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Review

3D surface acquisition systems and their applications to facial anatomy: let's make a point

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Abstract

In the last decades 3D optical devices have gained a primary role in facial anthropometry, where they find several applications from the anatomical research to clinics and surgery. With time the number of articles focusing on 3D surface analysis has raised, as well as validation studies which aim at verifying the reliability of different devices and methods of acquisition in comparison with other methods or direct anthropometry. This review aims at making a point in the field of 3D surface acquisition systems, describing the most used types of available devices and comparing the relevant outcomes in acquiring 3D facial models. Results show that currently stereophotogrammetric devices represent the gold standard, further improved by the diffusion of portable models. Caution should be given to the use of low-cost devices, more and more frequently described by literature, as often they do not meet the basic criteria for being applied to the anatomical study of face.

Keywords

3D optical scans, stereophotogrammetry, laser scanner, direct anthropometry.

Introduction

The quantitative assessment of facial soft-tissue structures, their reciprocal relationships and relative proportions represent an important task in clinics (Hammond et al., 2004). Diagnosis, treatment planning and follow-up examinations all need some kind of measurements that should be performed taking their peculiar three-dimensional (3D) configuration into account (Schwenzer-Zimmerer et al., 2008; Pucciarelli et al., 2017; Kimura et al., 2019; Sforza et al., 2018).

3D optical scans are devices able to acquire a 3D model of an object through surface imaging. The introduction of this technology has represented a revolution in anthropometry: metrical assessment of face had been previously performed through direct measurements by calipers, a low-cost method which has the main limits of being time-consuming, to depend upon patients' cooperation and to have some problems in repeatability (Wong et al., 2008). Not even instruments developed in later times such as electromagnetic and electromechanic digitizers could overcome the lack of permanent records of the face, and the opportunity to replace wrong or missing values. On the other side, the acquisition of a virtual model of the face allows to perform reliable and repeatable measurements, and to assess a novel set of met-

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rical parameters, including not only the traditional linear distances and angles, but also surface areas, volumes, differences between superimposed 3D models and geometric morphometric analyses (Winberg et al., 2006; Hong et al., 2017; Sawyer et al., 2009; Gibelli et al., 2015; Codari et al., 2015; Pucciarelli et al., 2017). Moreover, surface acquisition devices do not need physical contact with the face, thus avoiding the risk of skin compression (Douglas et al., 2003; Majid et al., 2005).

These methods of 3D acquisition have found several applications in a variety of disciplines involving the analysis of facial anatomy, from dentistry (Sterenborg et al., 2018) to aesthetic (Feng et al., 2019; Jimenez-Castellanos et al., 2016) and maxillofacial surgery (Sforza et al., 2018; Kimura et al., 2019), from the early diagnosis and follow-up of genetic and acquired pathologies (Pucciarelli et al., 2017; Dolci et al., 2018) to forensic anthropology (Gibelli et al., 2017a; Gibelli et al., 2017b).

In the last years the use of 3D surface acquisition systems has progressively increased, and devices improved as well: in the past 3D acquisitions could be performed only through static and expensive machines (de Menezes et al., 2010; Tzou et al., 2014) which limited the fields of applications and prevented the recruitment of some types of patients. Now the scenario is changing, with the introduction of modern portable and in some cases low-cost devices (Camison et al., 2018; Gibelli et al., 2018a; Gibelli et al., 2018c).

This review aims at taking stock of the situation in the field of soft tissue 3D facial imaging, describing the different types of available devices and the relevant advantages and limits. As the instruments are based on different technologies, should be used with dedicated protocols, and show specific limits, we will focus on those instruments that had been tested and used in our laboratory, thus providing also some practical information about 3D acquisition and reconstruction.

