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A low-cost system to acquire 3D surface data from anatomical samples

Davide Viggiano[1], Theodoros Thanassoulas[2], Cinzia Di-Cesare[1], Giovanna Cacciola[1], Nicola M. Giorgio[2], Theodoros Pitsios[3], Cosimo Passiatore[2]

[1]Dept. Medicine and Health Sciences, Univ. Molise, Campobasso, Italy; now at: Department of Cardio-Thoracic and Respiratory Science, Second University of Naples, Naples, Italy, [2]Dip. Salute Mentale e Fisica e Medicina Preventiva, Second Univ. Naples, Naples, Italy and [3]Anthropological Museum of the National and Kapodistrian, University of Athens, Athens, Greece

SUMMARY

The technology of optical 3D imaging sensors or 3D scanners (laser and structured light sensors) has become widely available over the last few years. A wider diffusion of this technique in anatomical laboratories could lead to a revolution in the field of anatomy: cadaver dissections could be easily documented in 3D, and specimens stored in museums could be easily scanned and the 3D models shared. In the present article, a simple, versatile, economical and widespread 3D scanner, the Kinect sensor, is validated to show its potential use for 3D scanning of anatomical specimens.

The comparison of 3D models of anatomical specimens (a collection of skulls) with the respective 2D photographs showed that 3D models were superior to the photographs, the latter being affected by some distortions due to perspective. Moreover, the 3D models allowed for measuring angles, distances, circumferences between every part of the model, or measuring volumes and surfaces, which, of course, were not available using the 2D images. Due to the low cost of this system, its simplicity of use and its widespread availability, it is desirable that in the future, anatomical specimens from museums will become more available as 3D objects. These could greatly simplify the quantitative analysis of rare specimens, such as fetal monstrosities or anatomical variations.

Corresponding author: Davide Viggiano, MD, PhD. Via De Sanctis snc, 86100 Campobasso, Italy.
E-mail: davide.viggiano@unimol.it

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INTRODUCTION

Many fields of science require exact knowledge of the shape of specimens, e.g. in archaeology, paleontology, plant studies, surgery and, of course, anatomy. In all these fields, the possibility to acquire and share images of the specimens has been pivotal for further development of knowledge. Some of these fields, specifically archaeology and paleontology, have undergone a revolution in the system of image acquisition: current approaches for image storage and sharing do not simply use planar images, but employ the new 3D scanner technology.

This new technology is impressive, because it permits a complete knowledge of the specimens, not only their outline and surface colors, but also all their 3D properties such as volumes and surfaces.

In the field of the clinical anatomy, 3D information is equally important, and 3D information of macroscopic structures has been used for clinical applications such as: building patient-specific synthetic abdominal anatomies (Condino et al., 2011), rapid prototyping for 3D preoperative planning for plastic surgery (Mandel et al., 2013), and documenting 3D muscle surface anatomy (Rana et al., 2013). Most of these examples derive the 3D

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information from CT scans or ultrasounds.

On the other hand, 3D optical scanners have been used less intensely, possibly because they are a new technology, such as for documentation and follow-up of surgical therapy (Bischoff et al., 2007), and for leg edema quantification (Hayn et al., 2013).

Therefore, the new 3D scanning technology promises to give rapid information without X-rays or ultrasounds.

A larger diffusion of this technique in anatomical laboratories could lead to a revolution in the field of anatomy: the cadaver dissections could be easily documented in 3D, and specimens stored in museums could be easily scanned and virtually shared. The possibility to scan anatomical specimens for data sharing would lead to previously unthinkable applications, such as interactive/ immersive applications (virtual and augmented reality).

In the present article we present a simple, versatile, economical and widespread 3D scanner, the Kinect sensor, and show its potential use for 3D scanning of anatomical museum specimens.

Our aim is to facilitate morphological investigations by providing a simple and economical system to acquire, visualize and measure 3D-data, for the international scientific community. The hope is that the large availability of a low-cost scanning system would greatly improve specimen-sharing among museums, which could be beneficial for the development of quantitative anatomical research.

