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Systematic Review

Emerging Roles of 3D Body Scanning in Human-Centric Applications

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Abstract: The three-dimensional (3D) body scanning technology has impacted various fields, from digital anthropometry to healthcare. This paper provides an exhaustive review of the existing literature on applications of 3D body scanning technology in human-centered work. Our systematic analysis of Web of Science and Scopus journal articles revealed six critical themes: product development, healthcare, body shape, anthropometric measurement, avatar creation, and body image. Three-dimensional body scanning technology is used to design and develop ergonomically coherent and fit products. In addition to its application in clothing, footwear, and furniture, its non-invasive and rapid image-capturing capabilities make it an attractive tool for clinical diagnostics and evaluations in healthcare. Given the exponential growth of digital interfaces, 3D avatars and body forms have gained popularity, and scanners facilitate their growth and adoption. The creation of anthropometric databases for various populations, from children to boomers and from adolescents to pregnant women, has been made possible with body scanning technology and has been helpful in several applications. This review highlights the growing importance of 3D body scanning technology in various contexts and provides a foundation for researchers and practitioners seeking to understand its utility and implications.

Keywords: anthropometry; avatar; body perception psychology; clothing development; ergonomics; healthcare

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1. Introduction

Digital representation of the human body in 3D has an emergent interest among academic and manufacturing communities due to its inherent advantages. Apart from esthetic art and photography, historically, healthcare diagnostic procedures and the clothing design process of apparel manufacturing significantly used human body dimensions [1], obtained predominantly using calipers and tape measures [2]. As technological advancements occurred in digital electronics, high-fidelity imaging using photo-sensitive chips came into existence, but it was still limited to 2D and was sufficient for several applications. With further research in image registration and numerical computation approaches, systems capable of translating 2D images into 3D representations using simultaneous imaging systems were realized. This led to the development of 3D scanning systems that focused on human body imaging.

Around 1895, X-rays were discovered, leading to the visualization of internal bone structures and setting the foundation for today's imaging technologies [1,3]. Following X-rays, computed tomography (CT) and magnetic resonance imaging were also invented and commonly used for 3D internal images [4]. While MRI and X-rays are highly regarded for internal imaging, especially in healthcare settings, digital body imaging today is a

very broad umbrella covering multiple technologies, including X-ray imaging, magnetic resonance imaging (MRI), computed tomography (CT) scans, ultrasound imaging, optical coherence tomography (OCT), dual-energy X-ray absorptiometry (DEXA), thermography (infrared imaging), photogrammetry, and 3D body scanning. Each body imaging technology has its own specific purpose and application, making it suitable for its respective diagnostics or analytical tasks.

Of the various imaging tools, 3D body scanning technology has shown versatile potential in producing 3D body images and can be a more generic imaging system to subserve medical diagnostics and product development. Unlike conventional anatomic imaging utilizing X-rays, MRI, and CT scans, which work from the inside out, 3D scanning yields practical surface measures [5]. The evolution of 3D body scanners began with their inception in the early 1960s, when the early scanners relied on the coordinated use of projectors, cameras, and lights [6]. Software and computational hardware were still nascent during that time. As laser scanning technology stabilized in the 1970s, 3D topographic mapping of fields and lands emerged [7]. Around 1985, scanners began to use white light and lasers for objects, as well as human body parts, and were able to improve the speed and accuracy of image capturing [6]. As computational power and data-storing technologies evolved, whole-body 3D scanning technologies using laser scanning, patterned light projection, and stereophotogrammetry became the industry standard [8]. Concurrently, the scanners shifted from manual operation to automatic imaging systems. In the late 1990s, scanners that use millimeter waves and infrared waves began to find their application in 3D scanning [9,10].

