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An Electronic Geometric Model for 3D Scanning of Human Body Segments and Its Use in Prosthetics and Orthotics. Causes of Defects and Methods for Their Elimination

K. K. Shcherbina, M. A. Golovin*, V. G. Suslyaev, N. V. Marusin, V. M. Yankovskii, and M. V. Zolotukhina

3D scanning is widely used in prosthetics and orthotics all over the world. Involuntary movements of the subject, variability of the scanning conditions, and the human factor (operator's errors) may reduce the accuracy of scanning and disrupt the surface structure of the recorded electronic geometric model, i.e., lead to the appearance of artifacts and defects. The article discusses the main causes of artifacts and makes an attempt at their systematization. Methods for eliminating artifacts during mobile laser non-contact 3D scanning and processing using Autodesk Meshmixer software are described.

Introduction

To interact with a digital copy of a material object in PC software, it is necessary to register its shape with the required accuracy [1]. This process is called reverse engineering. It consists in determining the geometric characteristics of the object and transferring this information to software. With an increase in the number of surfaces and the order of polygons that describe them, the accuracy of reverse engineering decreases. Biological objects (segments of the human body) have a relatively complex surface shape. 3D scanning is one of the ways to transfer information about a biological object accurately into computer software. It involves recording the coordinates of surface points [2] of an electronic geometric model (EGM) using a 3D scanner or a camera. After that, post-processing is performed [1].

3D scanners are classified into two types: contact and non-contact (mobile and stationary). Scanner technologies differ, as do the requirements for scanning conditions [3-5]. The requirements for external scanning conditions depend on the principle of operation of the equipment. For example, lighting requirements are more stringent for some optical scanners than for laser scanners and time-of-flight cameras [3].

The word "artifact" derives from a Latin phrase meaning "artificially made". In relation to scanning, an artifact is an element of the image that is not present in the object. Artifacts can occur during the initial processing and formation of an EGM and lead to EGM defects.

Modern computer-aided design systems implement mathematical algorithms for the automated elimination of surface defects with the possibility of fine tuning. Significant distortions of the surface shape of the EGM are eliminated by the operator.

When capturing moving objects, local fixation is used. Fixation tools modify the EGM of the registered object. If fixation is difficult to achieve, iterative techniques are used. Another way to solve the problem is to reduce the imaging time [6].

Optical photogrammetry and 3D laser scanning are the most accessible and widespread 3D scanning technologies [7]. The advantages of 3D laser scanning include: short duration of the procedure, reduced labor intensity, the ability to record information about the color characteristics of the surface (texture).

Research into the defects occurring in the process of EGM reconstruction and the methods for their elimination is an integral stage in the development of techniques

Federal Scientific Center of Rehabilitation of the Disabled named after G.A. Albrecht, St. Petersburg; Russia; E-mail: golovin@center-albreht.ru
* To whom correspondence should be addressed.

for training prosthetic and orthopedic specialists to use digital technologies in their work.

The goal of this work was to develop methods for elimination of artifacts arising during 3D scanning of human body parts.

Materials and Methods

3D scanning was performed in: 37 patients aged 40 to 64 years with amputation defects of the lower leg and hip, positives and negatives of plaster casts of stumps of these patients; 74 patients aged 7 to 17 years undergoing scanning for orthopedic functional braces, 101 standard mounting sockets for prosthetic lower legs and hips. The 3D scanner iSense (Occipital Structure Sensor, USA) was used. The obtained EGMs were processed using Autodesk Meshmixer software.

The basic surface reconstruction algorithm used radiometry to obtain an electronic geometric model. The parameters of radiation reflected from the surface of the object were measured. Camera's photosensitive elements were used as sensors. Next, a polygonal model consisting of multiple triangles was obtained. The 3D scanner used for the study had a spatial resolution $x/y = 0.9$ mm and a resolution depth of 1 mm at a distance of 0.5 m.

Cotangent discretization algorithms were used to transform the EGM [8]. Cotangent discretization involves normalization of the triangle vertices of the polygonal model.