MATERIALS AND METHODS

Specimens

The specimens used in this study were obtained from the Anatomical Museum of the Second University of Naples. This collection, begun in 1808, currently consists of over 1900 specimens (Viggiano and Passiatore, 2003). The Museum hosts a large collection of interesting teratological cases, which have been previously the focus of original neuroanatomical work (Viggiano et al., 2002). In this methodological work we have exploited the large collection of skulls deriving from excavations in Pompei and Pontecagnano, which have anthropological and historical relevance. Three different collections are hosted, which can be differentiated on the basis of the color of the enumeration.

In the present article, the collection from the necropolis of Pontecagnano has been evaluated, using best preserved samples, as reported in Table 1. All the skulls derive from adult subjects and did not show pathological signatures. One skull originally included in the study was not subsequently measured, because the scanning result was not optimal.

Table 1. Skulls used in this study.

Skull cat. n.	Gender
2	M
8	M
10	M
17	M
28	M
105	M
158	M
178	M
188	M
199	M
214	M
256	M
412	M

The 3D sensor system

For the present communication two 3D scanners have been tested: the Microsoft Kinect and the Carmine PrimeSense. The two sensors have nominally similar resolution, although the Carmine PrimeSense allows for the scanning of objects at closer distance. A pilot study showed that samples containing tiny details were best scanned using the Carmine PrimeSense, primarily due to the lower working distance. However, for larger objects, such as adult skulls, the two sensors worked equally well, giving overlapping results. Therefore, as the Kinect sensor is cheaper and more widespread, only this scanner has been further validated in this study.

The Kinect™ sensor is a 3D gaming console sensor for the Xbox 360 (Microsoft Corporation, Redmond, WA, USA).

The Kinect is available for less than 100 €, is USB-interfaced and operates projecting a structured light pattern of infrared points, which are acquired through a webcam and used for 3D recovery.

Basically, the Kinect hardware sensor transfers to the computer two kinds of information: depth data, in form of 3D point clouds, and a standard RGB image.

Scanning software and calibration

Since the 3D scanner returns the surface properties only a single visual position, objects need to be rotated during the scanning in order to obtain information from different sides. Basically, multiple scannings from different points of view must be then merged into a single 3D object using specific algorithms. It is important to note that these algorithms work on the basis of the similarity of the 3D surfaces from closer views.

To acquire the 3D scannings and automatically register the surfaces into a single object, the Skanect software (**http://skanect.occipital.com/**) has been used, a powerful 3D real-time scanning system which provides full color 3D model of an object; Skanect is fast (up to 30 frames per second) and a free version is available (in this work we have used the PRO version).

Based on this information, the Skanect software reconstructs a single dense surface model with smooth surfaces by integrating the depth data over time from multiple viewpoints.

A pilot study showed that the best procedure was to maintain the sensor fixed and to manually rotate the specimens 360 degrees, using a custom rotating table. The scans were performed with the sample at a distance of 70 cm from the sensor, and the sensor with an angle of 27° degrees (Fig. 1).

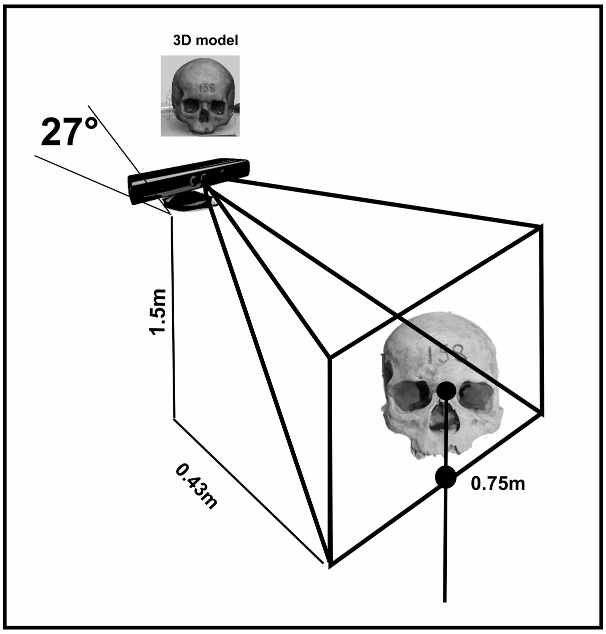
Image processing and measurements

3D scans were preprocessed using the freely available software Meshmixer (http://meshmixer.com/), in order to cancel all scanned objects that did not pertain to the sample (pieces of the glass container, the support, etc.) and to delete possible scanning artifacts.

