Accuracy and Repeatability of Limb Scans Obtained on the Semi-Automatic Measuring Station

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ABSTRACT

Designing individualized medical devices requires the collection of anthropometric data from the patient. This can be done by using the 3D scanning process. Despite many advantages, it has significant drawbacks, limiting the suitability of its use for many types of medical devices. This paper presents the design of measuring station that allows increasing the quality of the anthropometric data obtained in the scanning process of human limbs. The accuracy and repeatability of the data obtained on the station was presented and compared to reference scans. Moreover, owing to the automation of certain activities in the scanning process, operating the device requires the operator to have much lower competencies and workload.

Keywords: medical device, limb scanning, semi-automatic scanning, anthropometric data.

INTRODUCTION

Currently, owing to the rapid development of modern contactless measurement techniques, they are increasingly often used to perform anthropometric measurements [1, 2]. These methods render the traditional, previously used measurement methods obsolete. Some examples of the old methods are: measurement using the so-called Martin's set (anthropometer, trammel and slider) or measurements carried out on the basis of individual photographs showing anthropometric points applied to the body of the measured individual [3]. The techniques of contactless measurements allow obtaining a large amount of data in a short time, and depending on the method used, it is possible to measure the entire body or a selected fragment [4, 5]. The techniques of contactless measurements are divided into passive (photogrammetry) and active, depending on the used lighting source [6].

In the case of photogrammetric systems, the measurement consists in registering a series of multiple images of the same object, taken from different positions and their mutual positioning on the basis of characteristic common points. By combining the recorded data from at least two center projections of the same point, it is possible to unambiguously determine its spatial position and coordinates [7]. Usually, the measured object is covered with non-coded (markers) or coded (each one has an individually assigned number) targets and on their basis, photos are oriented with respect to each other. The algorithm processing photographs recognizes the targets and calculates the coordinates of the points representing them. Some of the photogrammetric systems also allow recreation of curves in space, based on contrasting lines on the object [8]. In this way, the information about the geometry of the human body being measured can be obtained, which can then be used to design individualized clothing [9, 10].

The active methods of non-contact measurements include: laser scanning, structural light projection and moiré fringes. In the case of laser scanning, systems are used in which the laser projection takes place in the form of a single point or in a form split by a moving prism of the line moving along the object [11]. In both cases, the image is registered by the photosensitive element and the distance of the laser spot from the head or the deflection of the band on the measured object is

calculated. In the case of anthropometric measurements, a faster method that allows more data to be collected in a shorter period of time is scanning using a single or multiple laser stripes. The projection of stripes on different sides of the object, which are shifted in the same plane with the same feed and recorded by several cameras at the same time, enables obtaining the data covering the greater part of the human body being measured [12, 13].

The second most popular group of active scanners includes the scanners using a structural light projection principle. According to the authors of the report [14], in the next five years these scanners will increase their market share by over 10% and are the fastest growing market segment. The essence of this method is lighting the measured object with structural light through a projector with the appropriate optical system and recording the distortion of these images by at least one camera. Grey code projection combined with phase shifted patterns is the most often used method – a sequence of defined patterns is displayed, in which encoded time-space information for each pixel of the camera is contained, and subsequent projected sets of images are shifted in phase [15].

In [18], the authors presented the concept and design of the device supporting hand scanning for the purpose of creating a personalized orthosis for this part of the human upper limb. Previously, when scanning patients with spasticity of the hand, it was necessary to have an additional person who would correct the abnormal, excessive tension of the patient's muscles (muscle hypertonicity) with their own hands during the scan. By use of additive manufacturing technologies, the authors developed a solution that effectively immobilizes the patient's hand in the position required to scan its internal side.

In an earlier work, these authors [19] showed that three-dimensional human hand scanning with structural light is a very good alternative to the traditional method of creating a plaster cast, which is definitely more uncomfortable and absorbing for the patient. Three-dimensional scanning with structural light, though slower than photogrammetric techniques, is – according to the authors – much better at mapping areas of the body, which can be obscured by certain positions of the metacarpus and fingers. Static scanning with structural light guarantees greater geometric accuracy and allows for better detection and removal of geometrical abnormalities in the scans that are related to the movement of the patient's

body during scanning. However, dynamic scanning, without the use of markers, is considered faster and easier to use, mainly due to the compactness of the devices and the possibility of manipulating them with hands during scanning. Unfortunately, the geometric accuracy obtained in dynamic scanning is smaller. Studies showed that in the case of hand orthosis, if only one side of the patient's hand is required for design, both static and dynamic scanning are good. However, if it is necessary to obtain a full digital hand model, e.g. for the design of a cosmetic prosthesis, there are considerable difficulties associated with keeping the patient's hand still during scanning. In [20], the structural light scanning of the full surface of the lower leg of the human body was successfully applied in the process of designing an individualized ankle orthosis.

