European Journal of Clinical Nutrition (2018) 72:680–687
https://doi.org/10.1038/s41430-018-0145-7

REVIEW ARTICLE

Digital anthropometry: a critical review

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Received: 12 February 2018 / Accepted: 20 February 2018

Abstract

Anthropometry, Greek for human measurement, is a tool widely used across many scientific disciplines. Clinical nutrition applications include phenotyping subjects across the lifespan for assessing growth, body composition, response to treatments, and predicting health risks. The simple anthropometric tools such as flexible measuring tapes and calipers are now being supplanted by rapidly developing digital technology devices. These systems take many forms, but excitement today surrounds the introduction of relatively low cost three-dimensional optical imaging methods that can be used in research, clinical, and even home settings. This review examines this transformative technology, providing an overview of device operational details, early validation studies, and potential applications. Digital anthropometry is rapidly transforming dormant and static areas of clinical nutrition science with many new applications and research opportunities.

Historical development

During the mid-nineteen eighties a request came in to Loughborough University located in the East Midlands of England from a textile manufacturer to provide comprehensive human shape data with the aim of facilitating garment manufacturing [1]. The company desired to explore the possibility of developing a "non-contact machine that is reasonably transportable and sufficiently speedy in operation to survey economically a large sample of the British population." What emerged in 1987 was the Loughborough Anthropometric Shadow Scanner or "LASS." [2] The developed device included a television camera, projector, and a 360° rotating table upon which the volunteer stood during the evaluation procedure. Thus the field of "automated anthropometry" was born [3]. The following three decades have seen rapid advances in methods designed to quantify human body shape that include laser and structured light systems, millimeter wave radar, and multi-view camera methods [3, 4].

Interest in automated, or digital, anthropometry has intensified with the introduction of relatively inexpensive optical imaging devices that replace the LASS system's television camera. Three-dimensional (3D) imaging devices are now or soon will be available that are practical for clinical installation and even individual home use. This review examines developmental aspects of these new instruments, issues related to their use in clinical settings, and their potential future applications.

Concepts

Three-dimensional scanners aim to create a high-quality representation of the whole human body surface using non-invasive optical methods. Because they rely on visible and infrared light (IR), 3D scanners capture information only from the surface of the body and require minimal, form-fitting clothing to be worn. This type of scanner is inexpensive and does not involve ionizing radiation, unlike other whole-body imaging methods such as computed tomography (CT) and dual-energy X-ray absorptiometry (DXA). For many day-to-day applications, such as estimation of % fat, 3D scanners hold significant advantages over more costly or invasive technologies. From a technical standpoint, obtaining useful information from 3D scans

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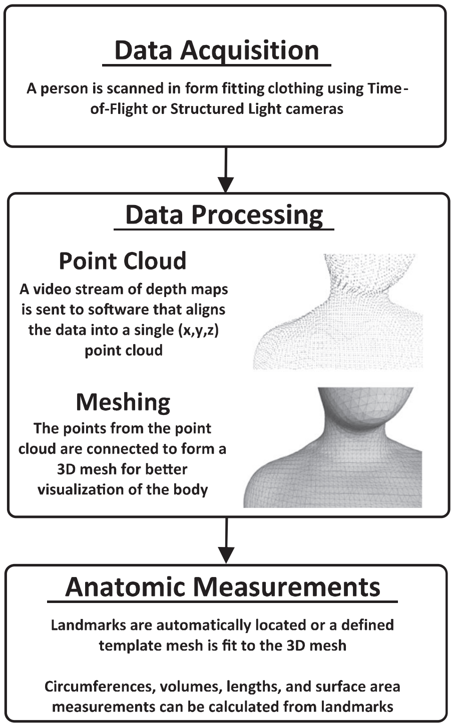

Fig. 1 Progression of steps from capturing the 3D optical scan to anthropometric data generation. The procedure sequence usually requires <1 min and requires form-fitting clothing to be worn for accurate measurements

occurs in three steps: data acquisition, data processing, and anatomical measurement (Fig. 1).

Data acquisition

In the following section, we describe the primary technologies that form the basis of accessible 3D whole-body surface scanners.