Stereophotogrammetry

Stereophotogrammetry is based on a light source (either patterned or conventional) to light the face, simultaneously acquired by two or more coordinated cameras oriented from different points of view (Majid et al., 2005; Wong et al., 2008; Plooij et al., 2009; Tzou et al., 2014). The device is able to record a dense polygon mesh together with facial texture and combines the quantitative mesh information with the qualitative reproduction of facial surface (Fig. 1). The finer the mesh, the better the outcome of facial acquisition. Generally facial stereophotogrammetric scans can reconstruct the face structure with a resolution of approximately 60 vertices/cm^2 in about 1.5-3.5 ms: the faster the scan, the less motion artifacts (Tzou et al. 2014; Gibelli et al., 2018b). Measurements obtained by stereophotogrammetry have a good precision and reproducibility, with random errors generally lower than 1.5 mm (Gibelli et al., 2018b). The position of some structures within the face such as the nostrils, ears and the chin region may limit the possibility of being viewed simultaneously by more than one camera. The problem can be partially resolved by increasing the number of cameras, with a higher monetary investment.

The chance of acquiring the entire face from different points of view at the same time and the high acquisition velocity render stereophotogrammetry the gold standard for facial scans, as it reduces at the minimum possible the bias due to involuntary

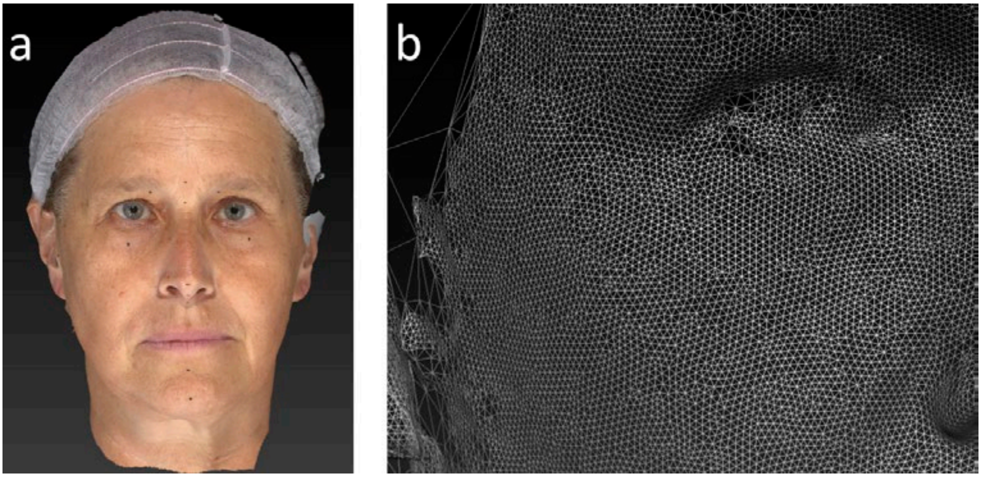

Figure 1. Example of textured scan (a) and mesh (b) of an acquisition by VECTRA M3 stereophotogrammetric device (Canfield Scientific, Inc.): the mesh is highly detailed and homogeneous, with defects in correspondence of hair and eyes.

movements (typically, eyes, nose and lips). Therefore, it is the ideal device for acquisition of not cooperative patients (such as children) and disabled persons with motor impairments.

Another advantage is the texture information which allows to label facial landmarks before the facial acquisition: previous landmarks labeling proved to improve accuracy in landmark recognition (Weinberg et al., 2004, Fig. 2).

The main limitations include the cost of the device (tens of thousands of euros circa), and the size of acquisition setting (Tzou et al., 2014) which sometimes prevent from acquiring patients who cannot be adequately hosted within the acquisition area (for example, patients in wheelchair). In addition, the devices are static, and therefore cannot be moved to meet permanently bedridden patients.

Laser scanner

Laser scanners acquire facial surface through a laser light and digital cameras. Accuracy and resolution are reported between 0.5 and 1 mm, with a mean scanning error of 1.1 mm (Fig. 3). During data acquisition, the laser light moves to scan the facial surface and approximately 10 s are necessary to obtain a complete facial image (Tzou et al., 2014; Gibelli et al., 2018c). As a consequence, the effect of possible involuntary facial movements is more evident than in stereophotogrammetry and may alter the final result (Schwenzer-Zimmerer et al., 2008). Critical parts for the acquisition are the ears, the nostrils and the chin; shadows and a dark complexion usually result in a hampered scan (Majid et al., 2005).