Technology-wise, laser 3D body scanners for human-centric applications predominantly rely on (a) triangulation, (b) time-of-flight, and (c) structured-light approaches [2,11]. Triangulation is a sensing approach where a sensor array receives a reflected laser stripe incident on an object emitted from a laser source, and the relative positioning between the source and the receiver is known. Depending on the distance between the laser source and the object of measurement, the reflected light can reach different positions on the sensor array, which can be used to compute the spatial position of each point on the object. By repeating the process with various positions and registrations, the 3D point cloud can be reconstructed. In time-of-flight scanners, the distance between a laser source and the object is computed using the time taken between incidence and reception, in the order of picoseconds [11,12]. The structured light approach uses triangulation but with a laser or a white light pattern instead of a beam. The pattern can be dots, bars, or other patterns, covering a larger area/volume, making these scanners notably faster compared to the stripe scanners. Stereophotogrammetry uses multiple cameras simultaneously via computational methods, determines each of the specific points on an object across the cameras (called matching), and estimates the position of those points in 3D space, thus creating a 3D point cloud [8,12,13]. Millimeter and infrared wave scanners use electromagnetic waves of 1 to 10 mm and 700 nm to 1 mm, respectively. Based on the features of the reflected wave, millimeter wave technology is used to classify human tissue versus other objects and is finding its application in airport security. Likewise, the infrared scanner computes the 3D shape similar to the laser-based scanner, except that it uses the waves of the infrared band [10,14–16]. More details on the technological aspects of 3D scanners can be found in these references [2,9,11,17].

Three-dimensional body scanning technology is becoming increasingly widespread across diverse fields, as it has been known for its non-invasive nature, affordability, and efficiency. Cheaper hardware, high computational throughput, portability, and submillimeter accuracy are other features that make this technology useful. Although 3D scanners cannot substitute X-rays or other internal imaging systems, they can augment the latter

whenever anatomical images at more surface levels are adequate for a study. For example, X-ray fluoroscopy can be augmented with 3D body scanners to study mandibular movements, reducing the total radiation exposure. While lead aprons and radiation shields were sometimes provided as precautionary measures against human radiation exposure [3], the development of non-invasive physical imaging was one of the many significant concerns that 3D body scanner technology could address. Being non-invasive, these 3D body scanners are safer, easier to use, and can rapidly produce digital images of the human body [18–20]. In comparing 3D scanning with conventional approaches, this method has fewer impacts on patient users' stress; it makes the quality higher and more precise.

In addition to facilitating anatomical feature acquisition of the human body, 3D body scanning's ability to capture detailed anthropometrical data has extended its application areas. Since the 1980s, 3D body scanning technology has been used in anthropometric measurements in clothing, product development, and healthcare [21]. Capturing detailed anthropometrical data on a person's body (e.g., shape, size, texture, color, and skin area) has become safe and efficient with 3D body imaging. These scanners can provide measurements without physical contact by generating highly accurate 3D images in seconds [4]. The 3D scanners typically use either optical light (white or blue) or laser light to capture the images of human anthropometry. Accurate and repeatable anthropometric measurements and body shapes are another crucial dimension of 3D scanners, leading to a better understanding of human body shapes and accurate size charting. Perhaps for this reason, they are employed in diverse fields such as healthcare, apparel manufacturing, and ergonomic product development [22].

This study aims to conduct a systematic literature review on various fields' diverse applications of 3D body scanning technology. Through thematic analyses, this study explored the diverse uses of 3D body scanners, from healthcare and fitness to apparel design, ergonomics, and digital animation. This paper identified six common themes to comprehensively understand how 3D body scanning is employed in different contexts and highlights its potential for future applications.

2. Materials and Methods

2.1. Data Sources

This systematic literature review (PRISMA) studied 3D body scanning applications across various fields. In July 2024, two databases (i.e., Scopus and Web of Science) were searched with the keyword "3D Body Scanning," resulting in 9094 studies listed. Since this study focused on the past decade, articles published between 2014 and 2024 were considered. After applying filters for the period, article type, language (i.e., English), and keyword relevance, 444 articles were retained. After eliminating 39 duplicate articles, 405 articles remained in the article pool for further screening (Figure 1).

2.2. Selection Process

The articles were screened in two rounds. First, titles and abstracts were reviewed to assess their relevance to the study's scope. Then, the contents of the articles were examined to determine if they aligned with this review's primary theme: how 3D technology has been used in digital body imaging and its application. Articles that did not use the human body or subject were excluded. For instance, the article titled "A case study for 3D scanning-based quantitative quality control during key stages of composite small craft production" was removed at the screening stage since this study focused on improving quality control for small boats in shipyards using 3D scanning and was not related to the human body. This process reduced the initial pool to 195 articles. Of these, 75 were excluded as they were unrelated to the study's focus. The remaining 120 articles (Figure 1) were selected for

thematic synthesis and qualitative analysis, which were further subjected to the exclusion criteria, resulting in a total of 112 articles.