Structured light scanners

These systems utilize controlled visible or IR illumination patterns projected across the imaging field of view. One or more cameras measure deformations in the light pattern over objects (e.g., a human body) in the scene [5]. This deformation information can be used to calculate per-pixel distance between the camera and the object and thus create a depth image using geometric triangulation.

"Light coding," one of the most common implementations of structured light, was developed by PrimeSense (Tel Aviv, Israel) and since acquired by Apple Inc. (Cupertino, CA). PrimeSense devices include an IR emitter that casts a dot pattern across the field of view. This technology was implemented in the first-generation Microsoft Kinect (Microsoft Corporation, Redmond, WA). The Kinect was the first consumer-grade depth sensing device to achieve wide commercial success, which helped to spur development and lower technology costs in the field [6]. Scanners incorporating variations of this technology include the Fit3D Proscanner (Fit3D Inc., Redwood City, CA), the TC^2 NX-16, KX-16 and 19B ([TC]² Labs, Apex, NC) and the SizeStream SS14 and SS20 (SizeStream, LLC, Cary, NC). The Naked 3D Fitness Tracker (Naked Labs, Inc., Los Angeles, CA) and Shapescale (Shape Labs, Inc., San Francisco, CA) are other consumer-targeted scanners expected in 2018.

Time of flight (ToF) scanners

These systems also employ coupled scene illumination (visible light or IR) and image recording using charge-coupled device or complementary metal-oxide semiconductor (CCD and CMOS) sensors [7]. However, instead of measuring pattern deformations, ToF scanners quantify the round trip time (RTT) for reflected photons to reach the image sensor in order to calculate depth. Previously used primarily for architectural and surveying purposes, ToF technology has become more broadly accessible with the introduction of the second-generation Microsoft Kinect. This technology is also used in the Styku S100 (Styku, LLC, Los Angeles, CA).

Scanner technology comparison

In general, structured light sensors have seen the broadest development due to their use of relatively inexpensive components (i.e., IR illumination source, conventional red–green–blue image sensors). Several manufacturers offer IR structured light sensors priced on the order of hundreds of dollars. The technique is well characterized and has been shown to be highly reliable [8]. One disadvantage of structured light sensors is the challenge of multi-device interference when numerous sensors are used in parallel. Overlap between the projected illumination patterns from each sensor introduces noise in depth measurements [9]. Historically, ToF technology has been less accessible due to the need for specialized high-speed circuitry. ToF sensors typically offer high frame rates and true depth measurement at each pixel, whereas structured light scanners may require some degree of interpolation in areas not covered by the scene illumination pattern. However, ToF sensors typically have significantly lower spatial resolution than similarly-priced structured light sensors due to their vastly higher data readout speed requirements [10].

Other technologies, including laser line scanning and millimeter wave imaging, have also been applied to 3D body surface imaging. These technologies have been adopted mainly in specific industrial and security applications as their higher costs prohibit widespread use in health-oriented settings [11].

Data processing

The software used to create and measure 3D body images accepts raw depth frames from the camera(s). From each frame, a list of unconnected (x, y, z) points in 3D space, called a point cloud, is extracted. Multiple point cloud images are captured during the scan. These point clouds are aligned and merged together to create a single point cloud that combines surface shape information from many angles around the subject.

Multi-camera systems with a static configuration (i.e., the sensors and subject are fixed during a scan) rely on pre-scan calibration for point cloud alignment. A calibration object such as a row of spheres or a flat checkerboard pattern is imaged from all camera angles. Common landmarks are identified and used to calculate the position and orientation of each camera. This information is then used to orient point clouds from a subject scan in 3D space.

Systems with a dynamic configuration (i.e., the sensor[s] and/or subject move during a scan) rely on frame-to-frame matching algorithms [12]. The most commonly adopted strategies are the iterative closest point (ICP) algorithm [13] and its variants. Consecutive point clouds are continuously aligned in a way that maximizes inter-frame overlap and minimizes the distance between corresponding points. The result is a large combined point cloud that includes surface information all around the subject.

Assembled point clouds are often connected in a process called "meshing." This produces a closed polygonal surface, a 3D mesh, on which measurements and analyses can be more effectively performed. The mesh can also be efficiently visualized using common open source or commercial rendering software.

