PART II – AN OVERVIEW OF 3D BODY SCANNING TECHNOLOGY

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Preface

PART I described the key concepts of traditional anthropometric measurement. While this method has remained the 'gold standard' for population surveillance for many decades, a new technology has emerged that has the potential to revolutionise the way anthropometric data are measured. The purpose of PART II was to introduce 3D body scanning by focusing on different scanning technologies, 3D measurement validity, its applications, and a summary of the potential challenges. Knowing the strengths and limitations of this technology is crucial for 3D anthropometric survey planning.

Overview

Throughout this book, 3D body scanning is discussed as a tool that captures anthropometric data. This Part (II) summarises what 3D body scanners are, the applications, types of body scanning systems, associated software, validity, reliability, and challenges.

Keywords

3D body scanning, scanning applications, laser line, structured light, reliability, scan processing.

Introduction

What is 3D body scanning?

A whole-body scanner is an optical 3D measuring system that produces a digital copy of the surface geometry of the human body. The purpose of the 3D scan is to capture an outside surface of the body using optical techniques in tandem with light sensitive devices without the need to touch the body.

Commercially made full-body 3D body scanners were available since the late 1990s [44]. They were initially made for anthropometric research, the clothing industry (individual and tailored clothing) [45], the entertainment industry (special effects in movies), computer animation and medicine (e.g. prosthetics and plastic surgery) all with the purpose of measuring the human body [46]. As the technology developed, it was used by western countries for systematic anthropometric population measurement for clothing and textile design. Current 3D body scanning systems, designed by different manufacturers, differ in the number (and quality) of cameras, scanning range, light sources, and also in the sophistication of the accompanying computer programs used for visualization and measurement analysis [25].

Why Measure Physique Using 3D Scanning?

The introduction of 3D scanning reduced the need to have consistent physical contact with the body. However, surface markers can be placed on the body as reference points to check. Scanners vastly increase the range of possible measurements and create a permanent record of body size and shape that can be archived and revisited. This is advantageous for traditionally ‘uncomfortable’ measurements such as crotch height (where some anthropometric protocols require the measurer to place an anthropometer on the inferior-lateral aspect of the male genitalia). Even if participants are scanned in tight fitting garments, the measurements can still incur a systematic bias.

The availability of 3D whole body scanners provides the ability to take rapid simultaneous measurements, and automated data extraction and analysis. It has the potential to revolutionise surface anthropometry [47]. With these new capabilities, it is possible to easily quantify dimensions such as projected frontal areas, limb volumes, limb cross-sectional areas, and abdominal cross-sections and volumes. It is also possible to quantitatively describe shapes and shape changes. The main driver behind 3D scanner development has been the apparel industry. The technology can enable the possibility of creating garments on demand, tailored to optimize fit for each individual.

Three-dimensional body scanning has synergies with human factors, where humanoid manikins can be rescaled using the extracted measurements and animated to perform specific tasks and to interact with the built environment. For example, using 3D manikins in engineering software suites such as SolidWorks© (Dassault Systems, Vélizy-Villacoublay, France). These techniques are already being employed in military research and in the design of transportation and operator workspaces [47].

Applications

Clothing and apparel

The clothing and apparel industry invest heavily in the development and improvement of 3D body scanning technology, due to its many implications. For example, 3D body scanning can be used to record many clothing measurements such as sleeve in-seam and waist girth [48, 49]. The measurements can then be matched to existing clothing size characteristics, allowing clothing manufacturers and retail outlets to choose appropriate inventories for their target population [48, 49].

Health and medical

The health and medical sector regularly use 3D scanning and modelling technology. The 3D scanner can be used to create implants, gloves, body shape, and prosthetics [50], holograms for human body imaging and garment creation [51]; detecting scoliosis in patient's back shape or scanning human feet to detect anomalies [52-54]. Body scanning technology is useful for measuring body surface area [55, 56] which is useful for determining dosages of many drugs (e.g. anticancer drugs [57]), the design of restraints [58] and developing shape indexes to monitor secular trends in body shape and limb volumes [59].

