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Potential Application of Temporal 3D (4D) Scanning to Ergonomic Design: State-of-the-art and its Perspectives

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Objective: This study aimed to provide a comprehensive review of literature on 3D and 4D scanning technologies and potential applications of 4D scanning techniques in ergonomic product design.

Background: Dynamic anthropometric data is needed to consider the changes of human body dimensions while using a product in the product design process.

Method: A literature review was conducted on 34 papers which were selected by the process of title screening, abstract screening, and full text screening.

Results: 3D scanning techniques can be classified into three catalogs: laser, structured light, and stereo photogrammetry. Though still challenging, 4D scanning systems self-built or commercialized have been developed. 4D scanning systems have been applied to understanding foot-shape changes and foot kinematics during walking, analyzing human facial movements, and evaluating the fit of sportswear design.

Conclusion: 4D scanning systems have great potential in design and evaluation of ergonomic products.

Application: The literature survey results can be of help to understand 4D scanning systems and their applicability in ergonomic design and evaluation.

Keywords: Temporal 3D scan, 4D technology, Stereo photogrammetry, Dynamic 3D anthropometry, Ergonomic design

1. Introduction

Anthropometry, the study of the measurement of the human body, is important in ergonomic product design. Anthropometric data have been collected conventionally by measuring the lengths, widths, depths, and circumferences of the human body using tape measures and calipers. However, the conventional measurements are limited values for product designers to perceive the shapes and overall sizes of the human body. In 1970s 3D scanning of human body using light projection technique appeared (Jones and Rioux, 1997). Although it is time demanding to analyze the scanned data, the 3D scanning technique provides more detailed and accurate measurement of the size and shape of human body. Currently, 3D scanning techniques for human body have been dramatically developed. With the revolution of computation power, 3D body scanning of the human body and analysis of the scanned data become easier and faster. Human body scan data have been used for various design applications including special protective gears for aircraft pilots (Bogović et al., 2018), facial mask design (Lee et al., 2013a; Morrison et al., 2015), bus seat design (Jung et al., 2016), sizing systems (Ball, 2009; Hsiao, 2013; Zhuang et al., 2010), human models (Ellena et al., 2016; Guan et al., 2012; Jung, 2018; Lee et al., 2013b; Li et al., 2017).

Dynamic anthropometric data are needed for better ergonomic product design to consider the changes of human body dimensions while using a product. Human body shape and size usually change in using a product, which can affect the usability of the product. For better usability, the dynamic changes of human body shape and size need to be considered in designing a product. For example, in sportswear design, not only the statistic anthropometric data of the human body but also the dynamic freedom of a specific motion need to be considered to avoid uncomfortable pressure to the body due to motion. Currently, in computer-aided sportswear design, athletes are first asked to imitate static postures in sport activities and then their postures are scanned by a 3D body scanner to establish their 3D body digital models for accurate anthropometric measurement of the athletes for better sportswear fitting (Choi and Hong, 2015; Chowdhury et al., 2012; Nasir et al., 2015). However, the imitated postures may differ from the actual postures in the sporting activities. Furthermore, extreme body motions usually occur in a few seconds in sporting activities. Therefore, it is hard to obtain all dynamic anthropometric data from static 3D scanned postures.

Recently, researchers have started using temporal 3D (4D) scanning to acquire dynamic anthropometric data for better product design. Nasir et al. (2015) studied skin deformation during hand movements for designing functional sports gloves to protect hands during sporting activities as well as ensuring hand functions such as grip and dexterity. Choi and Hong (2015) studied lower body skin deformation during knee joint movements for designing a functional sportswear. They scanned each subject at four different knee angles to analyze skin deformation by comparing the position changes of landmarks on the skin. Novak et al. (2014) studied the changes of foot shapes during walking for better footwear design using two optic cameras and one laser projector at a frequency of 30 frames per second (fps). Researchers have also studied contact stresses and stress-induced deformations between users and products in use for better product design and user experience. For example, Lee et al. (2018) measured the contact stress between the face of a pilot and the seal area of a pilot oxygen mask and the deformation of the seal area to evaluate the usability of the mask.