Distances have been measured using the freely available software Geomagic Verify Viewer (http://support1.geomagic.com/link/portal/5605/5668/Article/2344/Geomagic-Verify-Viewer-Download-Links).

The landmark points were identified by exploiting the possibility to colorize single vertex (texture mapping) using data gathered by the RGB color camera. The landmark points and measured distances are reported in Fig. 2.

To demonstrate the possible application of a surface measurement on 3D models, we have tested the hypothesis that the asymmetries of the frontal bone might be linked to asymmetries of the parietal bones. To this aim, the frontal and parietal bones have been 'virtually' dissected along the suturae from the 3D model, using the free software Meshmixer (www.meshmixer.com/); subsequently the surface of each bone has been measured using Geomagic Verify Viewer. The asymmetry index of the frontal or parietal bones was calculated by measuring the ratio of the difference between the surfaces of the right and left side and the total surface of the bone: the correlation of the



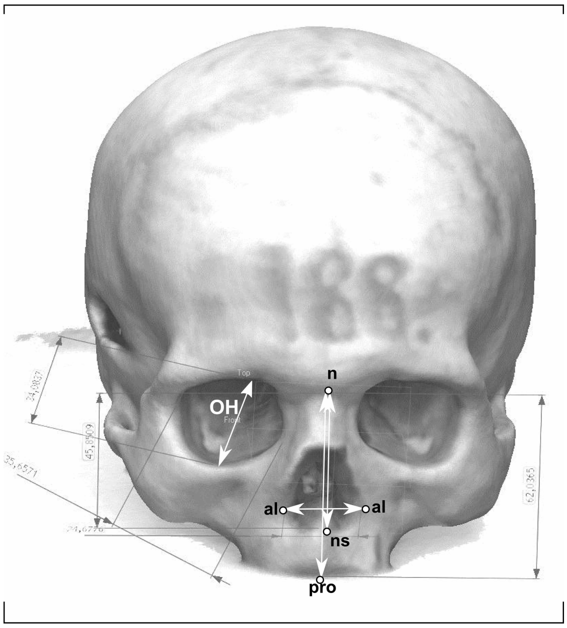


Fig. 1 (left). Acquisition settings for 3D imaging of anatomical samples. The 3D scanner was placed at a distance of 0.43 m from the specimen, with an inclination of 27°. The specimen was then manually rotated on a rotating disk in order to scan the entire surface. Small solids (parallelepipeds, cylinders) were also placed on the rotating disk, in order to help the reconstruction software to register images across different points of view.

Fig. 2 (right). The measurements from skull specimens. The image refers to a 3D reconstruction of one of our samples. n: *nasion* (centre of the fronto-nasal suture); al: *alar* (most lateral points on the external nasal aperture); ns: *nasospinal* (ip of the nasal spine at the inferiormost points of the nasal (piriform) aperture); pr: *prosthion* (most anterior point on the alveolar processes of the maxillae). The surface texture of the 3D scanning was detailed enough to allow a one-to-one mapping of anatomical landmarks between real objects and those *in silico*. The following distances were measured both on real specimens with a caliper and *in silico* on 3D reconstructed surfaces: OH: orbital height, the distance between the inferior and superior orbital margins; n-pro: upper facial height, the distance from *prosthion* (pr) to *nasion* (n); n-ns: nasal height, the distance from *nasion* (n) to the nasal spine (ns); al-al: the breadth of the piriform aperture.

Fig. 3. Exemplificative images of three sample skulls from the collection of the Museum of Anatomy, using standard photographs (on the left) and their 3D reconstruction based on the low-cost 3D sensor. The surface texture is detailed enough to allow to retrieve and measure major anatomical landmarks. Note that in classical photographic 2D images, some distortions of the sample occurs due to the perspective and the optics.

