution and thus a worse capturing of details.

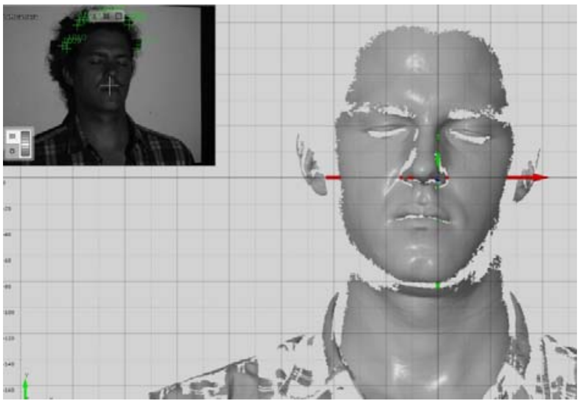


Fig. 13 ATOS Triple scan with headband, 1 snapshot

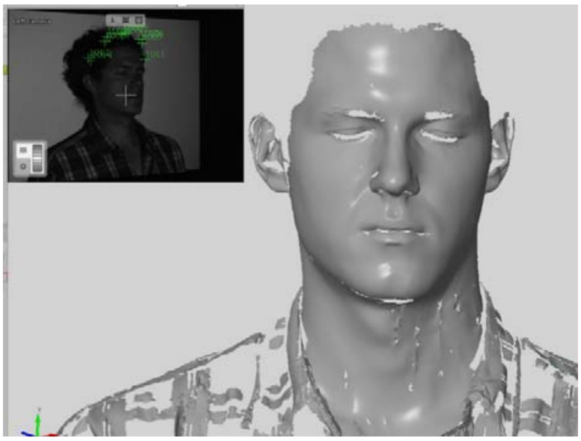


Fig. 14 ATOS Triple scan with headband, 3 snapshots

The digitization with a headband and reference points is more reliable, the alignment of snapshots always passed without problems. The results also show that two snapshots are sufficient. While scanning with the Scan Triple the swinging arm stand cannot be used because the scanning head is too big and too heavy, therefore the manipulation is worse and the scanning procedure is longer. As a conclusion from these tests it can be stated that for the face digitization with the use of the ATOS I still brings more advantages in ease of use and scanning time, while the resulting data are sufficient.

VI. Conclusion

The performed measurements and tests showed that in a case of the plaster cast digitization scanners with higher resolution stationary placed on a stand are more suitable. Regarding the details, the ATOS I and the ATOS TripleScan predominate among the tested scanners. However, they have higher requirements for the preparation of the scanning process (reference points, special tools, stand), ease of use is worse and handling demands are higher. Also these scanners are much more expensive.

For direct scanning of the patient the handheld scanners are more appropriate. They are not too sensitive to the change of the scanned object´s shape. Both handheld scanners reached similar results in the direct scanning of the patient. In terms of ease of use, measurement speed, data processing and quality of the resulting polygonal network ArtecMH can be a good choice.

Acknowledgment

The work described in this paper was completed in cooperation with the orthotic-prosthetic facility ING Corporation, s.r.o. in Frydek-Mistek and the Department of Rehabilitation, Faculty of Health Studies, University of Ostrava and the Institute of Machine and Industrial Design Faculty of Mechanical Engineering, Brno University of Technology. The present work has been supported by European Regional Development Fund in the framework of the research project NETME Centre under the Operational Programme Research and Development for Innovation - NETME Centre, ED0002/01/01, CZ. 1.05/2.1.00/01.0002 and project Application of Digital Technologies for Design, Manufacturing and Assesment of Custom—Made Orthotic and Prosthetic Devices, no. FR-TI3/388. All authors declare that they have no conflicts of interest.

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