Some of the published studies based on acquisitions through laser scanner include two different captures from the right and left sides, simultaneously performed by

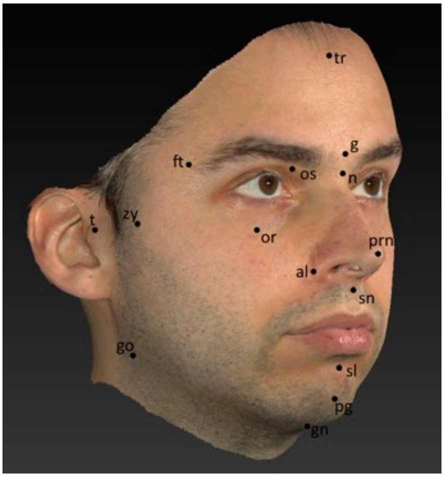

Figure 2. Example of landmarks usually labeled on the skin to improve anthropometrical analysis: tr: trichion; g: glabella; n: nasion; prn: pronasale; sn: subnasale; sl: sublabiale; pg: pogonion; gn: gnathion; os: sovraorbitale; or: orbitale; ft: frontotemporale; zy: zygion; t: tragion; go: gonion.

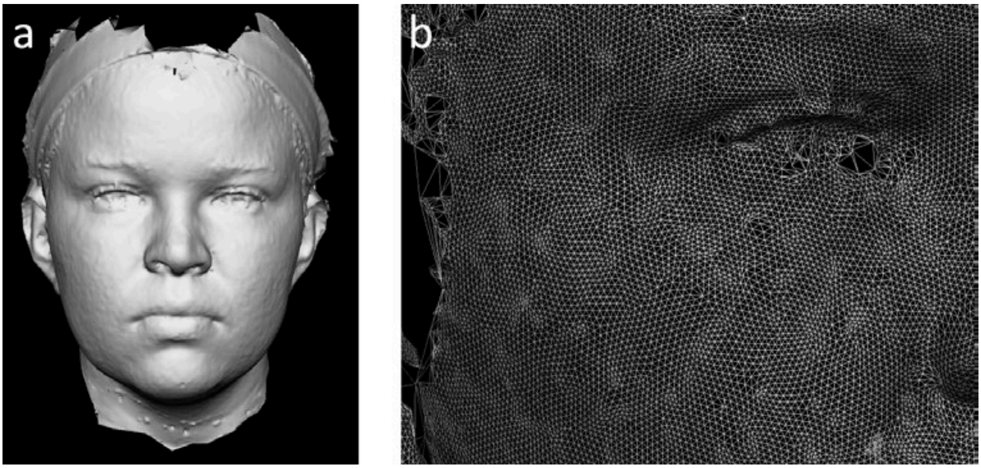

Figure 3. Example of scan (a) and mesh (b) of an acquisition by Vi910 laser scanner (Konica Minolta): the mesh is detailed, but affected by some not homogeneous areas due to involuntary facial movements during facial scan and between consecutive acquisitions.

two devices arranged in a pair (Kau and Richmond, 2008; Toma et al., 2009). This approach allows to reduce the influence of involuntary movements, but doubles the costs, as it requires two devices. However, recent literature observed that three consecutive models can be acquired separately (right side, frontal, left side), and merged, without appreciable modifications (De Angelis et al., 2009; Cattaneo et al., 2012;

Gibelli et al., 2018c). Clearly, in these cases the cooperation of the subjects is essential to limit motion artifacts due to the longer scan times.

The main limits of laser scanners are cost and the size of the device, as for the stereophotogrammetric ones: in addition, some models do not provide facial texture, preventing previous landmarks labelling. Laser scanner devices can be moved, although with difficulties because of their encumbrance.

The portable stereophotogrammetric devices

In the last years portable stereophotogrammetric devices have been introduced in commerce: these systems can obtain a facial model through a compact device and a laptop (Camison et al., 2018). In comparison with the static devices, the final acquisition is obtained through three consecutive scans (right side, frontal and left side) taken within a limited time period (Fig. 4). These new devices may extend the facial acquisition also to hospitalized patients as well as to subjects who cannot be hosted within the conventional stereophotogrammetric set.