Temporal 3D (4D) scanning techniques have become available in recent 10 years as the computation power and image processing algorithms have advanced dramatically. Previously, image acquisition and rendering were the most difficult parts in developing an efficient 4D scanner since it was hard to process large volumes of data in a short period of time. Nowadays, with the revolution of computation power of personal computer (PC) and advancement of image processing algorithms, measurement of dynamic anthropometric data has become possible by scanning and rendering human body motions at a designated frequency such as 60 fps with a high image quality (Popat et al., 2009). The present study reviewed 3D and 4D scanning techniques and their applications in ergonomic product design and suggest potential applications of 4D scanning techniques for better ergonomic product design.

2. Literature Survey Methods

In the present study a literature survey was conducted using the ScienceDirect database (https://www.sciencedirect.com) and the customers' publication database from 3dMD website (http://www.3dmd.com/3dmd-customer-research) with key words "3D motion scanning OR 4D motion scanning OR 4D dynamic scanning" and "ergonomic OR anthropometry OR design". A total of 617 papers were found as the search results. Then, two reviewers independently checked the titles and abstracts of the searched papers and selected relevant papers according to the following criteria:

(1) Anthropometry study using 3D/4D techniques
(2) Ergonomic design using 3D/4D techniques
(3) Development of 3D/4D scanning techniques

A total of 104 papers were screened by title screening, and then a total of 51 papers by abstract screening. After checking the full text of each of the screened papers, a total of 34 papers were lastly selected for review in the present study; of the papers, 4 papers were related to 3D/4D scanning techniques and the rest to the applications of 3D/4D scanning techniques.

3. Results

3.1 Core techniques of 3D/4D scanning systems

3.1.1 3D scanning techniques

Many researchers have reviewed 3D scanning techniques for various applications. Lane and Harrell Jr (2008) summarized 3D scanning techniques for orthodontology. Popat et al. (2009) discussed 3D scanning techniques for facial movement analysis. Daanen and Ter Haar (2013) reviewed 3D whole body scanners for garment industry. O'Connell et al. (2015) summarized 3D scanning techniques for breast surgery.

3D scanning techniques can be classified into three categories: laser, structured light, and stereo photogrammetry (see Table 1). First, laser scanning has the longest history among the three techniques and is achieved by geometry triangulation, as shown in Figure 1. In 3D laser scanning, a laser beam is projected onto the surface of a scan target. The surface of the scan target scatters the laser light and then the scattered light is collected by a detector at a known triangulation distance from the laser. The position of a surface point is then determined by calculating its x, y and z coordinates using trigonometry. Laser scanning can provide an accurate 3D scan model of a static target on a band-to-band basis, but it is not appropriate for scanning a person in motion due to its slow scanning speed (Lane and Harrell Jr, 2008).

Table 1. 3D scanning techniques and their applications

Authors	Year	Application	Scan area	Scan purpose	Technique	Scanner information		
						Model	Company	Country
Choi and Hong	2015	Sportswear design	Whole body	Multi-posture	Laser scanning	Whole body scanner	Cyberware Inc.	USA
Nasir et al.	2015	Glove design	Hand	Multi-posture	-	INFOOT scanner	I-Ware Laboratory Co. Ltd.	Japan
Chowdhury et al.	2012	Ski jumper design	Whole body	Multi-posture	Structured light scanning	NX-16 scanner	$[TC]^2$	USA
Chen et al.	2015	Medical	Ear	Static	Stereophotography	3dMD™ Cranial system	3dMD	USA
Weinberg et al.	2016	Anthoropometry	Face	Static	Stereophotography	3dMD™ face system	3dMD	USA

Table 1. 3D scanning techniques and their applications (Continued)

Authors	Year	Application	Scan area	Scan purpose	Technique	Scanner information		
						Model	Company	Country
Morrison et al.	2015	Functional mask design	Face	Static	Stereophotography	3dMD™ face system	3dMD	USA
Khatam et al.	2015	Medical	Breast deformation	Multi-posture	Stereophotography	3dMD custom built system	3dMD	USA
Niezgoda et al.	2013	Mask evaluation	Face	Static	Stereophotography	3dMD™ face system	3dMD	USA
Eggbeer et al.	2012	Prosthese design	Face	Static	Stereophotography	3dMD™ face system	3dMD	USA
Park et al.	2009	Anthoropometry	Whole body	Static	Laser scanning	Cyberwear WB4	Cyberware Inc.	USA
Seo et al.	2013	Skin deformation	Whole body	Static	Laser scanning	Whole body Color 3D scanner	Cyberware Inc.	USA
Sforza et al.	2013	Anthoropometry	Face	Static	Laser scanning	FastSCAN Cobra	Polhemus Inc.	USA

