LEG VOLUMETRY SHORT REVIEW

How to measure the leg volume with a 3D Scanner in a vascular environment. Our experience with Peel3D Handyscan®

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Abstract Background: Volume quantification with existing limb volumetry methods is difficult, either tedious or inaccurate and difficult to repeat. Our aim is to describe and validate a new technique for limb volumetry using the new technology of 3D surface scanning. Design and methods: A new 3D surface scanning device (3D Handyscan from Creaform®) was used to quickly and accurately measure limb volumes. Targets were placed on the limbs to facilitate scanning and to provide reproducible slice planes for reliable volumetry. This paper details the methodology used: device setup, target positioning, scanning technique, slice plane selection and volume calculation. Results: The accuracy of the measurements is 0.4% of limb volume. The inter- and intra-observer reproducibility is 0.5%. Conclusion: This new technique of limb volumetry is faster and more accurate than the other techniques and easily repeatable to assess the evolution and treatment of edema and lymphedema.

Keywords limb volumetry, 3D surface scanning, 3D reconstruction, leg modeling, edema

Introduction

We use a new technique of limb volumetry with the portable peel 3D peel2 CAD handyscan[1] from Creaform® (Figure 1). The technical specifications of this device are given in Table I.

It was tested in two clinical studies[2-4] on 20 volunteers with lower extremity occupational edema associated with long several hours of standing at the end of the day.

Objectives

To describe the methodology of this new leg volume technique.

To evaluate the accuracy, reliability and reproducibility of the 3D surface scanning technique using the peel 3D peel2 CAD handyscan.

Design and Methods

Description of the surface scanning procedure for limb volumetry

1- Running the software and connecting the device before scanning

Part size range	.3-3.0 m
Accuracy	Up to 250 mm
Mesh resolution	0.500 mm
Volumetric accuracy	0.500 mm/m
Measurement rate	550.000 /sec
Measurement resolution	0.250 mm
Scanning area	380 x 380 mm
Stand-off-distance	400 mm
Depth of field	250 mm
Light source	White light (led)
Colors	24 bits
Texture resolution	50 to 150 dpi
Positioning methods	Geometry / targets / texture
Weight	950 g
Dimensions	150 x 171 x 251 mm
Connection standard	USB 2.0

Table I - Technical specifications of handyscan 3D

We used a PC computer equipped with 64 gigabytes of RAM. The dedicated software Peel3d version 3 was used.

Step 1: We first need to connect the device to a PC computer with of 64K of RAM. A USB cable is connected to the computer and to the device. A power supply is also connected to the USB cable near the computer.

Step 2: We calibrate the scanning device by using a special box of targets (Figure 2). This must be done before to the first scan and then checked periodically (every month).

Step 3: Before scanning, the following software parameters are used and set to default:

- position: Method targets/geometry - Textures on;
- scan resolution: 2 mm (sufficient to get a high resolution 3D model);
- texture: apply texture - paint the targets.

2- Limb scanning technology

The subject stands still on a stool, with the two feet 40 cm apart and a free space of 2 m around the subject, so as to allow free rotation around the legs. (Figure 3) Round adhesive targets (Figure 4) are first applied to the skin, with 2 objectives:

- To facilitate alignment and matching during the scanning process to reconstruct the 3d mesh model and to define very accurate and reproducible section planes with 3 targets for volume quantification;
- To obtain parallel horizontal sectional planes, a laser beam is used to position the targets (Figure 4)

When you are ready, click the "digitise" button to start scanning.

Figure 1 - 3D Handyscan device (Peel 3D Peel 2 cad from Creaform®)

Figure 2 - 3D Handyscan calibration device with sample targets.