More and more companies find applications for 3D scanning, and the growing offer of these devices from the "low cost" segment enables their purchase and implementation even in small and medium-sized enterprises. The report [14] indicates that healthcare is the second largest industry in which spatial measurements are used immediately behind industrial manufacturing. A common obstacle in the implementation of this type of solutions is the problem of finding a worker with appropriate qualifications, who will be responsible for the entire measurement and data processing (preparation of the measuring device and measuring object, measurement, analysis of the data obtained and their optimization). In the case when similar objects are measured, the whole process can be partially or fully automated. An automated measuring station will not require service by a highly qualified, experienced operator; measurements can be carried out by technicians after a short training. An additional advantage of this solution is also shortening the measurement time.

This paper presents the author's novel prototype setup for semi-automated measurement using a cheap structured light scanner, aimed at gathering the anthropometric data for automated design of orthoses and prostheses for upper and lower limbs.

MATERIALS AND METHODS

The aim of this work was to develop the concept of a semi-automated station for spatial

measurements of the upper and lower limbs of people, who have to use medical supplies in the form of wrist or ankle orthoses during convalescence after injuries or during a therapeutic process (e.g. children with cerebral palsy). The results of measurements in the form of a triangular mesh in a further stage are used for the automated design process and additive manufacturing of individualized medical supplies, which is part of the global trend of customization of products [16, 17].

Validation of the station was carried out by performing ten measurements of an upper limb and a lower limb and then comparing the obtained results to reference scans. The reference scans were made using a professional GOM Atos Compact Scan 5M 3D scanner. Both reference scans and scans made on the developed stand were performed and compared for the same set of measured objects, i.e. upper and lower limb of the same test patient.

Moreover, nine patients of variable body types (aged 11-34, male and female) had their upper limbs scanned and the correctness of the obtained data was checked in a process of automated design of wrist hand orthoses.

The main requirements for this solution were:
- the station together with the used 3D scanner used should be composed of low-budget components, so that the target solution could reach the largest group of recipients,
- the design of the station is to be made simple and should enable the measurement of both the lower and upper limbs of a man from the age of 5, regardless of gender and body shape,
- the station is to be operated by one person who does not have to have special qualifications – short training at the station will be sufficient,
- the information on the digital representation of measured objects should be obtained from the smallest number of individual measurements (3D scans),
- the position of the person being measured should be convenient enough so that the person does not feel any discomfort during the measurements, but also guarantees proper stabilization of the limb,
- it should be possible to measure both right and left limbs at the station,
- the station should be pre-calibrated at the first assembly and the subsequent

calibration will not be required regardless of the measured limb,
- the digital geometry of the measured limb should represent a part of it that will allow designing an individualized orthosis in a further stage of the process.

The developed structure consists of three basic elements: a circle-shaped track, a 3D scanner placed on a platform moving along the track and a device fixing the limb placed inside the track and allowing a comfortable position to be assumed by the person being measured.

The use of the track enabled an easy and smooth change of the scanning position with the possibility of blocking the platform in specific positions, which was particularly important for obtaining the appropriate repeatability. The track consists of two rails made of round tubes. Due to the high price and the problem of obtaining the appropriate diameter of the track, a concept of steel pipes was abandoned and polyethylene pipes with a diameter of 32 mm and a wall thickness of 3 mm were used. In addition, these pipes are stored in coils with a diameter of 1m, causing their wrapping, which greatly facilitated obtaining the correct curvature of the track. Both track rails were permanently attached to the ground.