Anatomic measurements

Once a 3D mesh has been created, measurements of circumferences, widths, linear dimensions, and volumes require assignment of anatomical meaning to the mesh surface. Different scanners have their own accompanying proprietary body measurement software. Broadly speaking, however, the general measurement principles are similar [14, 15]. Major joints and limbs are identified as landmarks used to define body regions. The body point cloud or mesh is then sliced along various planes, often parallel to the floor or orthogonal to a limb. Convex hull or similar operations are applied to determine body circumferences and/or contour lengths.

Three-dimensional body scan measurement solutions were initially developed for custom apparel applications in industry or the military [3, 16]. Accordingly, commonly defined measurements are similar to those a tailor would collect such as the neck, arm and torso circumferences, and seat depth and width. Specific measurements are defined relative to identified landmarks within a body region. For example, waist circumference can be defined as the minimum circumference around the torso. Height can be measured as the distance between the floor and the point at the top of the head.

Some 3D body scanners allow user-customizable body measurements. More advanced methods involve registration of a defined template mesh to multiple acquired 3D body scans [17]. Given accurate registration, the template method allows for precisely defined custom measurements via simple point-to-point distance calculations across all scans.

Validation studies

With potential use in clinical settings or for large population studies [18], there is a need to validate the accuracy of anthropometric and volume measurements obtained by 3D optical body scanners. A potential issue in validating these measurements is that the "reference" standard flexible tape method can be highly variable [19] and there are often discrepancies in measurement locations [20]. A study conducted at the Mayo Clinic compared the variation of waist and hip circumference measurements obtained by 3D body volume index scanning system software (Plymouth Meeting, PA), which uses the TC^2 NX-16 scanner hardware, to inter- and intra-observer variation obtained manually and showed significantly less variation in the 3D scanner measurements [21]. Bourgeois, by contrast, found somewhat lower coefficient of variations (CVs) for repeated flexible tape circumference measurements compared to those by 3D optical imaging by the same highly trained observer (Table 1) [22].

Regional body volume measurement variation for the 3D systems was large compared to the reference DXA method in the study of Bourgeois et al. (Table 1) [22]. The repositioning that occurs between two DXA scans has minimal effect on the segmentation of the two-dimensional (2D) DXA image, while the slight difference in stance between two 3D optical scans can create more variation in the way the body is segmented for regional volume measurements. This could explain the larger observed variation in the 3D optical system measurements.

Most studies report good correlations between 3D optical anthropometric measurements and those obtained by reference methods. Ng et al. [20] found that the Fit3D Proscanner measurement outputs correlated favorably with

Table 1 Precision estimates for 3D vs. reference measurement methods

Measurement	CV (%)			
	Reference[a]	KX-16	Proscanner	Styku
Volumes				
Total body	0.2 ± 0.1	0.8 ± 0.6	0.7 ± 0.6	0.4 ± 0.4
Trunk	0.6 ± 0.5	1.0 ± 0.8	0.6 ± 0.9	0.3 ± 0.3
Left arm	1.5 ± 1.2	5.7 ± 4.4	3.9 ± 7.0	2.0 ± 1.6
Right arm	1.2 ± 1.2	4.1 ± 3.0	2.1 ± 4.8	2.4 ± 2.9
Left leg	1.0 ± 0.8	1.6 ± 1.7	2.4 ± 3.1	0.8 ± 0.9
Right leg	1.1 ± 0.7	1.6 ± 1.8	1.5 ± 3.3	1.4 ± 1.2
Circumferences				
Waist	0.2 ± 0.1	0.8 ± 0.8	0.8 ± 1.2	0.3 ± 0.4
Hip	0.2 ± 0.3	0.4 ± 0.4	0.4 ± 1.2	0.1 ± 0.2
Right mid upper arm	0.4 ± 0.2	2.6 ± 2.2	1.2 ± 1.0	0.8 ± 1.3
Right mid-thigh	0.2 ± 0.1	0.9 ± 0.9	0.7 ± 0.9	0.3 ± 0.5