Ergonomics and human factors

The use of 3D body scanners is widely used in the field of ergonomics and human factors. Body scan images can be imported, via human modelling programs, into virtual environments which have been scanned or created in computer-assisted design (CAD) applications, or in hybrid environments. With appropriate motion capture or task descriptions, the virtual bodies can be animated to perform specific tasks in a naturalistic way in a digital environment [60]. The user can also simulate whether the actions or tasks can lead to physical injury due to working in uncomfortable or awkward postures. Examples of popular DHM software are CATIA Human Builder (v5, Dassault Systems, Vélizy-Villacoublay, France), JACK (SIEMENS, Munich, Germany), V5 HUMAN and Realistic Anthropological Mathematical System for Interior comfort Simulation (RAMSIS, Human Solutions, Kaiserlauten, Germany) [61].

Sports science

Previous studies have shown that 3D body scanning is a useful tool in sports science research. The technology enables researchers to take multiple measurements of a larger number of athletes at any given time [30, 62] before various sports events. It also helps sports and exercise scientists to understand the physique specialisation for specific sports.

Other sports applications exist. For example, body scanners have been used to assess principal moments of inertia in elite athletes from gymnastics to ski jumping [63, 64], investigate how females' breast area measurements change, when wearing compression sports bras during running [65], inform 3D design and development of swimwear [66], develop sizing systems for football boots in the National Football League (NFL) [67] and assess performance errors in a golf swing [68]. It is also possible to quantify dimensions such as projected frontal areas (a critical factor in aerodynamic sports such as cycling and skiing)[69], limb volumes (which are strong predictors of sprint performance), limb cross-sectional areas (proportional to strength), and abdominal cross-sections and volumes (predictors of risk of diabetes and cardiovascular disease[70]) [71, 72]. It is possible to quantitatively describe shapes (and hence facilitate garment and equipment design) and shape changes (and hence describe what happens to the body during dietary and exercise interventions) [73].

3-D body scanners

Typically, 3D whole body scanners consist of at least one light source that projects a line or pattern on to the participants' body. Cameras record the image of the reflected light. On fixed laser scanners, the light source and camera both move in tandem (vertically) on the scanner pole. The images are then processed by computer software that is specifically designed to analyse the depth structure of the body surface (Figure 6). There are five common types of body scanners: laser line, structured pattern, multiview camera systems, millimetre wave systems and infrared systems. Each of these systems are discussed below.

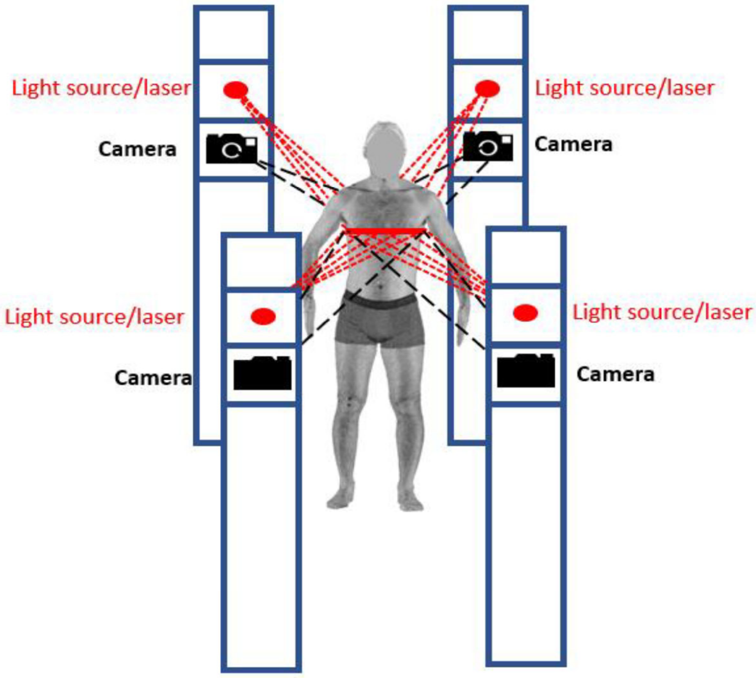

Figure 6. Typical layout of a 3D body scanner. The light source and camera are both mounted on a pole system. This is an example of a laser line system.