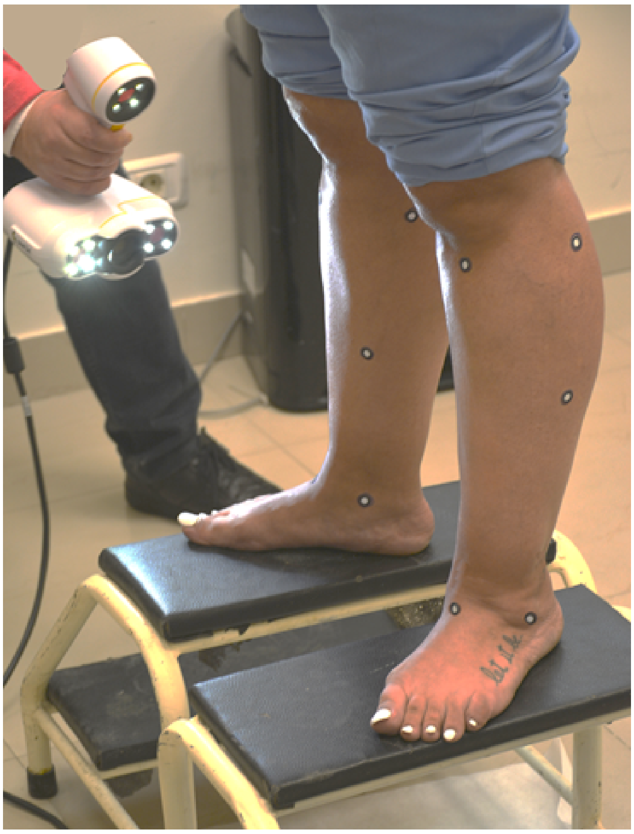

Figure 3 - Scanning of a patient (right leg) in standing immobile position.

Figure 4 - Laser beam alignment to ensure parallel horizontal planes for cutting.

Figure 5 - Scanning technique for upper limb lymphedema: suspend the limb by hand.

To scan the leg, the operator moves slowly up and down along the limb and rotates around the subject to cover the entire limb surface. The progress of the reconstruction of the entire limb must be checked in real time on the computer screen, to ensure that the surface is complete, and that there are no holes in the leg model.

The user then verifies that the limb surface is complete and that all targets have been correctly identified. Otherwise, the limb scan must be repeated.

When finished, the user presses the space bar to create the full mesh model and then again interactively verifies that there are no holes on the skin by rotating the 3D model.

The average scanning time (one limb) is approximately 90 seconds. The same leg should be scanned 3 times, to obtain an average volume.

A different scanning technique is used for the UPPER LIMB (Figure 5)

Here, the patient is lying on the back. The limb is suspended by the fingers with an angle of about 45 degrees, allowing the complete turn-around the limb with the device.

3- Reconstruction of the limb using textured 3D mesh models

The 3D models produced still require a number of graphical operations on the models in order to make them suitable for analysis (Figure 6). The rough leg models always have some defects, such as small irregularities, protrusions, or support parts.

These defects are corrected using the Handyscan software which provides appropriate and easy-to-use modelling tools, particularly for filling holes.

When the final 3D mesh model is obtained, the volume calculation of each segment takes about 2 minutes. High resolution coloured textures could be applied to the mesh surface, as shown in Figure 8.

4- Leg segmentation using dedicated software from Creaform® (Figure 7, right)

A section of the 3D model is created using the menu option "add a section plan" option from the menu by using 3 targets, and then clicking on the desired targets.

This is done by sectioning the limb by using a plan below the knee (3 higher targets) and at the ankle (3 lower targets). Once the section plane has been defined, the user can delete the segment highlighted in red, as shown on the Figure 7.

Figure 6 - Final result of 3D reconstructed left leg with texture and targets.

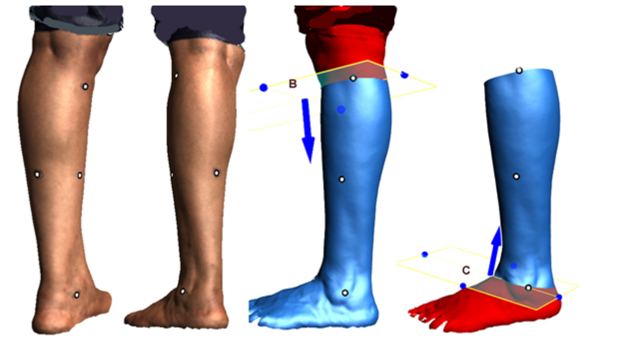

Figure 7 - Volumetric calculation using 3D modeling (First step) : Segmentation of the leg by 2 section planes automatically drawn by the 3 targets below knee (B) and ankle below the malleoli (C).