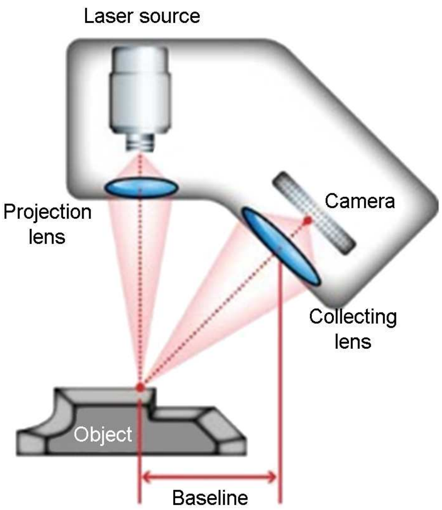

Figure 1. A schematic of 3D scanning laser triangulation technology (adopted from http://3dscanningservices.net/blog/need-know-3d-scanning)

Next, structured light scanning projects white light patterns, such as grid, dots, or stripes onto a subject and simultaneously captures the subject with a camera calibrated with the specifics of the projected light pattern (Lane and Harrell Jr, 2008) as shown in Figure 2. By recording the distortion of the projected light pattern, the captured images are processed to generate the subject's surface data. Then color texture information is registered to the surface data. The structured light scanning can be used for capturing a relatively small area. For scanning a large area, such as the face (from ear to ear) of a person, it is challenging to obtain an accurate

3D model since a 2-viewpoint capture is required in this case. For the 2-viewpoint capture, one light pattern from a viewpoint can be overlapped with the other light pattern from the other viewpoint. To avoid the interference of the two light patterns, images of the subject have to be taken in sequence. The sequential capture can increase scanning time and therefore can be detrimental to data accuracy while scanning a moving human subject (Lane and Harrell Jr, 2008).

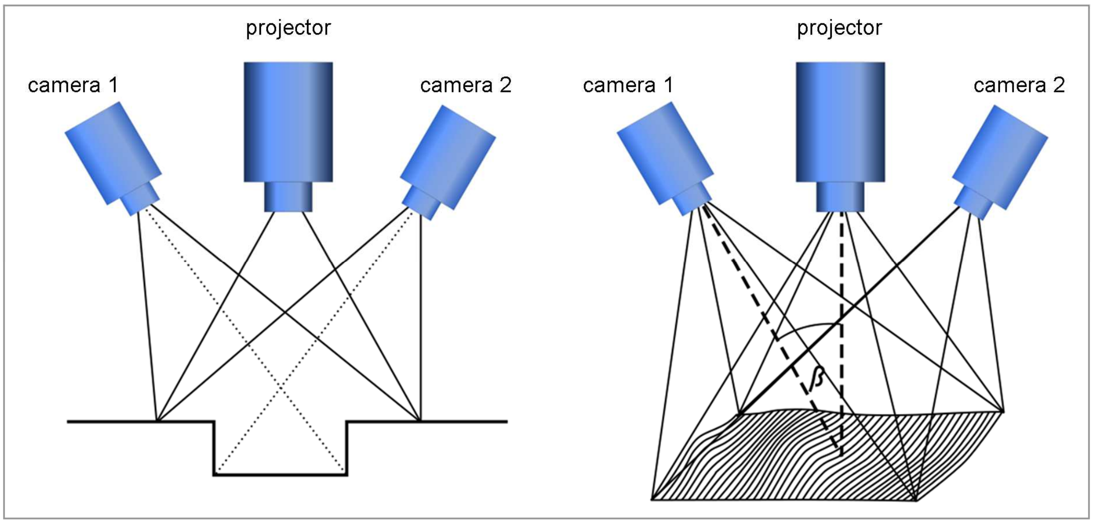

Figure 2. A schematic of a 3D structured light scan technique (adopted from https://www.wikiwand.com/en/Structured-light_3D_scanner)