The platform on which the 3D scanner was mounted was equipped with four trolleys. Each trolley consisted of two wheels, 80 mm in diameter, set at an angle of 90 degrees with respect to each other. The wheels consisted of a plastic hub with two 608ZZ bearings embedded in it and a full rubber tire made of 80 Shore A hardness in the A scale. The main part of the trolley is a 40x40 mm aluminum profile with a profile groove in which a groove is dedicated to the shape M8 screws. Wheels were mounted on the bolts, which made it possible to adjust the gap between them with nuts. In order to ensure proper support of the platform trolleys, an aluminum profile element was designed to slide into the profile, with a socket for the hexagonal head of the bolt securing the trolley to the platform. Additionally, in order to eliminate potential imperfections of the track, a 51104 thrust bearing was used. The design of the trolley is shown in Figure 1.

In order to enable changing the position of the scanner and scan from different directions, a shaped aluminum rail with a dedicated carriage with IGUS bearings of the drylin® W system was attached to the trolley. A photo tilthead was
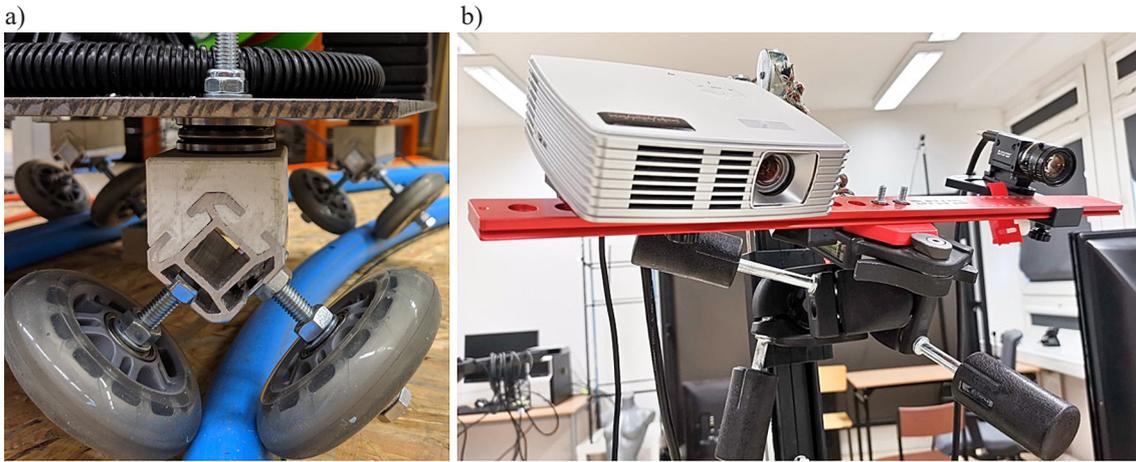
a)   b)

Fig. 1. a) Design of the moving platform with 3D scanner, b) fixing the 3D scanner to the rail

mounted to the trolley, enabling adjustment of the scanner position in three axes.

Due to the budget assumptions, the David SLS-3 structural light scanner was selected. It is a scanner consisting of a multimedia projector and one camera mounted on a common rail. The advantage of this device is its relatively low cost, the ability to measure large objects (up to 1000 mm) and the possibility of developing the structure with an additional camera. In addition, the software of this scanner works in an open system and allows changing all the parameters of the 3D scanning process, which is not possible in the case of professional systems such as GOM.

A steel rope connected to the DC motor was attached to the trolley and the position of the trolley was changed by pressing an appropriate button (going up or down) by the user. The set positions are achieved by disconnecting the motor power via the limit switch.

In order to ensure an appropriate repeatability of the achievement of the designated platform positions on the track, a bolt with a pin was used, which is placed in a hole made in one of the rails. In addition, there is also space on the platform for a portable computer that controls the scanner.

The model depicting the idea of the proposed structure is shown in Figure 2.