The leg is then segmented into 2 parts (half upper-leg and lower leg) by creating a sectional plane with the 3 mid-leg targets (Figure 8) by using the "create a line" function, then selecting the unwanted part, highlighted in red, of the volume to be cleaned.

5- Calculation of limb volumetry

For each isolated segment, volumetry is obtained using the "properties" mesh option (right mouse click).

This gives the number of triangles and vertices of the mesh, the volume in mm3, the perimeter of the slices and the barycenter of the model. (Figure 9)

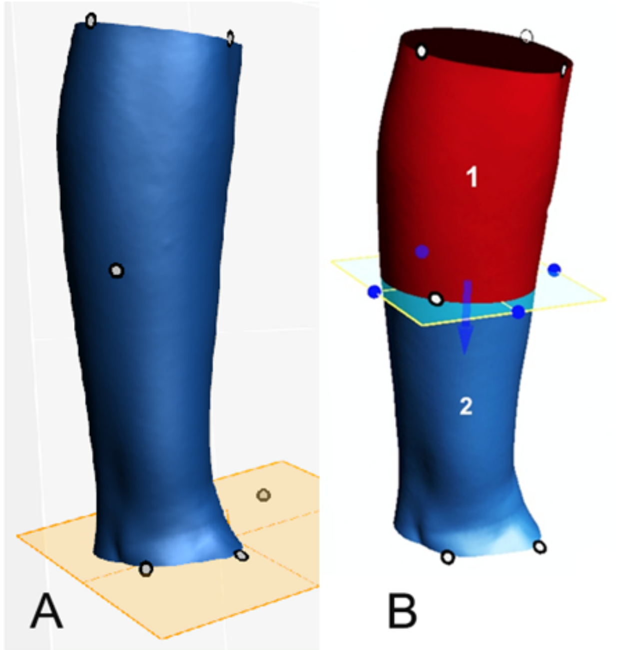

Figure 8 - Volumetric calculation using 3D modelling. A: Whole leg isolated. B: Segmented leg into several parts. Here 2 parts: upper leg (calf) and lower leg using a mid-leg section plane with the 3 targets.

Discussion

Methods to assess the volumetry of limb oedema and lymphoedema are controversial [5,6].

Several techniques of leg and arm volumetry techniques have been used in the past[7].

Water displacement leg volumetry is accurate[8,9], but tedious and associated with hygiene issues.

Optoelectronic measurement[10] is inaccurate. Photogrammetry[11] (Bodytronic 600) is not accurate enough. The tape measurement leg-o-meter[12] is time consuming and inaccurate.

The best solution for limb volumetry is to use of a portable 3D scanner[13-26] (Figure 1).

It allows fast, reproducible and very accurate measurement of the volume of the lower limbs and its different segments. An overview of limb volumetry techniques is given in table II.

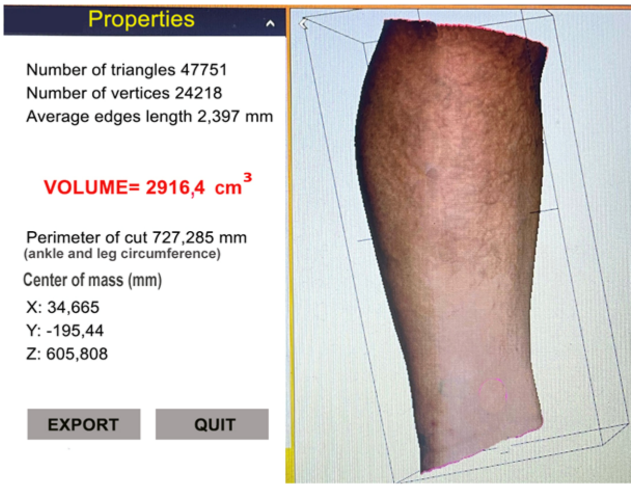

Figure 9 - Calculate leg volume with "mesh properties" option. (The perimeter is the sum of the perimeters of the leg and ankle cuts).