Laser line systems

Laser-based scanners use class 1 (eye safe, non-ionising) lasers to project light in an array beam onto the body surface from different sides. Multiple digital cameras capture the position of the projected light and software reconstructs the body contour of the acquired image via a mathematical algorithm which is based on triangulation. The system captures a series of surface points (typically between 700,000 and 1,000,000) with Cartesian coordinates.

Most systems house the sensor (laser) and cameras in four columns which are synchronized to scan the body from head-to-toe [47]. The column system is then enclosed in a curtain or fabric area for participant privacy.

The most popular laser line systems are the *WBX* or *WB4* (Cyberware, California. U.S.), *Vitus Smart XXL* (Human Solutions Ltd, Kaiserlauten, Germany) and the *Bodyline Scanner* (Hamamatsu Photonics, Hamamatsu, Japan) systems. The Cyberware WBX system shows good reliability and notably used in the movie industry as well as the Civilian American And European Surface Anthropometry Resource (CAESAR) survey which is often regarded as the first and largest civilian anthropometry survey to date [74].

The Vitus Smart XXL system is made in Germany and advertised as a portable device containing 4 poles (each with a laser scanning unit). These systems are often used in the Garment industry but are also used extensively by the US, Canadian, Australian and New Zealand Defence Forces.

Structured light

A cheaper alternative to laser scanning is white-light scanning. This technology is based on the use of projectors. They project a sequence of white-light stripes consisting of dots, bars, or any other light patterns on to the participant. The light pattern deforms as it falls on the body, and the resulting deformation is captured via cameras.

Structured light scanning systems are generally faster than laser line systems but take longer to process or extract measurements [48, 75]. The laser line system could also be considered a structured light pattern, but it has a strong time component because of its line sweep and therefore considered as a different class of light system. Compared to laser line, structured light systems have less moving parts which increases the life cycle of the scanning system while also being safer for the participant [76] and more portable.

Some scanners in this category are fully automatic and autonomous. For example, the *NX-16* (TC², North Carolina, U.S.) system can be operated by the participant or person inside the scanner who presses a button located on holding levers inside the scanning cabin. Recorded messages and video presentations inside the cabin give additional information and instructions [77]. The TC² system utilises multiple optical lenses to produce a 3D surface geometry of the body. It can scan the whole body in approximately 8 seconds and produces 140 body measurements [27].

The *Triform* or *TriBody*™ (Wicks and Wilson-Crowley Company, Hampshire, UK) uses white light to capture the 3D scan data in 12 seconds using 8 camera views. Multiple stripes of white light are used to capture the 3D shape of the participant. The light contains no visible rays, lasers, or other radiation. The resulting images are analysed automatically using the TriBody software that produces a 3D point cloud model containing approximately 1.5 million Cartesian (XYZ) co-ordinates [27]. Other popular models include the Mephisto EX-pro and Gotcha systems (4ddynamics, Antwerp, Belgium), 3D *Mega Capturor II* (InSpeck 3D, Montreal, Canada), *Cartesian* (SpaceVision, Tokyo, Japan) and *SYMCAD* (TELMAT, France) systems. More recent models include the Size Stream® (TAL Group, North Carolina, US), Fit3D ® (Fit3D, Inc, California, US), the hand-held portable Artec L scanner (Artec Group, Luxembourg) and the home-based Naked Labs® Scanner (Naked Labs, San Francisco, US).

Multi-view cameras

Multi-view systems produce a 3D image that is acquired from two or more cameras. A stereo-camera records two images at the same time from a different viewpoint. Next, sophisticated matching algorithms determine corresponding points in the two images to compute their 3D coordinates, resulting in a dense 3D points cloud [77]. The advantage of a stereo-camera system is that no laser line or light pattern is transmitted, and no sunlight or extraneous light artefacts can disrupt the pattern. However, using the line or patterns enables a 3D image with higher resolution and accuracy [76, 78]. An example of a system that uses this technology is *Flex 8* (3dMDbody, Atlanta, U.S.).

Millimetre wave

This class of body scanning technology is like X-ray machines found at various airports around the world. For increased privacy, the participants are not required to remove any clothing.

