Using photogrammetric 3D body reconstruction for the design of patient–tailored assistive devices

S. Grazioso[1], T. Caporaso[1], M. Selvaggio[2], D. Panariello[1], R. Ruggiero[3], G. Di Gironimo[1]
[1]Department of Industrial Engineering, University of Naples Federico II, Naples, Italy
[2]Department of Electrical Engineering and Information Technology, University of Naples Federico II, Naples, Italy
[3]Ortopedia Ruggiero Srl, Cardito, Italy
Corresponding author: stanislao.grazioso@unina.it

***Abstract*—The use of fast and accurate scanning systems for human body digitization might pave the way towards the development of less invasive processes for medical manufacturing. In this work, an advanced measurement system for human body 3D reconstruction is used to design tailored assistive devices. The system is a photogrammetric 3D body scanner developed by the authors.**

***Index Terms*—3D body measurements; assistive devices; medical manufacturing.**

I. BACKGROUND

The goal of assistive devices is to support individuals in daily living and/or working activities, thus enhancing their overall well–being. Examples include orthoses, prostheses and exoskeletons for supporting orthopedic care, rehabilitation, or even reducing the workload in industrial tasks. In order to be effective, an assistive device should be designed to precisely match the patient's anatomy. This explains why methods and technologies for exactly capturing the human body three–dimensional shape are needed.

Recent advances on reverse engineering techniques have led to the development of several commercial 3D scanners. Initially devoted to industrial applications, recently they have shown potentials for human body digitization [1]. Existing solutions are based on: (i) laser sensors; (ii) depth sensors; (iii) cameras. Currently, the only technology that guarantees an instantaneous acquisition process is photogrammetry, which allows the 3D body reconstruction from multiple photographs taken from different point of view around the human body. When multiple images of the same shape are available, the position of a 3D point can be found by intersection of corresponding projection rays. Fundamental for this technique is the calibration of the overall system for estimating the relative poses of the multiple cameras.

In the recent literature several examples about the use of photogrammetry for the assistive devices design are available. They include the development of: ankle–foot ortheses [2]; upper limb prosthesis [3]; prosthetic socket [4]; hand orthosis [5]. However, in most of documented cases, these devices are usually manufactured starting from body models reconstructed using rudimental arrangement of commercial cameras.

In this work we present the advantages of 3D photogrammetry to design custom–made assistive devices using a novel 3D body scanner tailored for health–related applications (INBODY, see Fig. 1). Then, we discuss the limitations of this technology and we report some future directions on the use of photogrammetric 3D body scanners for health–related applications which go beyond the custom fabrication of assistive devices.

Fig. 1. INBODY, a photogrammetric full body 3D scanner.

II. FUNDAMENTALS OF PHOTOGRAMMETRY

The basic idea behind the 3D photogrammetry is the stereo vision geometry, usually referred to as epipolar geometry. Figure 2 illustrates the epipolar geometry of a pair of stereo cameras, using the pin–hole camera model. When two cameras observe a 3D scene from two different positions, indicated by the reference frames $Ox_Ly_Lz_L$ and $Ox_Ry_Rz_R$, there exists a number of geometric relations between the 3D point P and its projections onto the 2D planes OX_LY_L and OX_RY_R that lead to constraints between the image points, which are indicated by the blue dots. These relations are derived based on the assumption that the cameras can be approximated by the pinhole model, so that the conversion from 3D to 2D can be referred to as perspective projection. When the relative position of the two cameras, indicated by the homogeneous matrix T_{LR}, is known, these geometric relations, referred to as epipolar constraints, are described by the fundamental matrix, which relates corresponding points in stereo images.

A more comprehensive reference on multiple view geometry in computer vision can be found in [6].

978-1-7281-0429-4/19/$31.00 ©2019 IEEE

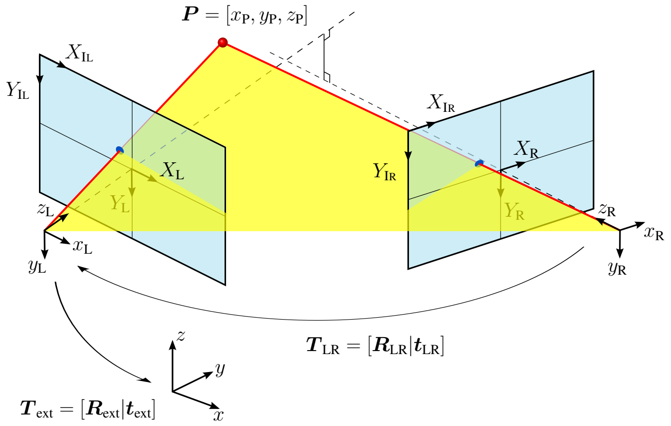

Fig. 2. Epipolar geometry of a pair of stereo cameras - pinhole model.