Lastly, stereo photogrammetry creates 3D models of a subject based on the fundamental principle of human eyes imaging. As

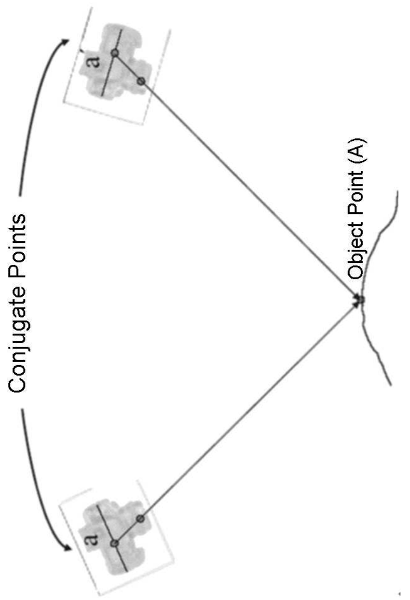

Figure 3. A schematic of 3D stereo photogrammetric technique (Adopted from Cheng and Habib (2007))

presented in Figure 3, two photographs of the subject are taken at a distance similar to the distance of a person's eyes to create a stereo pair of the subject with depth information recorded at the same time. Then stereo triangulation algorithms are used to identify and match the surface features of the two photographs to generate a composite 3D model and the color texture information is lastly mapped onto the model. An accurate geometry of the subject can be produced using patterns on the surface of the subject. The patterns can be either the natural patterns or landmarks on the surface of the subject such as skin pores, freckles, and scars on the face of the subject, which is known as passive stereo approach, or the combination of the natural patterns or landmarks on the surface of the subject and a projected unstructured light pattern, which is known as active stereo approach. The passive approach requires a careful control of the lighting conditions while scanning to minimize ambient spectral reflections, while the active approach can eliminate ambient spectral reflections and capture darker surfaces with the help of the projected unstructured light pattern.

3.1.2 4D scanning techniques

Though 3D scanning techniques are mature, 4D scanning is still challenging. 4D (or temporal 3D) scanning can be considered as a continuous 3D scanning of a subject within a time period for capturing dynamic information of the subject. Especially for scanning the full body of a person in a complicated motion, synchronized scanning images captured from different locations and viewpoints are needed. To freeze the motion, the capture speed of scanning images must be fast and a sophisticated algorithm is needed as well to generate a composite 3D model from synchronized captured images.

3dMD has successfully launched its 60-fps full-body 4D scanning system (Figure 4) based on the active stereo photogrammetry approach. Machine-vision cameras are used in the 3dMD scanning systems to achieve a high capture speed for scanning the human body surfaces in motion. Other 4D scanning systems which were self-built (Kimura et al., 2008; Novak et al., 2014; Thabet et al., 2014) or commercialized have been developed using different scanning techniques as presented in Table 2. Compared to 3D scanning systems, 4D systems can largely improve time efficiency and accuracy in dynamic anthropometric data acquisition. Furthermore, the natural motions of a subject can be captured by a 4D scanning system.

Figure 4. 3dMD full-body 4D scanning system in max-plank institute (https://ps.is.tuebingen.mpg.de/pages/4d-capture)

Table 2. 4D scanning systems

Authors	Year	Scan area	Technique	Scanner information		
				Model	Company	Country
Novak et al.	2014	Foot motion	Laser scan	MV-03M2M-CS	Point Grey Firefly	Canada
Al-Anezi et al.	2013	Face motion	Stereophotography	DI4D	Dimensional Imaging Ltd.	UK
Van den Herrewegen et al.	2014	Foot motion	Structured light scanning	DynaScan4D	ViALUX	Germany
Popat et al.	2009	Face motion	Stereophotography	3dMDface™ system	3dMD	USA
Thabet et al.	2014	Foot motion	Coded structured light scanning	4D foot Reconstruction system	University of Dundee	UK
Kimura et al.	2008	Foot motion	Coded structured light scanning	Self-built system	National Institute of Advanced Industrial Science and Technology	Japan

3.2 Applications of 4D scanning systems

The most common application of 4D scanning is foot scanning during walking to understand foot-shape changes and foot kinematics for better footwear design as shown in Figure 5. Novak et al. (2014) developed a 4D scanning system for 3D foot-shape measurement during walking at a speed of 30 fps based on a laser scanning technique. The system consisted of a walking platform with a glass plate inserted and four scanning modules to capture the foot shape from the top, bottom, and side views.