Results

Figure 1 shows a version of the flowchart of the technological process of 3D scanning used in prosthetics of the lower extremities. The variability of objects makes it possible to use various methods for collecting initial patient data for the purpose of modeling parts of prosthetic and orthopedic products (POP).

Scanning artifacts. The main external factors affecting the quality of scanning using handheld non-contact 3D scanners are: illumination, surface texture of details, shape of the object, object mobility, compliance with technical requirements for the 3D scanner (speed of movement, focal length).

Illumination. The main technical requirement for the room in which the scan is carried out is the absence of direct sunlight. Techniques for scanning in patients with stumps involve marking the skin of the stump to highlight projections of the condyles, ridges, and bone filings; zones of hypersensitivity, attrition, etc. are separately marked. A specific feature of scanning in patients with stumps is that the end face of the stump has to be illuminated.

Texture. Color heterogeneities in the object (for example, birthmarks) and a high reflection coefficient of the scanned surface lead to artifacts.

Surface shape. Artifacts appear in images of non-reflecting surfaces. An excess of soft tissue or scarring may lead to the appearance of such areas. Attrition, bone sawdust protrusions, or severe atrophy lead to the appearance

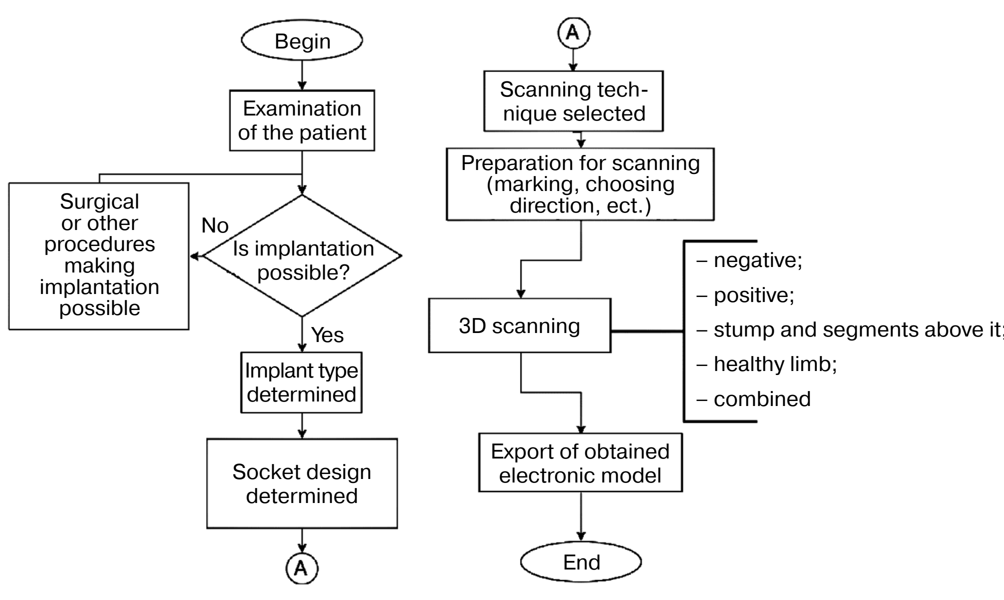

Fig. 1. Flowchart of the technological process of 3D scanning used in prosthetics of the lower extremities.

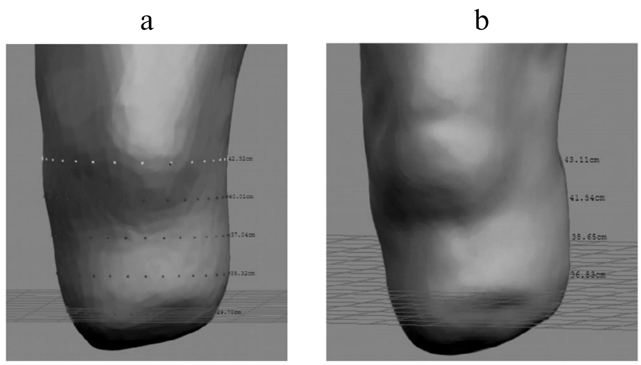

Fig. 2. EGM of the upper third lower leg stump in patient N. (55 years old, mine blast injury of the limb) together with cross-sectional measurement data: a) free stump; b) fixed stump.

of outlined facets. Movements of the object and the instrumental error smooth the edges of the digital copy. As a result, the accuracy of the POP modeling is reduced.