Active scanners use the reflection patterns of millimetre waves that have been projected on the body [76, 78]. The ultra-high frequency radio waves penetrate participants clothing, reflects off the body, and are then collected by a transceiver and processed [77]. Passive scanners process the millimetre (or radiation) waves that are emitted by the human skin [76, 78]. Millimetre waves pass through most clothing ensembles but not the skin. Thus, the shape of the body can be captured without undressing. This offers an advantage in time and effort, but may introduce an ethical problem because of the explicit nature of the resultant image which views the body as naked [76, 78].

Infrared depth sensing technology

Infrared (otherwise termed as depth sensing) body scanners use nonvisible wavelengths. This technology is relatively new compared to previous body scanner models. Some infrared systems utilise what is known as 'Time of Flight' technology. This refers to the time that an infrared ray takes to travel to the nearest object in its field of view, and back to its sensor [79]. This technology is more cost effective and portable compared to other scanners. Research suggests that this technology is not as accurate as larger, more expensive fixed scanners [44]. However, models such as the recent Styku® S100 (Styku, Los Angeles, US) model demonstrated nearly perfect reliability with negligible systematic and random errors in a recent study [72]. The earliest (and most recognisable) form of this technology is the Microsoft Kinect sensor on the Microsoft Xbox console (Microsoft Corporation, Redmond, WA, US). The technology is currently being used in today's high-end smartphones for taking depth-sensing photographs. For example, portrait mode which 'blurs' images in the background while accentuating the image of the object in focus.

Measurement extraction software

In addition to the hardware required to capture 3D scans, there must also be software dedicated than can interpret and extract body measurements. Some of the more commonly used systems are Cyberware's *DigiSize*, Headus' *CySize* (manual digital extraction) (Figure 7), Hamamatsu's *BodyLine Manager (discontinued)*, and Human Solutions' *ScanWorX* (offers both manual-digital and automatic-digital extraction). These programs can extract a large number of traditional measurements based on a known landmarking system or algorithm [21, 48]. These types of software can also measure contour distances, cross-sectional areas, surface areas and volumes [80].

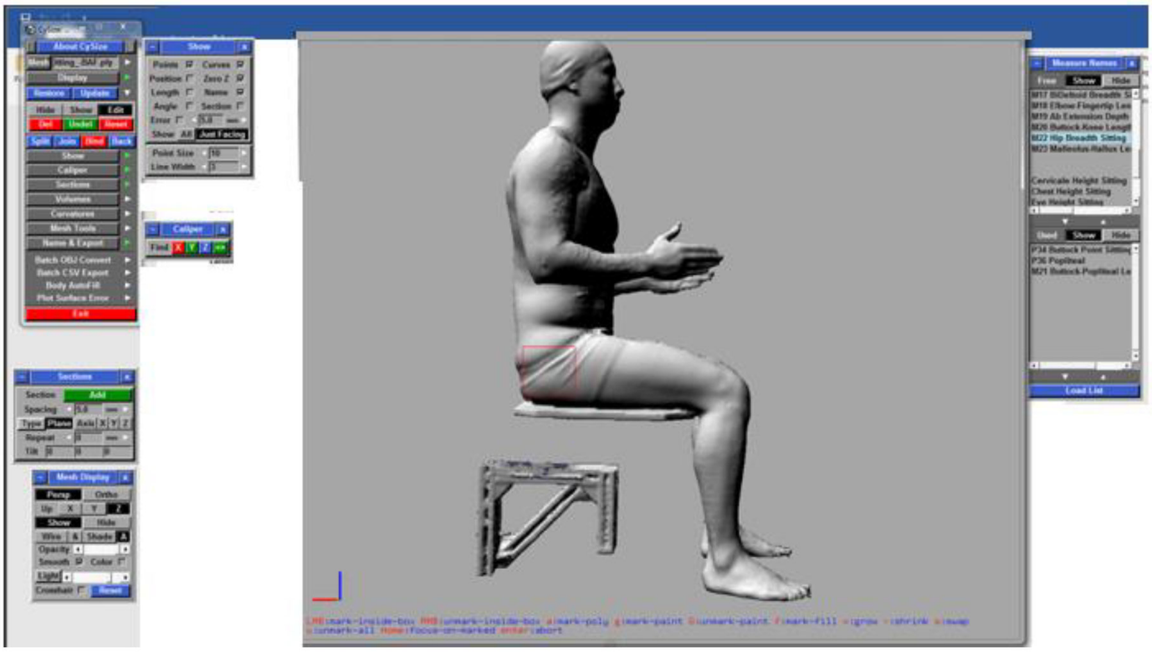

Figure 7. Headus' CySize output. Landmarks are placed physically, then identified and labelled digitally.