[a] DXA is the reference method for volumes and flexible tape measurements are the references for circumferences. Duplicate scans were completed for 55 subjects and the CV was calculated for each. Results are shown in X ± SD. Coefficients of variation (CV) [22].

flexible tape and air displacement plethysmography (ADP) for circumferences (waist and hip) and total body volume, respectively. Soileau compared the TC^2 KX-16 system to the more costly Human Solutions laser scanning system and observed only small differences in measurement outputs for large linear measurements but greater differences for small volume and circumference measurements [23]. Good correlations were observed by Bourgeois et al. [22] for Proscanner, KX-16, and Styku S100 systems between circumferences, regional volumes, and total body volume measured by flexible tape, DXA, and ADP, respectively. Although the systems differed in imaging technology and hardware, they performed similarly in relation to reference methods and all showed between-method systematic differences that revealed discrepancies in cutoff points and measurement landmarks.

A number of studies have aimed to use 3D optical images to predict body composition components such as fat mass and fat-free mass (FFM). Ng et al. [20] observed strong correlations between predicted fat mass and FFM of the whole-body and body parts (arms, legs, and trunk) and corresponding measured values from DXA in 39 healthy adults. Milanese et al. [24] showed that a number of 3D-acquired anthropometric measurements correlated significantly with changes in fat mass and % fat quantified by DXA in obese women. Additionally, efforts have been made to predict body volume and body composition from 2D smartphone images [25, 26]. Fat mass predicted from height, weight, and measures obtained by a single 2D side view were not significantly different than fat mass measured by DXA [25].

Technical concerns

Hardware

Three-dimensional optical scanner cameras collect data from multiple angles of the body. The hardware either requires multiple cameras that are positioned around the body that companies such as SizeStream and TC^2 have implemented, or a mechanism for rotating either the camera or the subject being scanned. Systems with multiple cameras are often large and cost more than those with a single camera, which is why the systems designed by several companies such as Styku, Shape Labs, Naked Labs (Redwood City, CA) and Fit3D include a platform that rotates the subject 360°. This design can pose a problem for young children or the elderly who may have difficulty holding a fixed position during the rotation phase of the scan. The incorporation of handlebars into the rotating Fit3D system base reduces movement, but the resulting 3D image includes the handles that can introduce artifacts when estimating some surface dimensions as might be of interest in detailed analyses.

Landmarking

Systematic differences between 3D optical and standard method measurements are evident and likely due to landmarking and cutoff point discrepancies [20, 22]. These differences prevent direct comparison of 3D optical data to large preexisting datasets from multiple scanning systems. Additionally, standard anthropometric measurements from a flexible tape measure require identifying bony protrusions on the body. It is not possible to palpate these protrusions on 3D avatars, making the task of landmarking more challenging. Some investigators use markers placed on the subject's body to make the landmarks easy to detect; however, this method can lead to inter- and intra-observer error [19] and defeats the purpose of quickly and easily obtaining anthropometric measurements. The armpits and crotch are usually easy to identify on an avatar and segmentation of body parts can begin at these points [27], but landmark detection can be particularly challenging on scans of participants with high body mass index, where the armpits, crotch, and bony landmarks may be obscured by significant soft tissue. Further work is needed to create reliable methods to identify and extract standardized anthropometric measurements defined by the United States Center for Disease Control [28] with 3D body scanners so that databases created from 3D optical imaging devices can be added to existing datasets.

Avatar repair

The 3D scan and its reconstructed geometry often has holes or gaps in occluded or hard-to-view regions such as the top of the head, under the arms, or between the legs. These data gaps may impact the accuracy of anthropometric measurements. Therefore, performing 3D scan repair is necessary, especially when the missing regions are large. At present, avatar imperfections are often simply fixed using commercial 3D modeling software or general context-insensitive hole-filling algorithms, which are designed to repair general geometric objects by maximizing smoothness or minimizing curvature variance near the missing regions [29]. These strategies, however, result in the loss of geometric detail. More accurate repair can be obtained by using *context-based* completion strategies, such as application of self-symmetry [30] or template models [31]. Self-symmetry is useful unless both symmetric regions are missing. Template-based completion is generally robust in dealing with various types of holes, but its accuracy is affected by the correspondence between the template and the incomplete model [12, 17] and the availability of a high-quality template that has similar geometry to the incomplete avatar. Another content-based completion method that can overcome the above sensitivity to template selection is to use a statistical shape model (SSM) [32] built upon available digital avatar collections. SSMs more effectively encode both the individual geometry and shape variance of real human body shapes [33], and hence, could be used to replace the single body template and greatly improve the robustness of 3D body scan completion.