Mobility. Tremor of body parts can be physiologically normal. In 3D scanning, tremor leads to an increase in the EGM dimensions. Figure 2 shows images of an EGM of the left lower leg stump in patient N., 55 years old, together with cross-sectional measurement data. The 3D scan shown in Fig. 2a was taken when the stump was flexed at 5 degrees and the muscles were relaxed. Figure 2b shows an image of the stump with a knitted stocking on it, leading to stabilization of the stump.

The artifacts, their manifestations and measures for their prevention and elimination are classified in Table 1. Some examples of defects described in Table 1 and the results of their elimination are shown in Fig. 3.

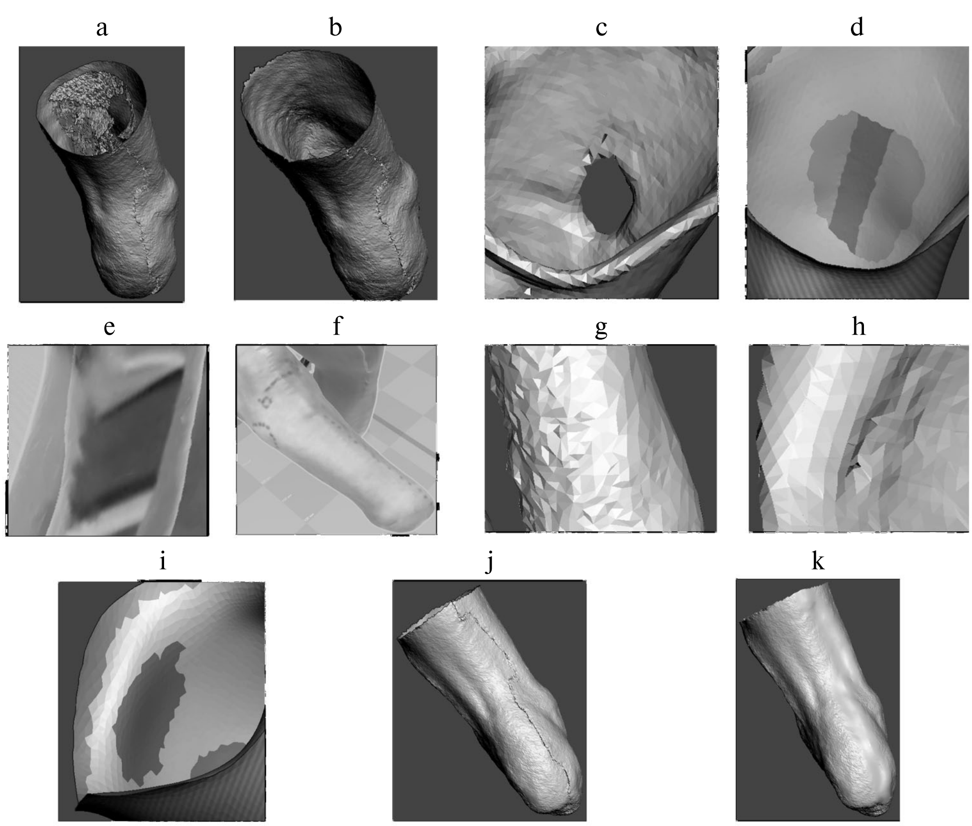

Fig. 3. Examples of defects and results of their elimination in various 3D scanned objects. Duplication of polygons in the EGM of the lower leg stump: a) initial model; b) after processing. Ruptures of the surface of the mounting socket for prosthetic hip: c) initial model; d) after processing. Absence of textures in the EGM of a limb: e) superposition of texture of another object over the EGM; f) EGM of the lower leg stump (Pirogov's amputation) with correctly registered texture; g) surface irregularity of the EGM of the hand (the angular velocity of the 3D scanner is two times higher during scanning of the left part). Self-intersection of the surface of the EGM of the mounting socket for prosthetic hip: h) initial model; i) after processing. Distortion of the EGM of the lower leg stump in the closure region (seam): j) initial model; k) after processing.