Comparison of 3D surface scanning with other techniques for limb volumetry (Table III)

The study by Paoli[19] describes the available devices using 3D scanning technology, comparing architecture, handling, acquisition time, accuracy and cost. The best choice for limb scanning is the portable solution as represented by handheld scanners.

The assessment of upper limb lymphedema using the lymph3Dlab software by Vitali[20] et al. was performed using the Microsoft Kinect v1 as a scanner. They found a difference between water displacement and 3D between -6,75 cm3 and +9,40 cm3.

Yang[21] et al. assessed venous edema in the lower limbs by comparing the tape method with 3D surface scanning (3DLS). They showed a strong correlation between the circumferential and 3DLS methods (r^2 = 0.9065). The 3D had a high intra- and inter-operator reliability. A Bland-Altman plot showed satisfactory agreement between the two methods. The 3D method showed greater bilateral limb differences than the circumferential method.

Yu[22] et al. assessed compared direct measurement (DM) with 2 scanning techniques :hand 3D models using a Gemini structured light scanning (SL) system and CT scanning.

They found no difference between DM, SL and CT in 10 healthy adults. The absolute percentage error was 4.69 ± 2.33% and 4.88 ± 2.22% for CT and SL scanning, respectively.

Bahadori[23] performed a systematic review of several studies which are summarized in Table II.

Mestre[24] compared the water displacement method with 3D scanning using 2 independent observers in 30 CVI patients, 30 lymphedema patients and 30 healthy adults.

He found that 3D laser scanning showed repeatability of data obtained between observer 1 and 2. However, laser scanning overestimated volume by 90 ml compared to WD.

Hayn[25] studied 18 knees after arthroscopic surgery. He showed that strong correlations were found for 10 reference points but not for the points of curvature (1–8 cm above the ankle)

Cau[26] compared leg volumetry in 11 healthy and 21 obese women. He found statistically significant differences in volume between the 3D scanner and the tape measure. The 3D laser surface scanner is better at detecting uneven limb shapes than the tape measure.

Hirai[18] compared the ease of use and accuracy of a halogen-light 3D scanner in measuring of foot oedema in 23 healthy volunteers. The data showed good reproducibility for the ankle and calf, but poorer reproducibility for the foot.

Table II
Comparison between the techniques of limb volumetry

Technique	Device	Accuracy	Time (min)	Drawbacks
Water Displacement	Water tank	++	15	Hygiene issue
Tape Measurement	Leg-o-meter	+-	20	Tedious not accurate
Photogrammetry	Bodytronic 600	+	2	Not accurate
Optoelectronic	Perometer	+-	1	Not accurate
3d surface scan	Peel3D	++	2	Cost

Table III
Studies comparing 2 techniques of limb volumetry (by Bahadori)

Author	Year	Population	Comparison	Device	Result
Paoli	2020		available devices		
Vitali	2019	5 healthy	WD vs 3DS	lymph 3Dlab	preliminary study
Yang	2020	30 CVD	CM vs 3DLS		3DLS accurate, rapid & reliable strong correlation R^2=0.9
Yu	2020	10 healthy HANDS	DM vs SL vs CT	Gemini structured light scanning	DM inferior
Mestre	2014	30 CVI/30 healthy 30 lymphedema	3D surface scan vs WD	Hand-held 3D scan	3D Accurate and reproduc-ible but overestimates vol.
Hayn	2013	18 knee arthoscopy	3D scan vs Tape	Kinect 3D camera sensor	Strong correlation 3D cost effective as home monitor
Cau	2018	11 healthy females 21 obese females	3D scan vs Tape	Hand-held 3D scan	More accurate for even limbs
Hirai	2012	23 healthy feet	3D scan / foot	Halogen light 3D	Reliable & reproducible excluding foot