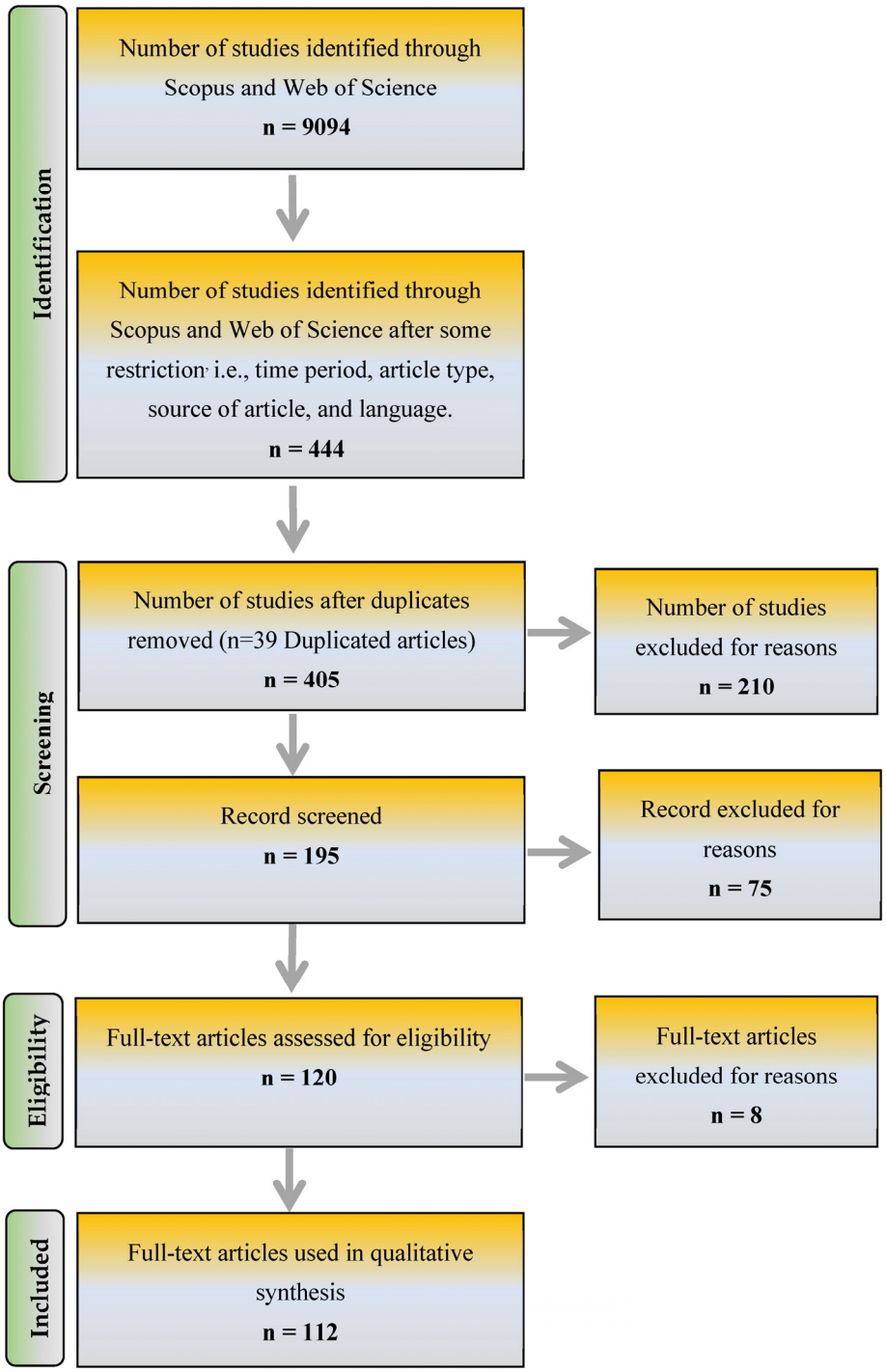


Figure 1. PRISMA flow diagram addressing screening and the article selection process.

2.3. Inclusion and Exclusion Criteria

The primary criteria were shaped based on two critical aspects during the full-text analysis. First and foremost, consideration was given to studies investigating anthropometric body dimensions in specific applicable domains, e.g., healthcare. Second, articles that aimed to improve the quality of 3D body scanners were excluded. In other words, studies exploring the reliability and validity of the 3D body scanner, developing a new 3D body scanner, or reconstructing an existing 3D body scanner were disregarded. For example, the study "Virtual anthropology? Reliability of three-dimensional photogrammetry

as a forensic anthropology measurement and documentation technique" was removed since it focused on assessing the reliability of the 3D body scanner as a tool for producing body dimensions and illustrating body images. The inclusion and exclusion criteria are as follows.