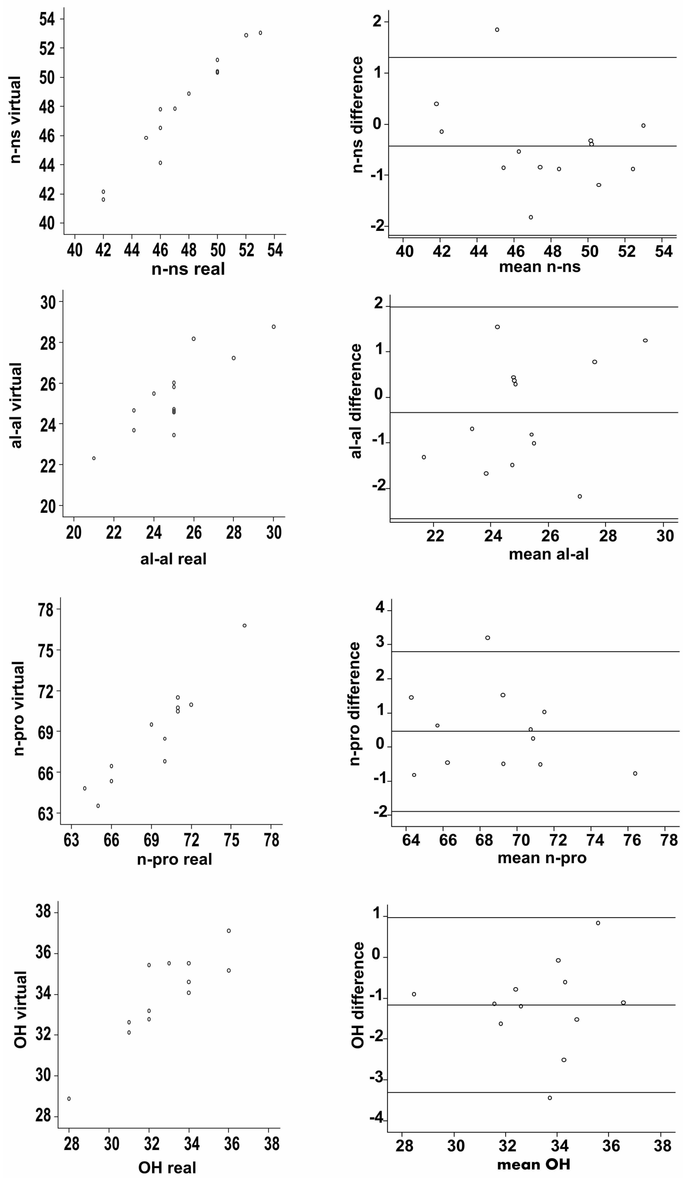


Fig. 4. Validation of measurements obtained on 3D virtual images compared to classical measurements with calipers. **(Left)** Scatter-plots of the real *vs in silico* measurements; **(Right)** Bland-Altman plots. The four comparisons refer to the measurements defined in Fig. 2.

frontal and parietal asymmetry indices has been then calculated.

Statistical analyses

In the method comparison analyses, the values of the outcome measure for the Microsoft KinectTM and the measurements on the real objects were compared using Pearson's correlation, and Bland-Altman 95% limits of agreement. Statistical significance was determined at the 2-sided 0.05 level.

RESULTS

Fig. 3 shows exemplificative images of three sample skulls from the collection of the Museum of Anatomy, using standard photographs (on the left) and their 3D reconstruction based on the low-cost 3D sensor. Overall, the 3D reproductions were remarkably close to the photographs, the latter being affected by some distortions due to the perspective. The possibility to colorize the vertices of the 3D object allowed for the identification of tiny details, such as suturae and small holes and notches on the surface.

The surface density of the sampled points was on average 1.5 points/mm^2, and the average distance of two points (vertices) was 1 mm. However, the resolution was not homogeneous across the sample, and on smooth surfaces, perpendicular to the scanning beam, it was possible to achieve a maximum resolution of 0.1 points/mm^2 with a between-points distance of 0.2 mm.

Using small objects with very regular shape (cylinders, prisms, parallelepipeds) we first tested the reliability of linear measurements. The results showed a high correlation between the measures on the real objects compared to those on virtual objects (Pearson's corelation = 0.995, intraclass correlation coefficient=0.997±0.995 (correlation score ± 95% CI)).