Limitations of this surface scanning technique:

The number of targets used depends on the desired segmentation: 3 targets define a plane section, so we need 6 for the whole leg volumetry, 9 for a segmentation in 2 parts and 12 for 3 separate parts of the leg. However, only the 3 upper targets (below the knee) and the 3 lower targets (above the ankle) are mandatory. The other targets can be placed anywhere on the leg. In fact, it is more accurate and faster to define the parallel cutting planes using the 3D software.

Volume assessment can be possibly repeated after several days it requires a skin marking around the targets and precautions during washing in order to replace the missing targets.

The usefulness of the targets is not only for the slicing planes but also to facilitate the 3D matching of the model during acquisition.

The software offers several functions to improve the 3D mesh model.

One could be very useful: closing holes in the surface of the model, but it should be used only for a small and flat surface, with the appropriate option of this function (flat, curve).

The scanning of feet and hands remains a problem, especially the hidden surfaces of the fingers toes and soles. Some specific devices have been proposed for this purpose for the foot [14,18] and for the hands [22].

Volumetry of the upper limbs is possible and offers new perspectives in the study of lymphoedema. This is particularly useful for monitoring progress during treatment.

For upper limb volumetry, the position and technique are different (see figure 5)

Reproducibility and accuracy of the 3d surface scanning technique

The 3D Handyscan is very accurate for studying the leg volumetry with an accuracy of 0.5% of the leg volume, or approximately 12.5 ml. In addition, this method allows a very fine analysis of the volume variations, including the segmental variations of the leg.

For example, according to Vayssairat[9] et al. the accuracy of the water boot is 0.7% for 2 consecutive measurements of the legs of the same patients by 2 different observers. The intra-individual variability was 1.3%, for 12 repeated measurements of the same leg on different mornings. The other methods had higher error coefficients. Compared with the other methods used, it allows staggered measurements which the water boot does not.

Our results regarding repeatability and interobserver reproducibility are confirmed by Schiltz[15] et al. who found a mean volume of 2.488 ± 0.011 litres in 20 legs. The mean volume of the different examiners was not significantly different ($F_{(2,18)} = 1.579$, $P = 0.233$).

Etzel[16] performed leg volumetry in 82 subjects. Accuracy was assessed by calculating the relative percentage differences between repeated leg volumes. The mean relative differences between paired left and right leg volumes were 0.73 ± 0.62% and 0.82 ± 0.65%, respectively.

Ashby[17] compared leg volume measurements in 15 volunteers using water displacement and 3D surface scanning. The 3D scanning method had less systematic bias and narrower limits of agreement (±1%, and 3–5%, respectively) than the water displacement method (1–2% and 4–7%, respectively). The correlation coefficients for all reliability comparisons would all be considered as ‘very strong’ (all 0.94 or greater)

In our first clinical study[3] we assessed the reproducibility of the method by computing the coefficient of variation of all 120 examined leg volumes . Each leg was scanned 3 times before and after the study (4 minutes interval between each scan).

The first four subjects, had their legs scanned by one single operator (48 volume measurements). The next six subjects, each had 3 scans performed by 3 different operators (72 volume measurements)

The overall coefficient of variation (CV) over 120 leg scans was 0.5% (+/- 0.1% CI at 95%).

Thus, the accuracy of the leg volumetry measurements, i.e. the minimum volume variation detectable by this technique is 12.8 ml for an average scanned leg of 2550 ml, i.e. 0,5% of the leg volume.

The CV obtained with the first four subjects, scanned by the same operator was 0.45%.

and the CV of the next 6 subjects, scanned by 3 different operators was not significantly different (0.55%). We therefore achieved a good both intra- and inter-observer reproducibility.