TABLE 1. Classification of Artifacts

Artifact	Manifestation	Possible cause	Recommendations, measures for prevention and elimination
Duplication of polygons	Duplication of coordinates of registered surface points with a shift to the center of the model, forming polygons with opposed normals (3 to 70% of the total number of polygons)	1. Incorrect focal distance. 2. Transparent object. 3. Movements of the object during scanning (including tremor)	1. Adjust illumination. 2. Change surface texture (tone): use fine powder, stockings, markers. 3. Fix the object
Surface discontinuity	The absence of registered coordinates of the points of a surface area of the scanned object, leading to a failure to construct polygons for this area (1 to 15% of the surface area)	1. Incorrect focal distance. 2.Transparent object. 3. Movements of the object during scanning (including tremor)	1. Adjust illumination. 2. Change surface texture (tone). 3. Apply algorithms of polygon construction using EGM profile (*Bridge* and *Inspector* tools)
Distorted texture	The EGM textures do not match the textures of the scanned object by color or intensity, or are completely absent (up to 90% of the surface area)	1. Illumination of the scanned object does not meet the technical requirements. 2. Mirror texture of scanned area	1. Adjust illumination. 2. Change surface texture (tone). 3. Reduce the angular velocity of the 3D scanner
Surface irregularity (an increase in the distances from the polygon centers to the mean surface profile)	Multidirectional normal vectors of adjacent polygons constructed from the registered coordinates of surface points (up to 60% of the surface area)	1. Scanning rate does not meet the technical requirements. 2. Limitations on the maximum number of registered points	1. Check the settings of the 3D scanner. 2. Reduce the angular velocity of the 3D scanner. 3. Change the number of polygons (*Remesh* and *Reduce* tools). 4. Smooth the model (*Smooth*)
Intersection of the inner and outer surfaces of the object	When scanning a thin-walled object, a rupture occurs in the inner and outer surfaces of the EGM, and the inner and outer surfaces join at the edges of the rupture (up to 35% of the surface area)	1. Transparent object. 2. Surface areas with sharply contrasting textures	1. Change surface texture (tone). 2. Apply algorithms of polygon construction using EGM profile (*Bridge* and *Inspector* tools)
EGM distortion in the closure region (seam)	Distortion of the registered coordinates of surface points caused by the movements of the object during 3D scanning	1. One-pass scan. 2. Movements of the object (including tremor)	1. Fix the object. 2. Use multipass scan. 3. Reduce the angular velocity of scanning and change periodically the scanning area. 4. Use different camera angles. 5. Use shape adaptation (*ShrinkSmooth*)

The application of the recommendations given in Table 1 was verified empirically. A study subgroup was selected, in which scanning was performed with due regard to the influence of external factors. It included 5 out of 37 patients with amputation defects at the shin level, 20 out of 74 patients undergoing scanning for orthopedic functional braces, and 20 out of 101 standard mounting sockets for prosthetic hips. Minimization of the influence of external factors resulted in a decrease in the frequency of artifacts from 18 to 2%: 75% of the artifacts were due to the duplication of polygons in the EGM of the lower leg stump; 15%, due to the surface irregularity of the EGM of the human body in patients undergoing scanning for orthopedic functional braces; 10%, due to the lack of texture in the EGM of the leg stump. Defects occurred in patients of both age groups: 7 to 17 years and 40 to 64 years. Other types of defects have not occurred. The time of post-processing of the models has been reduced from 5 to 2 min.

Conclusions

Even if the requirements for scanning conditions are met, EGM surface artifacts may arise during 3D scanning of human body segments. The accuracy of electronic geometric modeling can be improved both qualitatively and quantitatively using appropriate techniques of 3D scanning and software tools for manual and semi-automatic processing of EGMs. It is also important to know the basic principles of the scanning technology used for modeling. Proper preparation of the object for scanning reduces the time required for EGM processing.

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