III. THE INBODY 3D SCANNER

INBODY (shown in Fig. 1) is an instantaneous photogrammetric 3D body scanner for healthcare applications [7]. It is based on three main pillars:

1) Photogrammetric techniques for 3D body reconstruction;
2) Ring–based hardware architecture for wrapping the human body shape with multiple cameras;
3) Multi–thread client–server software architecture for ensuring a synchronized camera shooting.

The number and placing location of image sensors was selected such that there is at least a 60% overlap between two adjacent images, a necessary requirement for an accurate digitization [8]. Starting from the pictures, classic imaging processing techniques are used for point cloud generation and surface meshing [6]. All these ingredients have lead to the development of a full body scanner with the following features:

- Instantaneous data acquisition of human body shapes (the acquisition process requires less than 50 ms [7]);
- High 3D reconstruction accuracy of human body shapes (the INBODY–reconstructed shape of a static mannequin presents an average 3D deviation of 1 mm with respect to the same model reconstructed with a 3D laser scanner assumed as reference [7]).
- High definition and textured meshes.

The instantaneous and non–invasive process of data acquisition using INBODY make this scanner attractive in a large number of health–related applications. However, in this paper we are only interested in explaining how INBODY can be used to fabricate custom-made assistive devices

IV. PHOTOGRAMMETRIC–BASED DESIGN AND DEVELOPMENT OF CUSTOM ASSISTIVE DEVICES

The photogrammetric–based approach to the design and development of bespoke assistive devices using INBODY is shown in Fig. 3. This process involves two phases: (A) data acquisition and processing of the human anatomy; (B) design and fabrication of the assistive device.

Since INBODY can provide a full body scan of the patient, it can be used to aid the design of most of wearable assistive devices, such as: orthopedic helmets, upper and lower limb prostheses and orthoses, spinal orthoses, ankle–foot orthoses, robotic exoskeletons.

A. Data acquisition and processing

During the data acquisition, the patient is asked to stand inside the scanner in a proper position, depending on the assistive device to be manufactured. An operator starts the scan process by using the INBODY graphical user interface (GUI). The data processing is performed using an apposite software package. The time required for the data processing depends on the client laptop used in combination with the scanner. Using a standard laptop, the time required for the digitization procedure of the body is between three and six minutes, depending on the desired resolution [7]. The output of INBODY is an STL file, which replicates the human body model with a proven magnitude of accuracy in the order of 1 mm [7]. The 3D model is ready as input for the design process. Moreover, it serves as digital medical record to monitor the patient improvements over time.

B. Design and fabrication

The previously obtained 3D model of the patient's anatomy is used by a technician to design the assistive devices. In this phase, general–purpose CAD software packages or CAD softwares tailored for prosthetics and orthotics are usually used. When the design is ready, the fabrication can be either performed through subtractive or additive manufacturing techniques. In the first case, the STL file of the design is converted using an appropriate CAM software to generate the path of a multi–axis milling machine. The latter fabricates the negative side of the assistive device from a polyurethane foam. Then, vacuum forming of plastic sheets on the milled foam, together with some refinement processes, generates the assistive device. In the second case, the assistive device is manufactured directly by adding materials layers using 3D printers.

V. EXAMPLE: DELIVERING TAILORED SPINAL ORTHOSES FOR SCOLIOSIS TREATMENT

Scoliosis is defined as a sideways curvature of the spine. When the involved curvature are not severe to require surgery, its treatment is carried out through spinal orthoses. The digital photogrammetric method using INBODY has been implemented in a real orthopaedic center (Ortopedia Ruggiero Srl, Cardito, Italy) for the design of custom–made spinal orthoses. The orthoses manufactured using this methodology have shown an enhanced wearability with respect to those previously developed in this center [9]; furthermore, these orthoses have reached an average score of 2.4 at the OPUS quality metrics [9]. OPUS is the accreditate standard of the American Board for Certification in Orthotics and Prosthetics to evaluate the quality of ortheses and prostheses [10].

To date, INBODY has been used to successfully deliver more than 1500 spinal orthoses.

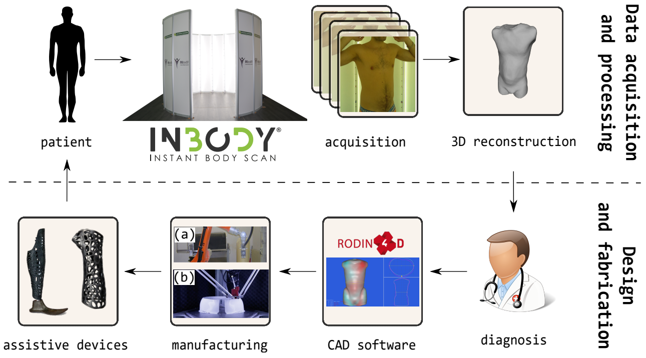

Fig. 3. A digital photogrammetric method to design custom assistive devices. From top left: 3D body reconstruction using INBODY scanner (https://www.instantbodyscan.com/). Design of the assistive device using Rodin4D software (http://rodin4d.com/). Fabrication through: (a) subtractive manufacturing techniques using a KUKA robot (https://www.kuka.com/); (b) additive manufacturing using a WASP 3D printer (https://www.3dwasp.com/).