Volumetric changes during the scanning period

When we compared the volume change during the 3 repeated leg surface scans, we observed a medial volume increase of 0.5% in 100 measurements and a medial volume decrease of 0.4% in the remaining 20 measurements.

These values are lower than the scan variation. Thus, there we did not observe a significant increase in volume during the repeated surface scans (8 to 15 minutes)

In our second study[4] (in press) we observed a medial decrease in total leg volume of 81 ml (2,9%) after wearing a multi-component bandage during 4 hours.

To avoid artefacts caused by patient movement, a rotating plate could be used.

The main limitation of this technique is that foot volumetry is not possible. Some authors [14,18]have suggested the use of special devices to assess foot volume.

From a clinical point of view, our first study [3] showed that the appearance of leg swelling in this population is progressive during the day. In fact, if when we compare the both legs with compression and without compression, the decrease in volume is approximately 36 ml in the Readywrap group and the increase in volume is 40 ml in the control group. These results show that the edema in a population that works in a constant standing position throughout the day is approximately 80 ml.

The portable 3D Handyscan could also be useful in orthotic and prosthetic applications, two medical specialties within the healthcare technology field, that require the scanning of the human body with non-contact devices in order to design and manufacture orthoses or prostheses.

Conclusion

Three-dimensional reconstruction and modelling of limb morphology allows 3D surface data to be collected quickly, non-invasively, accurately, reliably, and cost-effectively.

3D Handyscan enables accurate assessment of limb volumetry through 3D surface scanning. Variations in limb volume of approximately 12 ml (0.5%) can be detected. It is also quickly repeatable to assess the limb volume changes throughout the day, including the segmental volumes. This improves the definition and understanding of venous edema and lymphedema, as well as their treatment.

References

1) https://www.aniwaa.com/fr/produit/scanners-3d/peel-3d-peel-2-cad/.

2) Channa Yahathugoda, Michael J. Weiler, Ramakrishna Rao et al. Use of a Novel Portable Three-Dimensional Imaging System to Measure Limb Volume and Circumference in Patients with Filarial Lymphedema. Am J Trop Med Hyg. 2017;97(6):1836-1842.

3) Taha W, Benigni JP, Uhl JF, Carpentier PH, Filori P, Bishara R. Performance of an adjustable compression wrap in occupational leg swelling. Phlebology. 2024 Jun;39(5):302-309.

4) Benigni JP, Uhl JF, Taha W, Filori P, Balet F. Behavior of a multicomponent multilayer bandage in a warm environment. Results in volunteers with a pitting edema. Journal of wound care 2024 (in press).

5) Langendoen SI, Neumann HA. What's new in veins? Perspect Vasc Surg Endovasc Ther. 2011 Dec;23(4):229-32.

6) Chromy A, Zalud L, Dobsak P, et al. Limb volume measurements: comparison of accuracy and decisive parameters of the most used present methods. Springerplus. 2015;4(1):707.

7) Rabe E, Carpentier P and Maggioli A. Understanding lower leg volume measurements used in clinical studies focused on venous leg edema Int. Angiol. 2018 37 437-43.

8) Eberhard Rabe, Markus Stu#cker, Bertram Ottillinger. Water displacement leg volumetry in clinical studies - A discussion of error sources. BMC Medical Research Methodology 2010, 10:5 https://www.biomedcentral.com/1471-2288/10/5.

9) Vayssairat M, Maurel A, Gouny P, Baudot N, Gaitz JP, Nussaume O. Leg volumetry: a precise method for quantification in phlebology [La volumétrie: une méthode précise de quantification en phlébologie]. J Mal Vasc. 1994;19(2):108-10. French. PMID: 8077857

10) Stanton Awb , Northfield JW , Holroyd B. , et al. Validation of an optoelectronic limb volumeter (Perometer®). Lymphology 1997:30:77-97.