Like traditional anthropometry, 3D body scanning measurement extraction software requires landmarking. It would be sensible for all software to have a universal standard for identifying landmarks. Unfortunately, this is not the case as most software suites use different or ill-defined landmarks [21].

With regards to measurement extraction software, manufacturers may provide information about 'what' landmarking systems they use, but the process of 'how' the algorithms create measurements in line with those standards remain unclear due to commercial sensitivities. For example, the measurements in the automatic measurement function within *ScanWorX* (Figure 8) is based on a combination of ISO 7250:2010 and ISO 8559:1989 standards. Unfortunately, there is no validation research available assessing how well this software performs these measurements or what body types provide optimal landmark recognition and measurement accuracy.

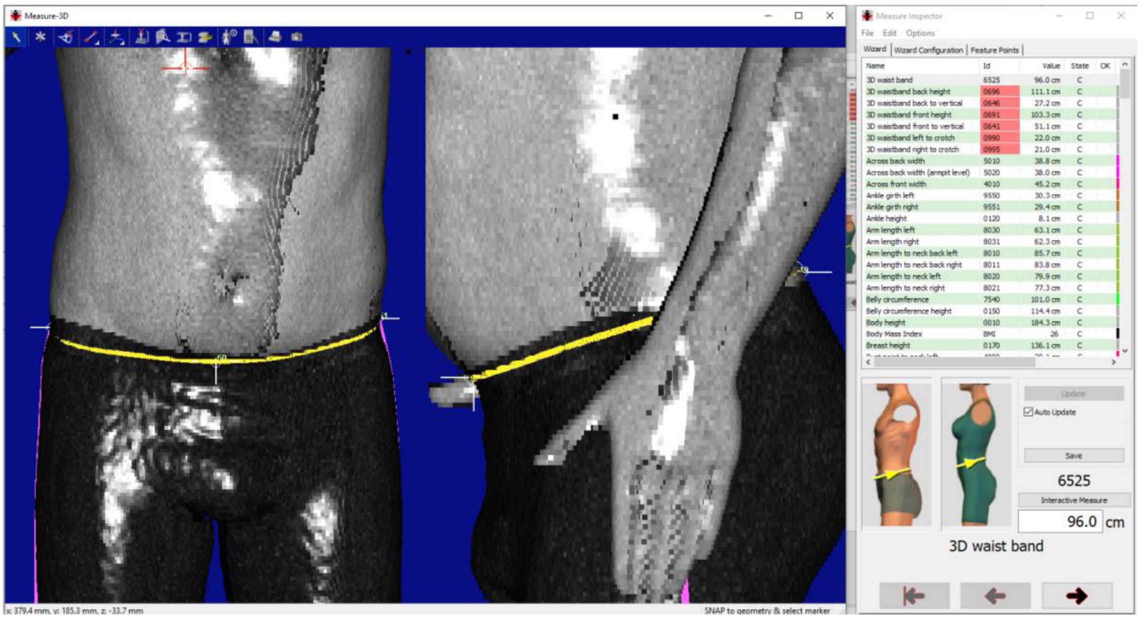

Figure 8. ScanWorX (Anthroscan) output showing the automatic measurement function.

Whatever system is used, it is imperative that the software can identify landmarks correctly. According to Buxton, Dekker [81] landmarks can be identified in three ways:

- Automatic landmark recognition (ALR) – this refers to extraction without human intervention using two methods:
  a. Template matching – The software creates a base template with all known measurements marked out. The template is then deformed to match the scan data. The system then extracts the XYZ co-ordinates of the known measurements.
  b. Curvature matching – The software detects known measurements based on surface shape. An area of the scan is isolated then a search is performed to identify a point based on slopes and gradients.
- Digital landmark recognition (DLR) – this refers to a user identifying locations and placing landmarks on the completed scan.
- Physical landmark recognition (PLR) – the user places landmarks (adhesive balsa triangles or reflective discs) on the participant before they are scanned. Using colour and texture recognition capabilities, the software can automatically identify these landmarks in XYZ space. The software can also be programmed to 'zone in' on special landmarks by recognizing features of the landmarks (e.g., zoom in on all objects that are 30 mm in diameter).