The third element of the position is the grip for fixing of the scanned limb. Two different handles were used; separate for the upper and lower limb. Both handles are made of aluminum profiles and consist of a saddle on which the scanned person sits and a part immobilizing the limb. In both cases, the constructions allow the adjustment of the components and adjustment to the age and size of the limb of the person. Both constructions can be easily dismounted as well as placed in a dedicated place within the entire station. Figure 3 shows the design of both holders.
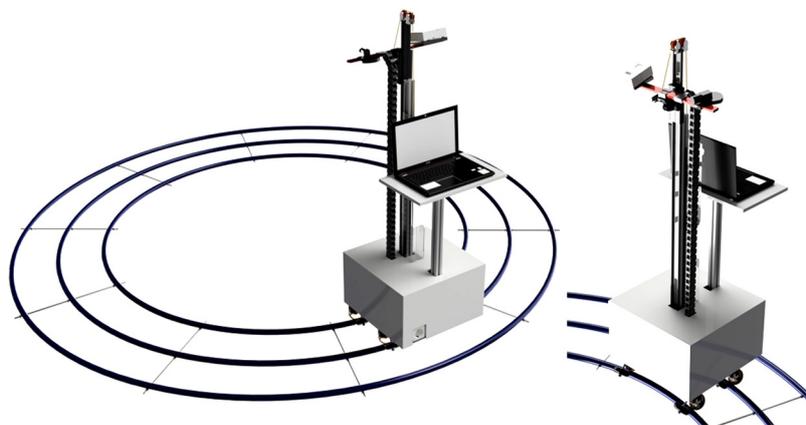

Fig. 2. Design of the station for automated 3D scanning
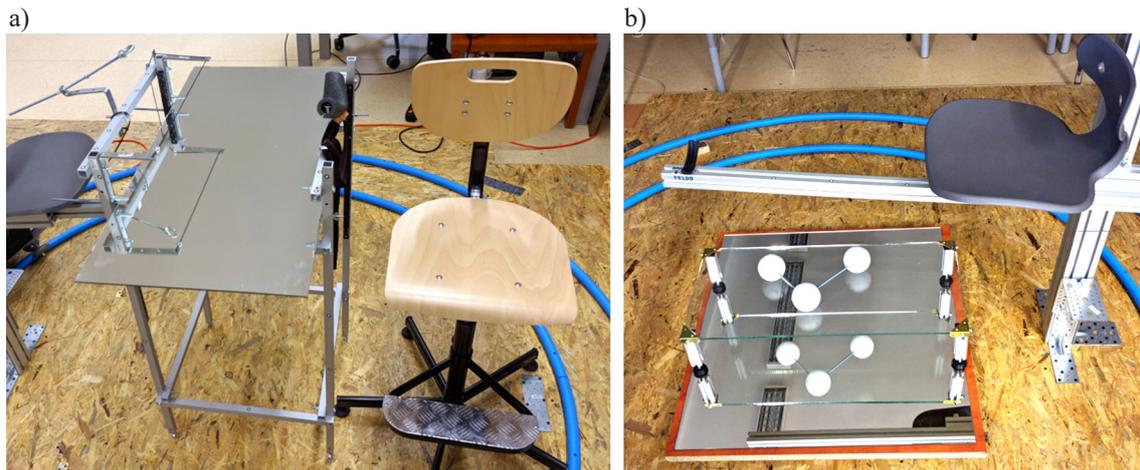
a)   b)

Fig. 3. Design of the handle for 3D scanning: a) upper limb, b) lower limb

The course of the scanning procedure depends on the object being measured. A total of 6 measurements are performed for the upper limb, in four platform positions on the runway. After the first measurement, the operator releases the lock and moves the platform to the second position, in which the platform is blocked again. Analogously, the measurement is carried out in the third and fourth positions. After the fourth measurement, the operator with the engine control buttons moves the cart with the head and scanner to the bottom position on the guide and then the measurement is performed in the platform position as in the fourth and first measurement. The same procedure is performed for lower limb, except for that 8 measurements are made: four in the upper position and four in the lower.

In order to speed up the process of scanning and exporting data, the operator uses a macro which starts the 3d scanning process in each position and after its completion exports the triangle mesh with the appropriate name to the indicated folder. After the measurement is completed, the files are automatically downloaded from the folder by the next macro, the task of which is to transform individual scans into a common coordinate system, filtering point clouds and re-triangulating to the final 3D model.

In order to determine the appropriate translations and rotations necessary for the transformation of individual scans, the position had to be calibrated. The calibration is carried out only once and until there is a change in the settings of the head on which the scanner is mounted or the position of the platform relative to the track is changed, there will be no need to re-determine these parameters.

The calibration procedure consists in performing measurements in the standard positions for the measurement of hands and legs, with the measuring object being a dedicated calibration device, consisting of three spheres connected by means of a threaded rod. The calibration device is shown in Figure 3b. The use of spheres made it possible to determine three points (geometric centers of balls), on the basis of which a local coordinate system was defined for each scan, followed by translations and rotations for individual axes.