2.3.1. Inclusion Criteria

1. Research specifically uses 3D body scanning technology to assess human body images or body dimensions across various domains.
2. Articles addressing 3D body scanning for anthropometric analysis, human body modeling, and applications directly involving human subjects or human body images.
3. Studies published between 2014 and 2024 to ensure the inclusion of recent applications of 3D body scanning technologies.
4. Articles published in English to maintain consistency in language and analysis.

2.3.2. Exclusion Criteria

1. Studies' primary focus is on non-human applications of 3D scanning, such as non-anthropometric product design or industrial uses of 3D body scanning unrelated to human body assessments.
2. Studies focusing on developing, improving, or testing the reliability or accuracy of 3D body scanning or associated software without addressing human body measurements or direct human applications.
3. The exclusion of conference abstracts, opinion pieces, or editorials on the applications of 3D body scanning technology.

Figure 2 illustrates the distribution of selected articles within the specified time frame (i.e., 2014–2024). Most articles retained for thematic analysis were published within the past five years, specifically between 2019 and 2024.

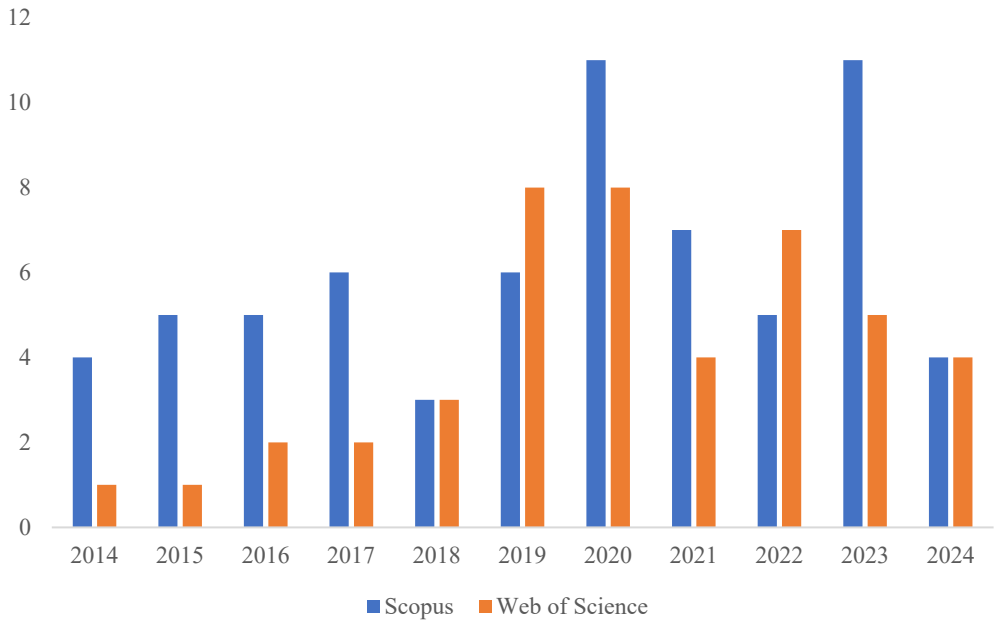


Figure 2. Year-wise distribution of selected articles for thematic analysis.

3. Review Findings and Discussion

Three-dimensional body scanning technology, being an advanced tool capturing the human body, has enhanced human body-centered analysis across various fields, such as product development, body shape, healthcare, anthropometric measurements, avatar creation, and body image. This technology facilitates tailoring products that better suit

individual body types, with major implications for clothing, medical assessments, and consumer satisfaction. Product development has been enhanced from improved apparel sizing and patternmaking to ergonomically designing seats using human body dimensions. It supports non-invasive body imaging for enhanced prediction and assessment options in healthcare. Three-dimensional scanning technology enables the capture of anthropometric data from various subject populations. The gaming and avatar creation industries then utilize this precise information to create realistic and functional digital avatars featuring diverse populations. Finally, body image-related research benefited from 3D body scanning by studying perceptions of body appearances and potentially following how people interact with their body images. This systematic review retrieved six main themes as the primary application of 3D body scanner technology to study human body information. These six themes are body image, body shape, product development, avatar creation, anthropometric measurement, and healthcare (Figure 3). The themes and possible sub-themes retrieved from this systematic study are presented in the following sections.