Applications

Digital anthropometry

Digital anthropometry is one of many biomedical applications for 3D optical scanning systems (Fig. 2). Anthropometric dimensions such as wait circumference and waist-to-hip ratio are frequently used for cardiovascular risk assessments, but these estimates often vary between observers [19]. Circumference measurements from 3D optical devices provide consistent measurements [21] and correlate favorably with the traditional flexible tape measurements [22]. Further improvements to these measurements will allow more accurate landmarking on subjects of all shapes and sizes along with measurements that reflect the location of traditional anthropometric sites described by the Center for Disease Control [28].

Body composition and shape evaluation

Traditional measurements of body composition in research settings may expose subjects to radiation or be costly and impractical when applied in clinical settings. With the development of inexpensive 3D optical imaging devices, obtaining measures of body composition in the clinical or even home setting can be safe, practical, and relatively inexpensive. Using statistical analyses and large datasets from a diverse range of subjects, statistical prediction models can be created from 3D optical scan measurements. These conventional prediction models can be created using measurements taken directly from the 3D optical images or with advanced analyses with variance captured by the method referred to as principal component analysis (PCA). PCA requires that the vertices on each 3D optical image represent the same location. To achieve this, marker points can be placed manually or automatically by software on the

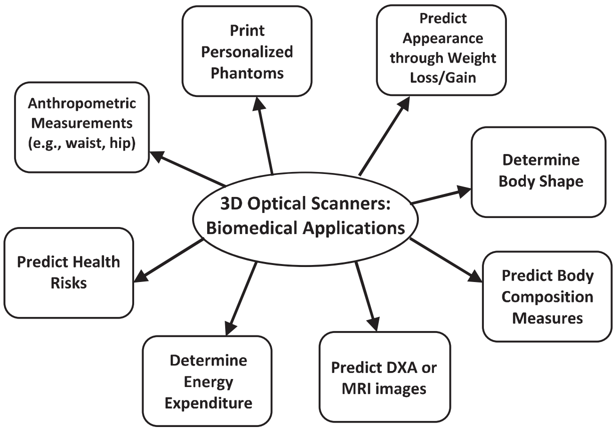

Fig. 2 Some biomedical applications of 3D optical imaging

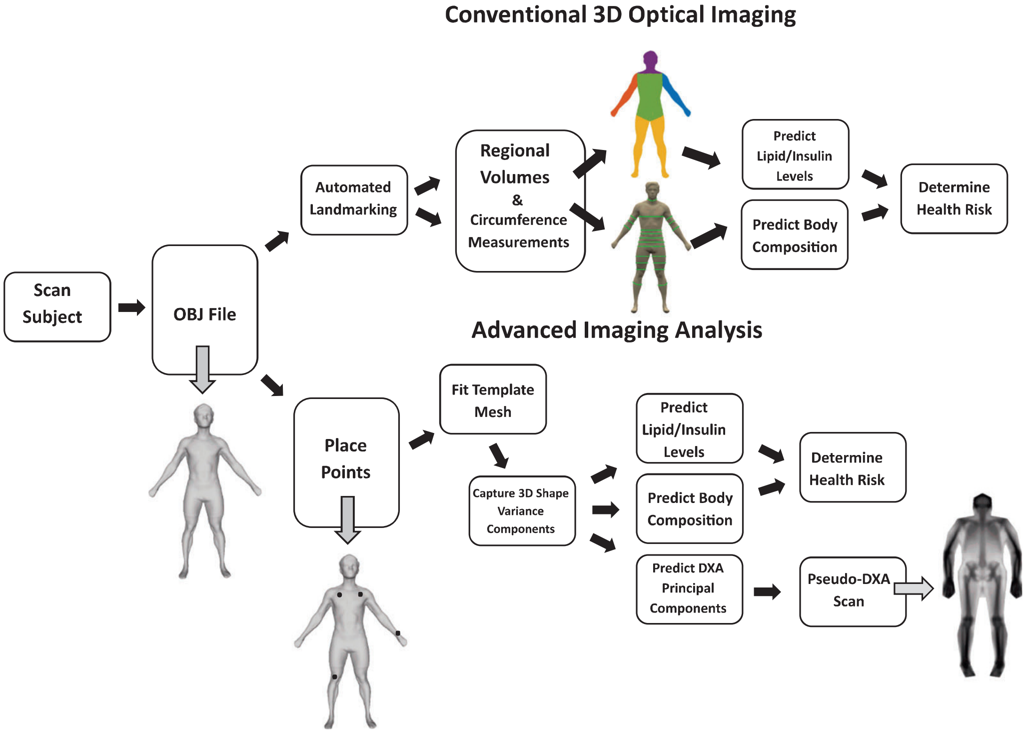

Fig. 3 Steps taken from the 3D optical scan to several potential applications. At present most commercial systems use conventional modeling approaches to predict body composition, blood biomarkers, and health risks. A more advanced approach in development uses mathematical techniques and placed marker points to capture 3D shape variance and to then link these subject characteristics to blood biomarkers, body composition, and health risks. Methods such as these can also be used to develop pseudo-DXA and MRI scans. DXA dual-energy x-ray absorptiometry, OBJ Wavefront 3D object

image and a template mesh can then be aligned [17]. From there, values for the principal components can be obtained and used to predict blood marker levels, body composition, or principal components for DXA or MRI that can then be used to predict the appearance of a “pseudo-DXA” or “pseudo-MRI” scan from the 3D optical image (Fig. 3).