RESULTS AND DISCUSSION

The developed station allows for repeatable measurements of lower and upper limbs. Owing to fixed positions in which the platform is blocked and from which individual scans are taken, it is possible to translate them into a common coordinate system. Figure 4 shows the raw data obtained from the measurement of the upper and lower limb and the scans after translation into the common coordinate system.

The individual surfaces prepared in such a way are then fit to each other in an automatic manner, using the best-fit type algorithm and further processed into one watertight triangle mesh. The experimentally determined positions of the platform and the orientation of the scanner made it possible to minimize the number of individual scans, and thus shorten the time needed to measure the limb as well as reduce the inconvenience experienced by the person measured at the stand. This is especially important for the people whose injury is quite recent or for children. The total
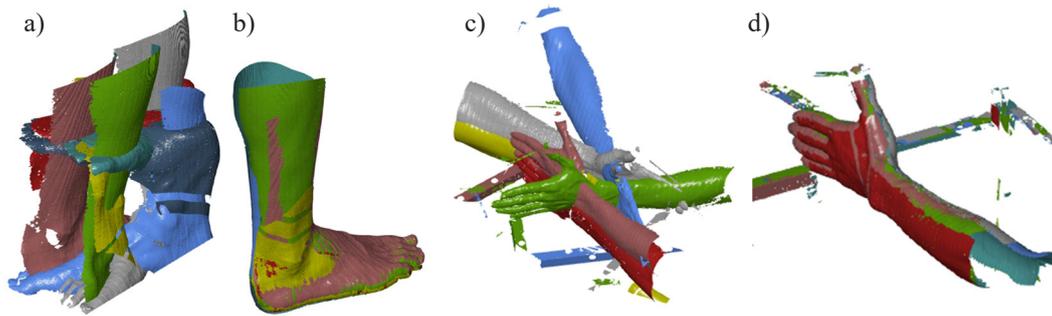
Fig. 4. The result of the measurement of the lower limb: a) before translation,
b) after translation and upper limb: c) before translation, d) after translation

mean measuring time for the upper limb determined from 10 attempts was 270 seconds, while for the lower limb it was 510 seconds.

Comparative tests were carried out, in which the operator tried to reach the set positions without the platform and track as accurately as possible, using only a stand column equipped with blocked wheels on which the 3D scanner was mounted. The average time of measurement of the upper limb was 7 minutes 15 seconds, and for the lower limb 13 minutes and 25 seconds. In addition, the repeatability of the obtained triangle meshes in the single-position range was compared. The maximum difference between individual 3D scans was not greater than 1.5 mm, while in the case of a 3D scanner mounted on a manually adjustable column, the average difference between the obtained geometry was approx. 8 mm, which turned out to be too high and the best-fit algorithm combining scans was unable to connect them.

The results of comparison between the reference scans of upper and lower limb with ten measurements made on the stand are presented in Table 1. Fitting the measurements to the reference data was carried out through the best-fit algorithm in the GOM Inspect software, with a result of an average error value.

Figure 5 presents a comparison of reference data to the data gathered on the implemented workstand, with visible, yet acceptable deviations.

Average fitting error, both in the case of upper and lower limbs, was lower than 1 mm. The authors assumed 1 mm as a threshold value, above which the reduced accuracy may make the prosthesis unproperly fit to a given patient. Therefore, the workstand presents appropriate accuracy. Moreover, as can be seen in Fig. 5, the highest deviation value was around the fingers and the elbow joint (for the upper limb), which is where no data is gathered for automated design of orthoses. In this case, the scanner measurement field is wider than the actual needs, so the data is redundant and could be trimmed after the scanning, which will be implemented in the future version of data processing macros.