The main weak point of these stereophotogrammetric instruments is the need for three consecutive facial scans, with an increment of facial involuntary movements and a less detailed final 3D model (Camison et al., 2018).

Two validation studies have been published in the last years, focusing on a portable stereophotogrammetric device. Camison et al. (2018) analyzed the repeatability of linear measurements between the portable device and a traditional static instrument. In addition, a superimposition procedure was performed registering the facial model

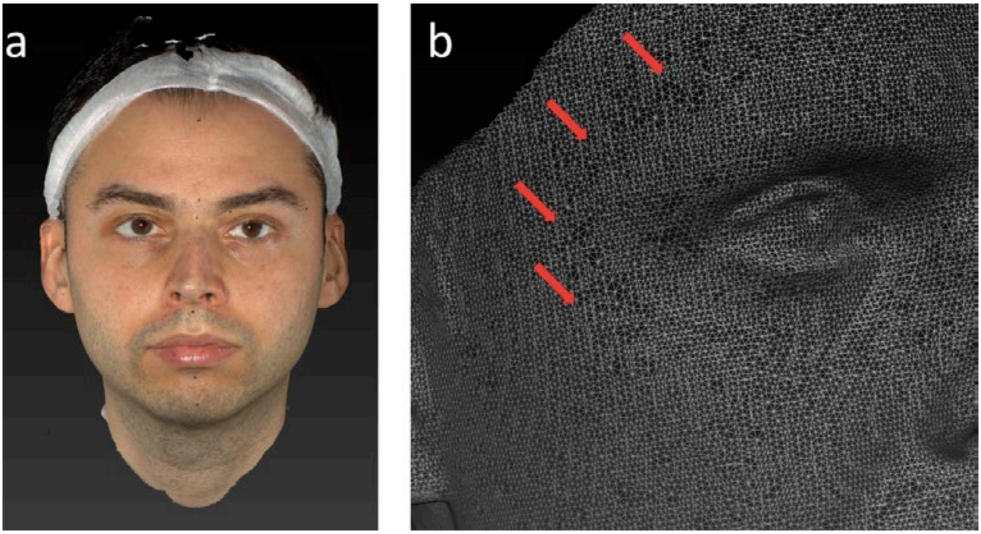

Figure 4. Example of textured scan (a) and mesh (b) of an acquisition by Vectra H2 portable device (Canfield Scientific, Inc.): the mesh is highly detailed; defects can be found in correspondence of areas shared by two consecutive scans (red arrows).

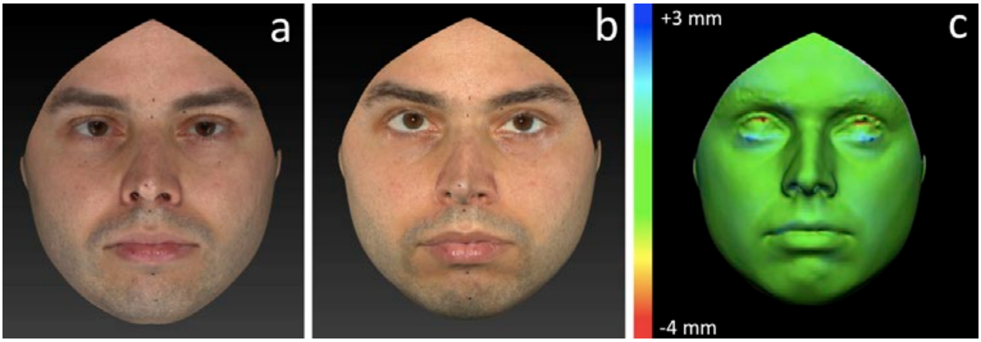

Figure 5. Example of 3D-3D superimposition between a scan from static VECTRA M3 system (a) and portable VECTRA H2 system (b), with chromatic sheet representing more concordant (green) and discordant (blue, red, yellow colors) areas between the two scans. As one can observe, most of facial surface is green indicating high concordance, but for eyes because of involuntary facial movements.

produced by the portable instrument onto that provided by a fixed one produced by another company (Camison et al., 2018). Their results confirmed that the stereophotogrammetric portable device is sufficiently accurate for most clinical applications.