Fig. 4. Spinal orthosis for scoliosis treatment manufactured using the photogrammetric method (courtesy of Ortopedia Ruggiero Srl, Cardito, Italy).

VI. DISCUSSION AND FUTURE DIRECTIONS

The main advantage of using 3D photogrammetry is the *instant* acquisition of human body shapes, especially important to deliver custom–made assistive devices. This brings the following benefits:

- no body sway, thus effective 3D reconstructions;
- reduced compliance asked to patients, who are not subject to high cognitive and neuromuscolar loads;
- improved patients satisfaction and reduced stress of operators.

Furthermore, the photogrammetric 3D body reconstruction is *non–invasive* for the patients, as cameras are harmful and no markers are needed on the human body for the digitization. A photogrammetric full body scanner as INBODY, beyond the aforementioned advantages, brings the following benefits the manufacturing of medical devices:

- possibility to scan, with the same instrumentation, different anatomic surfaces of the human body (head, limbs, trunk, full body) with accuracy similar to laser systems;
- simplicity of usage. The experience gained in the last years of INBODY use in real manufacturing scenarios has underlined that this system is simple to use for technicians and requires a limited maintenance. This is important since orthopaedics and rehabilitation centers might not have high–skilled technical staff.

In summary, photogrammetric 3D body scanners might benefit patients and clinicians with instant, non–invasive and accurate systems for human body reconstruction. These models are necessary to manufacture several assistive devices typologies, which are used for treatment of patologies and/or mobility dysfunctions. The main limitation of photogrammetry is due to the computationally demanding algorithms for image processing. This still limits its use for real–time applications.

Beyond manufacturing of custom–made devices, photogrammetric 3D body scanners might be used in other health–related applications. Indeed, 3D body models can be used in: (i) posture analysis; (ii) screening and monitoring of pathologies related to morphological alterations of the body surface; (iii) monitoring of diet and fitness programmes; (iv) cosmetic treatments.

Our future activities will consider the use of INBODY in some of the listed applications.

This work is an example of how advanced measurement systems applied to the human body can be used to improve current approaches for manufacturing of medical devices.

REFERENCES

[1] P. Treleaven and J. Wells, “3d body scanning and healthcare applications,” *Computer*, vol. 40, no. 7, pp. 28–34, 2007.

[2] M. L. Sivak, R. G. Ranky, J. A. DiPisa, A. L. Caddle, K. L. Gilhooly, L. C. Govoni, S. J. Sivak, M. Lancia, P. Bonato, C. Mavroidis *et al.*, “Patient specific ankle-foot orthotic device,” Sep. 16 2014, uS Patent 8,838,263.

[3] J. M. Zuniga, M. Major, J. Peck, R. Srivastava, J. Pierce, and N. Stergiou, “Technical and clinical considerations for the development of 3d printed upper-limb prostheses for pediatric patients.”

[4] A. Hernandez and E. Lemaire, “A smartphone photogrammetry method for digitizing prosthetic socket interiors,” *Prosthetics and orthotics international*, vol. 41, no. 2, pp. 210–214, 2017.

[5] S. J. Day and S. P. Riley, “Utilising three-dimensional printing techniques when providing unique assistive devices: a case report,” *Prosthetics and orthotics international*, vol. 42, no. 1, pp. 45–49, 2018.

[6] R. Hartley and A. Zisserman, *Multiple view geometry in computer vision*. Cambridge university press, 2003.

[7] S. Grazioso, M. Selvaggio, and G. Di Gironimo, “Design and development of a novel body scanning system for healthcare applications,” *International Journal on Interactive Design and Manufacturing (IJIDeM)*, vol. 12, no. 2, pp. 611–620, 2018.

[8] K. Kraus, *Photogrammetry: geometry from images and laser scans*. Walter de Gruyter, 2007.

[9] S. Grazioso, M. Selvaggio, T. Caporaso, and G. Di Gironimo, “A digital photogrammetric method to enhance the fabrication of custom-made spinal orthoses,” *JPO: Journal of Prosthetics and Orthotics*, vol. 31, no. 2, pp. 133–139, 2019.

[10] A. W. Heinemann, R. Bode, and C. O’reilly, “Development and measurement properties of the orthotics and prosthetics users survey (opus): a comprehensive set of clinical outcome instruments,” *Prosthetics and orthotics international*, vol. 27, no. 3, pp. 191–206, 2003.