Validity

Many studies have investigated the reliability and/or validity of scan-derived measurements compared to more traditional (e.g. ISAK) systems. Body scanners have been shown to measure body volumes, circumferences and lengths more rapidly and accurately than traditional techniques [82]. Jaeschke, Steinbrecher [83] discovered strong correlations between automatic and traditional measurements for body height; however, the automatic measurements generally 'overestimated' most other measurements. Choi and Ashdown [84] demonstrated that automatic-derived measurements provided significantly larger values using traditional measurements for waist circumference. However, the differences in waist circumference may be the result of skin compression experienced during the traditional measurements [83]. Wells, Treleaven [40] found that traditional measurements were more accurate at predicting buttock girth and hip girth, while Glock, Vogel [59] found that body height, waist, upper arm, calf and hip circumference showed high validity for both traditional and body scanner methods. Zhang, Zheng [85] compared measurements obtained from the NX-16 TC^2 scanner with the equivalent tape measurements for the mid-arm, thigh, and ankle circumferences. All showed relatively high correlations (0.89, 0.90, and 0.93, respectively).

Wells, Stocks [86] compared the NX-16 (TC^2 scanner) with traditional measurements for chest, waist girth, waist width, waist depth, knee girth and calf girth on 1,484 children. All traditional measurements were successful, but the 3D scans were successful in only 71% of the children. The unsuccessful scans were attributed to body movement (inside the scanner during scanning) or the lack of calibration at the start of each data collection day [39].

The accuracy of the body scanned measurements can be influenced by procedural and postural issues. For example, Kuehnapfel, Ahnert [87] observed systematic differences for body height, waist girth and hip girth measurements. This was attributed to measurement errors with regards to participant posture and movement artefacts. Lu, Wang [88] found that scanning participants with their palms facing backwards reduced the differences between scan-derived measurements and equivalent traditional measurements. Lu and Wang [89] also found that that the scan-derived measurements can achieve satisfactory accuracy and precision if the variation caused by the participants scan posture is controlled. Adding supporting devices within the scanner helped ensure the participant maintained a consistent posture during the scan. The anthropometrist should be skilled in posturing the participant and prompting the participants with regards to breathing during the scan (e.g. hold their breath).

Challenges

The following will discuss several shortcomings of 3D body scanning with respect to collecting anthropometric data.

Cost

Compared to traditional techniques, body scanning systems are expensive. The costs of various scanning systems in 2013 ranged from US$10,000 to US$240,000 [76]. In comparison, a standard Anthropometry kit cost US$1,539 (e.g. RossCraft Centurion Kit http://www.thehumansolution.com/centurion-kit.html).

Identification of bone landmarks

Some landmarks will not show on digital scans as they may be obscured by skin, adjacent limbs, and superficial tissue. Examples are the acromion and the tibiale laterale, particularly in participants with significant muscular build. To help with identification, bone landmarks stickers or specialised markers are placed on the selected site to aid in post scan analysis [90].

Size, portability, and space requirements

Most whole-body scanners are bulky systems which require an area to suit its dimensions. The Vitus XXL scanner, for example, requires a height clearance of almost 3 m and a floor area of approximately 2.5 m^2 x 2.5 m^2. This is not ideal for typical office workspaces. In general, when compared to traditional techniques, 3D body scanners need a larger space to set up, take longer to physically set up, require competent trained scanner operators (unless the participant controls the scan like the TC^2 system), and time is needed for calibration and re-calibration.

Postures

Traditionally, anthropometric measurements are taken when the body is in anatomical position or like this position (Figure 9). For example, placement of the participant's head in the Frankfort plane, having arms relaxed by their side, both palms facing anteriorly, fingers extended towards the ground, and thumbs facing away from the body. This technique may not be useful for 3D scanning as the posture may obscure certain parts of the body from being scanned [30].