11) Bodytronic 600® (Bauerfeind AG, Zeulenroda, Germany)

12) Berard A, Kurz X, Zuccarelli F, et al. Reliability study of the Leg-O-Meter, in patients with chronic venous insufficiency of the leg. Angiology 1998:49:169-173.

13) Redlarski G, et al. Application of 3D Whole Body Scanning in Research on Human Body Surface Area, in Proc. of 3D BODY.TECH 2017 - 8th Int. Conf. and Exh. on 3D Body Scanning and Processing Technologies, Montreal QC, Canada, 11-12 Oct. 2017, pp. 60-65.

14) Thulesius O, Norgren L, et al. Foot-volumetry, a new method for objective assessment of edema and venous function. Vasa. 1973;2(4):325-329.

15) Schiltz D, Diesch ST, Kiermeier N, et al. Digital volumetric measurements based on 3D scans of the lower limb: a valid and reproducible method for evaluation in lymphedema therapy. Ann vasc surg 2024;105:209-17.

16) Etzel L, Schenck TL, Giunta RE, Li Z, Xu Y, Koban KC. Digital Leg Volume Quantification: Precision Assessment of a Novel Workflow Based on Single Capture Three-dimensional Whole-Body Surface Imaging. J Digit Imaging. 2021 Oct;34(5):1171-1182.

17) Ashby J, Lewis M, Sunderland C, Barrett LA, Morris JG. The Reliability and Validity of a Portable Three-Dimensional scanning System to Measure Leg Volume. Sensors 2023;23:9177.

18) Hirai M, Iwata H, Niimi K, et al. Improvement of a three-dimensional measurement system for the evaluation of foot edema. Skin Res Technol. 2012;18(1):120-124.

19) Paoli A, Neri P, Razionale AV, Tamburrino F, Barone S. Sensor Architectures and Technologies for Upper Limb 3D Surface Reconstruction: A Review. Sensors 2020;20:6584. DOI 10.3390/s20226584.

20) Vitali A, Regazzoni D, Rizzi C, Molinero G. (2020). 3D Scanning Procedure for the Evaluation of Lymphedema of Upper Limbs Using Low-Cost Technology: A Preliminary Study. In: Rizzi C , Andrisano AO , Leali F , Gherardini F , Pini F , Vergnano A. (eds) Design Tools and Methods in Industrial Engineering. ADM 2019. Lecture Notes in Mechanical Engineering. Springer, Cham. DOI 10.1007/978-3-030-31154-4_16.

21) Wen-Tao Yang, Kai Zheng, Hua-Liang Ren, Sheng-Xing Wang, Ming-Sheng Sun, Chi Gong, Wang-De Zhang, Chun-Min Li, Han-Jun Jiang. Three-dimensional laser scanner as a new tool for measuring lower limb volume in patients with chronic venous diseases. J Vasc Surg Venous Lymphat Disord 2023;11(1):127-135.

22) Yu F, Zeng L, Pan D. et al. Evaluating the accuracy of hand models obtained from two 3D scanning techniques. Sci Rep 2020; 10:11875. DOI 10.1038/s41598-020-68457-6.

23) Bahadori S, Immins T, Wainwright TW. (2022) Volumetric assessment of lower limb oedema using 3D laser scanning technique: a systematic review. Journal of Medical Engineering & Technology, 2022;46:1:40-45, DOI 10.1080/03091902.2021.1970841.

24) Mestre S, Veye F, Perez-Martin A, et al. Validation of lower limb segmental volumetry with hand-held, self- Mestre S, Veye F, Perez-Martin A, et al. Validation of lower limb segmental volumetry with hand-held, self- positioning 3D laser scanner against water displacement JVSLD 2014;2(1):39-45.

25) Hayn D, Fruhwald F, Riedel A, et al. Leg edema quantification for heart failure patients via 3D imaging. Sensors. 2013;13(8):10584-10598.

26) Cau N, Corna S, Aspesi V, et al. Circumferential versus hand-held laser scanner method for the evaluation of lower limb volumes in normal-weight and obese subjects. J Nov Physiother. 2016;6(4):2.