Table 1. Results of comparison of scans to reference data

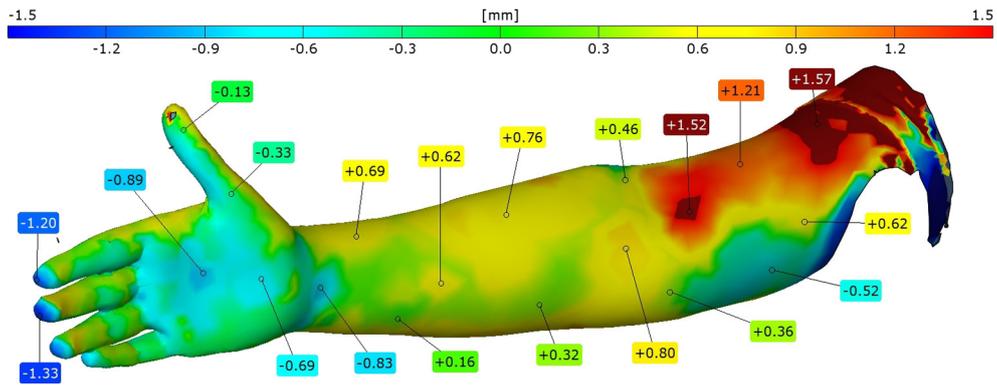| Measurement number	Upper limb		Lower limb	
	Average fitting error [mm]	Scanning time [s]	Average fitting error [mm]	Scanning time [s]
1	0.77	265	0.52	506
2	0.62	278	0.47	508
3	0.81	266	0.6	512
4	0.55	275	0.47	510
5	0.76	272	0.54	511
6	0.82	268	0.61	516
7	0.98	269	0.42	509
8	0.65	270	0.53	511
9	0.74	273	0.56	509
10	0.9	265	0.48	508
Average	0.76	270	0.52	510

Fig. 5. Colorful deviation map, comparing a reference scan of upper limb to a scan no. 4 performed on the workstand
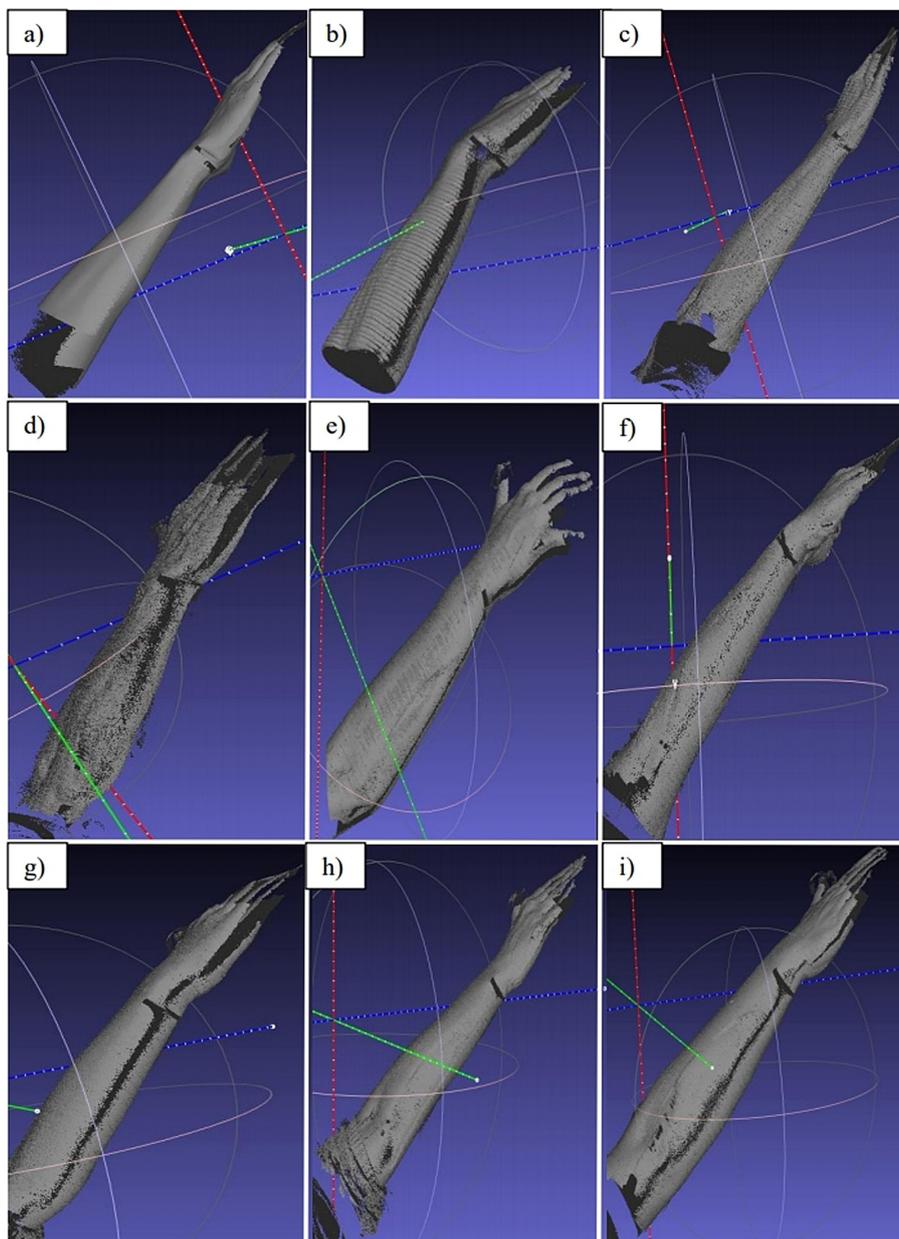