In two recent elegant studies [18, 34], Loeffler-Wirth and colleagues show how body shape differences across children and adults captured with a 3D laser system can be allocated to distinct phenotypes that have relevance to human growth and health. These kinds of applications will be transformative in the search for genes that regulate body size and shape.

Development of body composition and shape indices will be facilitated in the future by the availability of large carefully collected datasets that combine the efforts of multiple centers using similar scanning devices and/or universal software that delivers results from identical body landmarks. Two examples of large currently available 3D optical datasets that include conventional and digital anthropometry measurements are SizeUSA ($n > 10{,}000$) [35] and the Civilian American and European Surface Anthropometry Resource Project, “CAESAR” ($n > 4000$) [36].

Health assessment

Similar to body composition approaches, statistical methods can be used to derive predictors of health risk through 3D optical imaging measurements. Moreover, new shape indices can be developed from 3D scans and these shape estimates have the potential to predict health outcomes. This capability of 3D optical imaging arises from the vast number of measured body surface dimensions that allow for the first time discovery of detailed health risk phenotypes far beyond the “apple-pear” classification now in use.

Conclusions

Anthropometry is one of the oldest methods used to assess the size and shape of the human body [33]. Calipers, weight balances/scales, tape measures, and calibrated rulers are among the tools that have been used for centuries to assess bodily dimensions and remain in use today. A rapid and exciting transformation, however, is now taking place that moves anthropometry to the modern age with the introduction of digital anthropometry. This transformation is so rapid and profound that the field has yet to accommodate all of the new ideas and concepts brought in by this technological revolution. Our review provides a broad coverage of how these systems operate and their potential value, not only in research settings, but in the clinic and even the home. This burgeoning field is one to watch closely for new innovations in the coming years.

Acknowledgements We acknowledge the input provided by optical device manufacturers on the operational details of their respective systems.

Author contributions SBH, BB, BKN, MJS, XL, and JAS drafted the manuscript; SBH and JAS provided necessary logistical support; SBH, BB, BKN, MJS, XL, and JAS edited the manuscript for intellectual content and provided critical comments on the manuscript.

Funding This work was partially supported by two National Institutes of Health NORC Center Grants P30DK072476, Pennington/Louisiana; and P30DK040561, Harvard; and R01DK109008, Shape UP! Adults.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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