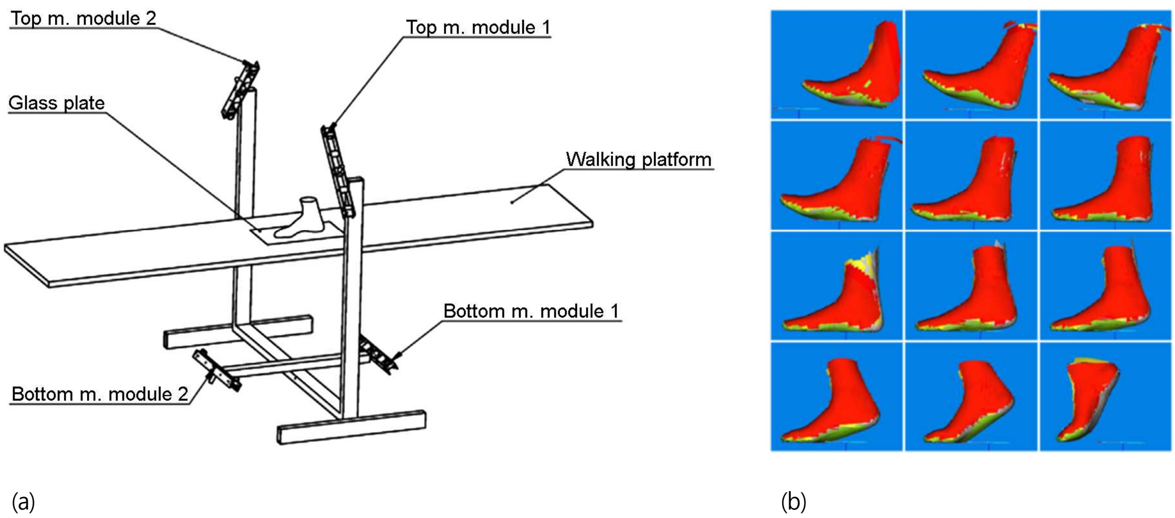

Figure 5. Temporal 3D foot measurement system: (a) foot-shape measurement during walking, (b) 3D foot shapes captured during gait (adapted from Novak et al., 2014)

From the captured foot shape, foot dimensions including width, height, girth, and section orientation can be analyzed to study various effects on foot-shape change such as a bare or shod foot and the shoe's stiffness condition for better footwear design. Van den Herrewegen et al. (2014) studied multi-segmental foot kinematics during walking by the Dynascan4D scanning system consisting of five scanning units (ViALUX, Germany) at a capturing speed of 32 fps. They concluded that compared to the traditional marker-based technique, the 4D scanning technique provided easy and fast measurements of multi-segmental foot kinematics and could be used for calculation of other parameters such as shape deformation and segment delineation.

4D scanning has been applied to the analysis of human facial animation. Al-Anezi et al. (2013) scanned facial animations of 32 subjects using the DI4D scanning system (Dimensional Imaging Ltd., Glasgow, UK) at a scanning speed of 60 fps with 23 anthropometric landmarks marked on the face. They compared the locations of the automatically tracked landmarks with those of the manually digitized landmarks and found a small mean distance (< 0.55 mm) between them.

The application of 4D scanning to sportswear design has started. 3D static scanners are mainly used to generate 3D surface

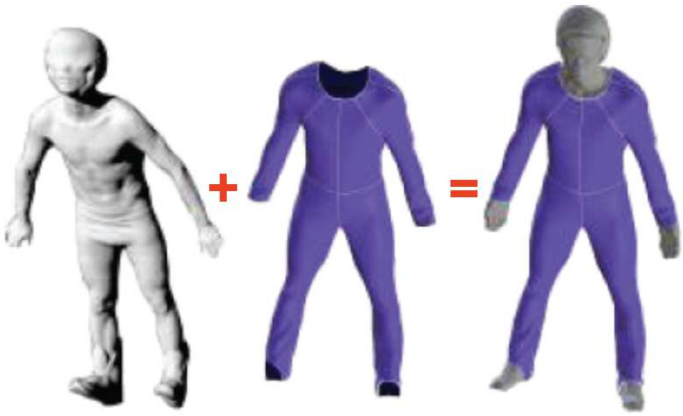

Figure 6. Sportswear design using 3D scanning techniques (Chowdhury et al., 2012)