Fig. 6. Scans of the test patients made on the workstand [21]

Table 2. Interference values between input scan data and generated orthoses

Patient No.	1	2	3	4	5	6	7	8	9
Interference [mm³]	$4.4 \cdot 10^3$	$2.91 \cdot 10^3$	$2.78 \cdot 10^4$	$3.12 \cdot 10^4$	$2.47 \cdot 10^3$	$3.92 \cdot 10^4$	$3.15 \cdot 10^3$	$1.56 \cdot 10^3$	$1.22 \cdot 10^4$

A separate analysis was performed in order to find out whether it is justified to perform 8 scans for the lower limb (preliminary studies have shown that it was necessary). By making test alignments omitting two extra scans, it was found that 6 measurements are enough to obtain a full image of lower limb, so that the procedure was unified for both limbs.

Figure 6 presents the raw data in the form of point clouds obtained during the scanning of the test group of nine people. On the basis of the point clouds, the subsequent reconstruction to a triangle mesh followed by its optimization (reduction of the number of triangles, smoothing and closing of discontinuities in the mesh). The geometry prepared in this way fed the reference intelligent CAD model in which orthoses were automatically generated.

The correctness of the obtained models was tested by a value of interference (total collision volume) between the automatically generated orthoses and the input data (anthropometric 3D scans). It is presented in Table 2. The procedure was performed using collision analysis in the Autodesk Inventor 2019 CAD system, with MeshEnabler plugin. The scans were loaded and assembled with orthosis 3D model, then the collisions were automatically calculated.

The interference values are acceptably low – they are no higher than several cubic centimeters on the surface of the whole forearm (the orthoses were generated for the whole forearm and part of the hand), which does not influence the overal fitting value. Moreover, most of the interference volumes occur in the elbow area, not in the thumb and wrist areas, which are the most crucial. The interferences are also caused by the imperfect CAD model, which must be improved in further works.

CONCLUSIONS

The designed and built structure of the automated limb measurement station fulfills its task. This makes it possible to shorten the time of measurements and, what is more, the time spent by the scanned person at the station. The station in the presented form is universal and it is possible to conduct anthropometric measurements regardless of sex or body structure of a measured person over 5 years of age. In addition, lower and upper limbs can be measured, both left and right. The tests confirmed the applicability of this construction to anthropometric measurements, on the basis of which the earlier mentioned orthoses are designed and manufactured.

The accuracy and repeatability of the data obtained on the work stand is fully acceptable for the needs of automated design of individualized orthopaedic supplies, and the quality of data after optimization ensures proper generation of orthoses using a reference intelligent CAD model.

In addition, the station can be further developed until full automation of measurements. In case of changing the motor responsible for moving of the scanner head along the Z axis into a motor that can be controlled by the microcontroller, as well as implementation of a motor controlled the same way for the movement of the platform between the positions on the track, it will be possible to remotely launch the movement of the scanner and reach the subsequent positions. In such a case, the measurements will be able to be performed even by the patients themselves, and the role of the station operator will be only to check whether the position of the person being measured is correct and whether the data obtained as a result of the measurement is correct. On the other hand, it will increase the costs of building the station and will force the introduction of additional control systems, the functions of which, in the current form of the position, are fulfilled by the station operator.

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