In more complex situations, such as skulls, the surface resolution was poorer in irregular regions, particularly in depressed areas, such as the bottom of the orbital and nasal cavities. This was largely due to the occlusion of the walls, which did not permit an optimal sampling of these small surfaces. Since these were the most critical regions in the sampling, we decided to test the measurement of spatial lengths across them.

As depicted in Fig. 3, the correlation between the measurements on the real objects compared to the virtual object depends on the type of measurement.

There was excellent correlation for n-ns and n-pro measurements (Pearson coefficient=0.973 and 0.945 respectively; $p<<0.01$), whereas al-al and OH measurements showed lower, but highly significant, correlations (Pearson coefficient=0.846 and 0.88 respectively; $p<0.01$). The Bland-Altman plot (Fig. 3) and regression analysis showed very small mean difference, which was not significantly different from zero, for all measurements.

Since the accuracy of the measurements was by far better on simple objects than on skulls, the lower accuracy of skull measurements was likely due to a difficulty to define exactly the same landmark points on the virtual objects and on the real object. It is plausible, in fact, that the landmark point considered on real objects is less precise compared to the virtual object, which can be magnified and the precise point selected with greater accuracy.

Finally, the analysis of the asymmetry of the frontal and parietal bones showed that the two asymmetry indices are not significantly correlated, as shown in Fig. 5.

DISCUSSION

In the present article we show that it is possible to acquire relevant anatomical data using a widely available, low-cost 3D scanning sensor, the Kinect sensor. We also provide information on the reliability of the reconstructed 3D objects for linear measurements and for surface data. Our data are in agreement with a previous work, which validated the Kinect sensor for the measurement of volumes

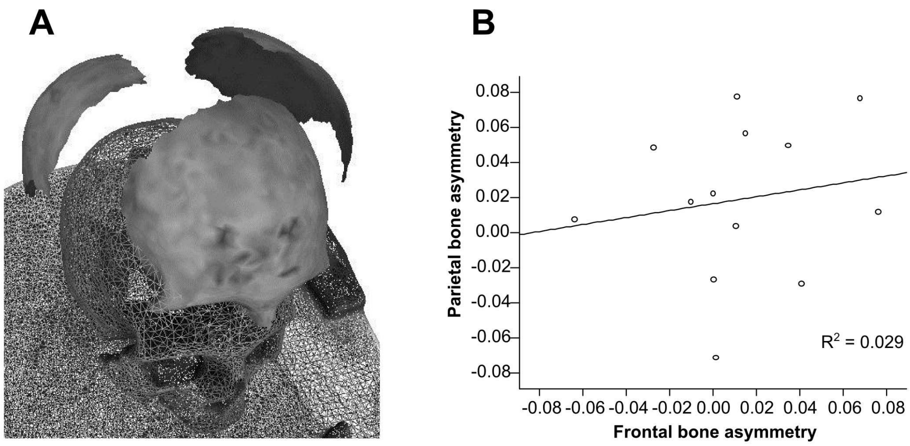


Fig. 5. Virtual dissection of the parts of the skull and testing of relatedness of asymmetries of the frontal and parietal bones. **(A)** The frontal and parietal bones have been manually dissected in the virtual model along the suturae, using the software Meshlab. **(B)** The asymmetry index (difference of the surface of the right side and left side divided by the total surface of both sides) is plotted for the frontal bone and parietal bone. There is no clear correlation between the two asymmetry indices.

of body parts (Weiss et al., 2011; Molnár et al., 2012; Tong et al., 2012; Bonnechère et al., 2014a, 2014b). Optical 3D imaging sensors or 3D scanners (laser and light structured sensors) have become relevant over the last years, and some instruments are now commercially available (Blais, 2004). During the 1970s and 1980s the development of 3D laser scanners, mainly in the mechanical field, led to three major types of operation: Triangulation-based scanners, time of flight scanners and phase-Shift scanners (Sansoni et al., 2009; Merchán et al., 2011; Friess, 2012). The Kinect sensor is an interesting hardware, with a low cost but a good 3D scanning ability. To interpolate depth data it uses (as many other kinect-based scanning softwares, e.g. Recontructme, Kinectfusion etc) algorithms such as the Iterative Closest Point algorithm (ICP), which find the best alignment of two point clouds. The algorithm is implemented in the Kinect Fusion, a set of libraries included with the Kinect SDK. This algorithm allows to move the sensor around an object or to rotate an object while maintaining the sensor fixed, and integrating the point clouds from different points of view.