(a) (b)

Figure 7. 4D scanning systems in major sportswear manufacturers: (a) Nike (http://www.3dmd.com/tag/nike/) and (b) Under Armour (http://www.3dmd.com/category/application/anthropometric)

models of athletes at different static postures and anthropometric data are analyzed from the 3D surface models for sportswear design. Chowdhury et al. (2012) described their methodology for a computer-aided design of a high performance ski jumping suit from the 3D scanning of an athlete body (Figure 6). However, 3D static scanners have difficulties in capturing a continuous and natural motion while doing a sport. For better sportswear design, major sportswear manufacturers, such as Nike and Under Armouor have started applying 4D scanning techniques to their product design as shown in Figure 7.

3.3 Potential applications in ergonomic design

4D scanning has great potentials in ergonomic studies and product designs that require dynamic anthropometric data. Since 4D scanning captures the changes in shapes and sizes in accordance with human motions, it can allow ergonomists to simultaneously examine the motions and deformations of the human body. Therefore, the dynamic anthropometric data measured by a 4D scanning system can be utilized to better fit a product to the human body. For example, dynamic hand anthropometric data can help understand the relationships between kinematics and skin deformation of human hands and can be applied to improve the realistic simulation of digital human models for product design and evaluation. In addition, dynamic face data can be used in designing ergonomic face-wearing products such as oxygen mask, eye glasses, and head mounted display by considering the effects of face anthropometric measurement due to speaking and body motions.

4. Discussion

4D scanning systems can measure dynamic anthropometric data that are highly demanded for modern product design. Since the human body is not rigid, it changes its shapes, sizes, and postures during the use of a product. An ergonomically designed product needs to accommodate those changes for better usability. Therefore, dynamic anthropometric data during the product usage need to be acquired and analyzed for designing the product. Previously, several static product-use postures were usually captured by 3D scanners to measure dynamic anthropometric data. However, the data acquisition process takes time and a subject has to maintain a static posture during each 3D scan. Furthermore, the acquired data are not continuous and adequate for product design. 4D scanning systems can solve these problems by capturing a continuous product-use motion at a designated capturing speed (e.g., 10 or 60 fps) to provide sufficient 3D surface models of the subject. Practitioners can select data from any frame they are interested in to analyze for product design.

Accurate and automatic tracking of the locations of anthropometric landmarks marked on the body surface of a subject can facilitate the analysis process of the dynamic anthropometric data captured by a 4D scanning system. Manual digitization of landmarks is a tedious task for practitioners, especially for 3D models captured at a high frequency. With the help of automatic tracking of the locations of anthropometric landmarks, changes in body dimensions such as width, length, circumference, area, and volume can be automatically measured, which can dramatically reduce time and effort for analyzing dynamic anthropometric data.

4D scanning systems have great potentials in ergonomic design and research, although the systems have not been widely adopted. Since 4D scanning provides a precise record of 3D human body surface models in motion, one of its major applications would be garment design, especially sportswear. Like Nike and Under Armour who already started applying 4D scanners to their sportswear design, more sportswear manufacturers will pursue 4D scanners to provide better product designs. Besides, 4D scanning systems can be applied to protective suit design such as flight suit, spacesuit, and protective suit for front-line workers. Eventually, the systems will be applied to fashion garment design (Daanen and Ter Haar, 2013). Except garment design, 4D scanning systems can be used for ergonomic design of other products such as hand-held products and facial products. 4D scanners can help understand the entire product-use process including the interaction between a subject and a product and the deformations of human body and product. Lastly, 4D scanning systems can be used for ergonomic evaluation of products and work environments. The systems can be used to monitor the product-use process and subjects' activities in a specific work environment to help disclose potential problems with the product design.

Since the present study is focused on the applications of 4D scanning systems to ergonomic product design, other applications including medical areas and computer graphics are not addressed. In the near future, 4D scanning systems will be used for ergonomic design and evaluation of products.

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