Another validation study was published by Gibelli et al. (2018b): in this case, both the reference stereophotogrammetric static device and the portable one were produced by the same company. Again, the portable system was reliable in assessing linear measurements, angles and surface areas; however, volumetric measurements and 3D-3D registration procedures were affected by facial movements, increased by the need for consecutive captures (Fig. 5).

The major limits of the current instruments are represented by the necessary higher patient compliance, and by the cost (a few thousand euros circa): in addition, the device needs to be used with a high-performance laptop. Otherwise, it can be used storing the images on a memory card, for off-line elaborations, but it does not allow the operators to immediately verify the correctness of facial acquisitions.

Low-cost devices

Recently, novel and more economical portable devices have been developed, to widen the diffusion of 3D acquisition technology. An example is the Sense® 3D scanner, a hand-held scanner with a spatial x/y resolution of 0.9 mm and a depth resolution of 1.0 mm at 0.5 m (Fig. 6). It costs a few hundred of euros circa and can acquire a face in less than one minute (Fan et al., 2017).

However, at our knowledge, presently the Sense® device has been applied only in one published scientific article, where it was used to scan the face of a cadaver for the assessment of 3D modifications due to the decomposition process (Caplova et al., 2018). Only a validation study is available (Gibelli et al., 2018a): the device proved to give a reliable acquisition for the assessment of linear and angular measurements in case of inanimate subjects/objects (Caplova et al., 2018), but was is not reliable enough to be applied to clinical contexts.

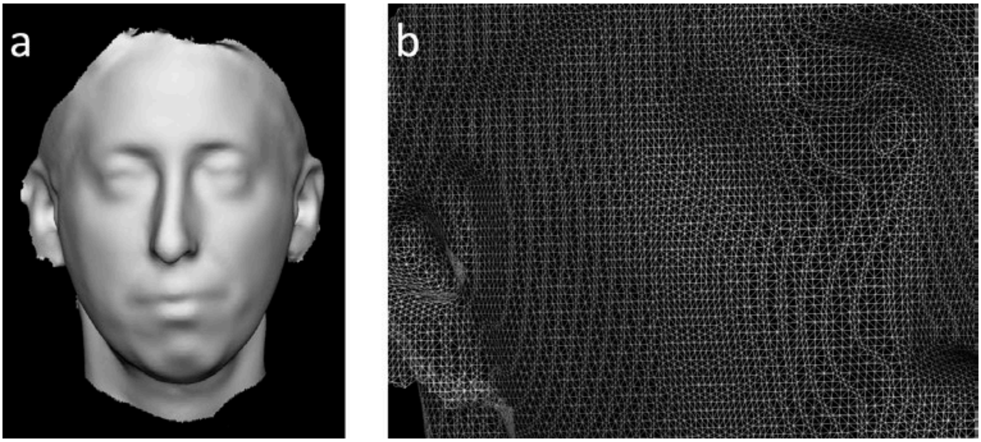

Figure 6. Example of textured scan (a) and mesh (b) of an acquisition by Sense laser scanner portable device: the mesh is less detailed than those obtained by the other facial scan methods.

Maués et al. (2018) compared facial scans obtained by a conventional fixed stereophotogrammetric device with the Microsoft Kinect® scanner. The relevant facial models were superimposed, and the distances between them were obtained. On average, the difference between the two methods was lower than 0.5 mm, but some areas had higher discrepancies. The authors concluded that the device showed a reasonable accuracy, thus proposing it as a possible resource for facial analysis.

Finally, in the last years other low-cost systems have been developed, including 3D acquisition applications for smartphones and tablets (Koban et al., 2014). However, they have not been validated for their application to research and clinical contexts.

Conclusion

3D optical surface acquisition systems have progressively widened their application fields. In addition, technology has improved with the development of novel devices which may be reliably used in the clinical context. The choice of the most appropriate instrument vary from time to time, in relation to its use and the characteristics of the patients to be analyzed. Validation studies are crucial to verify the reliability of novel procedures and to compare performances with gold standard methods.

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