Clinical relevance and application in the field of anatomy

We have recently used the Kinect sensor for kinematic analysis of upper limbs in karate practitioners (Romano and Viggiano, 2014). This sensor has been already used in forensic sciences (González-Jorge et al., 2014), plant measurements (Nock et al., 2013), human morphological measurements (Molnár et al., 2012), patient size estimation (Cook et al., 2013), breast morphology quantification (Henseler et al., 2014) and leg edema measurement (Hayn et al., 2013; Lu et al., 2013).

Several museum projects aim at share and freely make accessible 3D scans of museal objects, both for the large public and for investigators. The 'online 3D museums' based on laser scanning surface data for now interest mainly the museums of paleontology: see the beautiful online repository of fossils of the Museum of Paleontology of the University of Michigan (https://umorf.ummp.lsa.umich.edu/wp/) and the paleoview 3D site of the Marshall University (http://paleoview3d.marshall.edu/index.php), the 3D museum by the University of Oregon and University of California (http://3dmuseum.org/), which exploit surface 3D laser scanners. Other 3D databases exploit CT scans to obtain 3D models: the freely available Digital Morphology Museum Kupri of the Kyoto University (http://dmm.pri.kyoto-u.ac.jp/dmm/WebGallery/index.html), the Digital Morphology of the University of Texas at Austin www.digimorph.org/), the 'visible interactive' series from Ohio University, run by Lawrence Witmer (http://www.oucom.ohiou.edu/dbms-witmer/projects.htm).

The importance of these 3D resources in scientific research is also attested by the large amount of publications based on the Digimorph database (see e.g. http://www.digimorph.org/publications.phtml). Finally, we must mention the great detail and interactivity of the 3D models at the University of Michigan Fossil Database (https://umorf.ummp.lsa.umich.edu/wp/), where the visitor may visualize, zoom, rotate the specimens.

It is important to stress the qualitative and quantitative difference of these 3D databases from classical 2D image archives, such as the Will's Skull Page (http://www.skullsite.co.uk/), the Comparative Mammalian Brain Collection (http://brainmuseum.org/index.html), the E-skeleton Project of the Dept. Anthropology of Univ. Texas at Austin (http://www.eskeletons.org/index.html), or the Virtual Zooarcheology of the Arctic Project by Idaho State University (http://bones.iri.isu.edu/).

The 3D models, in fact, allow for the possibility to measure angle, distances, circumferences between every part of the model, or to measure volumes and surfaces, which, of course, is not possible with 2D images and is cumbersome on real objects.

The resolution of the Kinect sensor is optimal for large anatomical specimens. However, it does not work adequately in the case of small samples such as fetal skeletons. Moreover, it is not sufficiently detailed in the case of very irregular samples with concave areas, which limit the access of the laser light. However, these limitations are in part overcome by the possibility to retrieve the color of single vertex in order to obtain the landmark points.

The scanning method used here does not allow us to represent equally well the base and the top of the skull: it should be emphasized that this can be obtained by taking a second scanning of the same object placing it up-side-down and then merging the two resulting 3D models (e.g. with the free software Meshlab): this at the expense of a larger computational and scanning time.

To show a possible application of 3D models and their superiority compared with 2D data, we calculated the surface area of the two parietal bones and the two halves of the frontal bone of each scanned skull. We then tested the hypothesis that the asymmetry of the frontal bone (petalial asymmetries) is correlated to the asymmetry of the parietal bone, a problem which could not been directly assessed before, using surface measurements. The results showed that the asymmetry of the frontal bone is unrelated to the asymmetry of the parietal bones.

Due to the very low cost of this system, its simplicity of use and its widespread availability, it is desirable that in future time anatomical specimens from museums will be available as 3D objects, which could greatly simplify the quantitative analysis of rare specimens such as fetal monstrosities or anatomical variations.

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