Many systems have a strict requirement for adopting certain postures in the scanner. Participants are required to adopt a static posture for a short amount of time. Automatically derived measurements can be dependent on the quality of the posture within the scanner. For example, some measurements are calculated based on Cartesian (XYZ) co-ordinates on the body. An incorrect posture can lead to a shift in these co-ordinates. A classic example is body height. When standing in the Frankfort plane, the system may define height as the highest point on the head. If the participants posture was too far forward, then this point on the head may change, resulting in a different measurement.

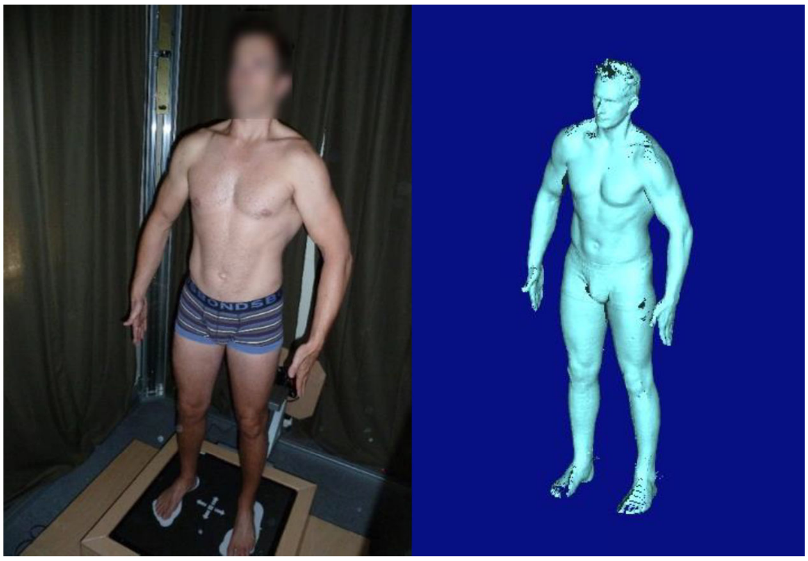

Figure 9. An example of a scan posture within the Vitus XXL. Body postures vary from participant to participant and if not controlled, is a potential source of measurement error.

Missing data due to shading

There are points on the body where the laser cannot detect. Examples include the armpit and crotch area, sides of the torso, and inside of the arms and legs [30]. There are problems with defining a person's correct height due to the amount of hair that rises above the scalp. Some scanners cannot differentiate between the hair and head [90]. Parts of the head can appear missing if reflected light from hair is not captured by the cameras, potentially making it impossible to identify the vertex, and therefore capture height.

Landmark extraction

Earlier we presented three methods in which landmarks can be identified using measurement extraction software (ALR, DLR and PLR). All have their limitations which must be considered prior to developing a survey protocol or procedures:

- The ALR method does not recognize variations in shapes and sizes [91] and only has pre-set measurements (e.g. it is difficult to add ad-hoc measurements) [81]. It is also difficult to locate landmarks accurately without palpation [30].
- With DLR, is the difficult to identify bony landmarks (e.g. acromion) on participants who may have a lot of adipose tissue or musculature on that area [81].
- With PLR, some landmarks require additional features to make them stand out in the scan. For example, one cannot use a flat disc landmark to identify the left-acromion, but instead, opt for a raised land marker to highlight this point to the user [91].
- PLR has additional time burden, feasibility issues, and the invasive nature of touching the participant.

Security and confidentiality

Another shortcoming of 3D body scanning revolves around the security and confidentiality of the participants scan images. For example, scan images are stored on computers which, if not appropriately protected, is potentially open to 'cyber-attack (e.g. 'hacked') through various connections to the internet [75]. People are also potentially identifiable from facial/bodily features or unique markings such as tattoos.

Summary

There are many uses for 3D body scanners today. From an anthropometric data collection perspective, 3D scanners can collect more measurement information on participants in much less time. The accuracy of 3D scanning is improving over time as the level and sophistication of technology increases. Furthermore, 3D body scanners are becoming more portable and accessible to the public (e.g. hand-held scanners). Despite several shortcomings, 3D scanners still deliver functionality that is simply not possible with traditional techniques, such as recording shape and volume information, and the ability review measurements retrospectively for verification and error control. Part III will now focus on how 3D body scanners contributed to various military anthropometric surveys.