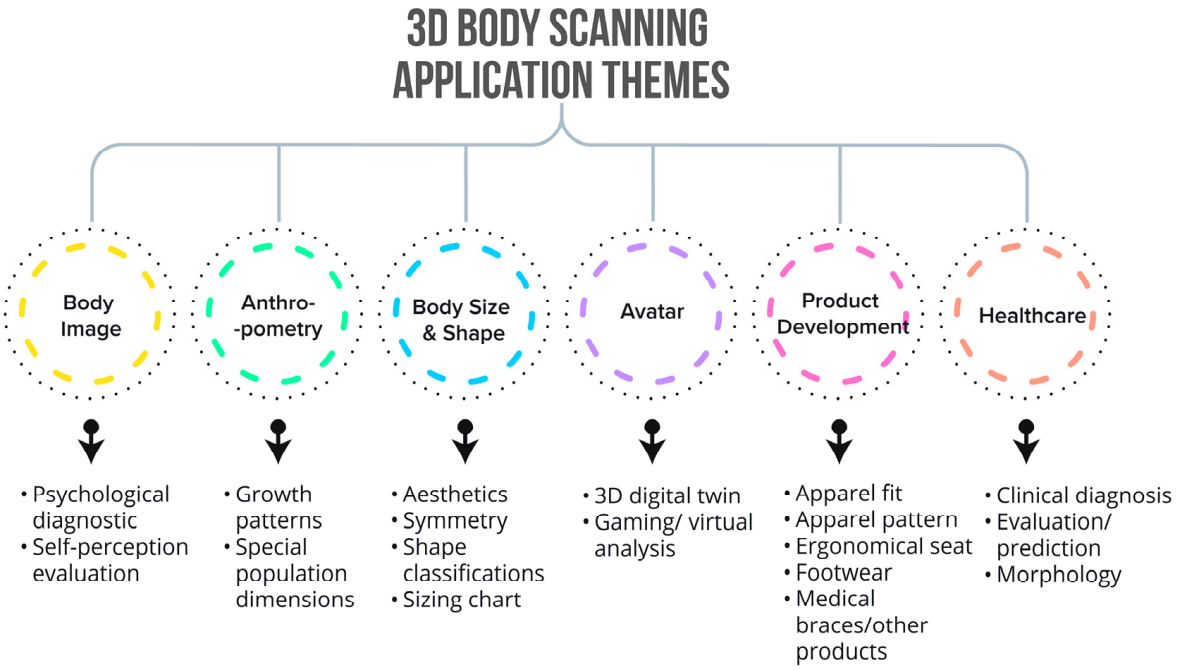


Figure 3. Themes and sub-themes highlighted from this systematic study.

3.1. Product Development

The application of 3D body scanning technology has been instrumental in industries like apparel, furniture, and medical wear by allowing designers and manufacturers to create products that fit individual body shapes. This technology improved pattern-making practices, body size charts, and functional apparel design in the apparel field. In furniture design and protective equipment, ergonomic design is facilitated by capturing the entire 3D anthropometry. This thematic analysis highlights the potential of 3D body scanning in product development to improve personalization, safety, and comfort.

3.1.1. Pattern-Making in Apparel

Three-dimensional body scanning technology has altered pattern-making in the apparel industry, from offering standardized sizing to customized clothing solutions with higher accuracy and speed. This transition meets consumer demands for a better fit and comfort with increased consumer satisfaction.

Several studies addressed the impact of 3D body scanning on pattern development, focusing on various aspects of garment fitting and accurate body measurements. Wagner et al.

developed a new classification system for men's underwear patterns by identifying significant anthropometric differences between Chinese and Russian males [23]. Similarly, Su et al. explored creating individualized pant patterns using 3D scans of female participants, showing that unique body measurements directly influence pattern design [24]. Wu et al. addressed traditional sizing issues by introducing a new torso classification for women based on 3D scanning measurements, leading to eight new torso subtypes for improved dress fit [25]. Bespoke shirt patterns have also been enhanced by using 3D scanning technologies, resulting in a better fit compared to traditional ready-to-wear options [26].

Concerning pattern-making in the apparel industry, designers and researchers have been emphasizing the need to develop new measurement systems to meet the needs of people with different body types. Customizing personalized apparel through made-to-measure (MTM) systems, namely experience-based grading rules and artificial intelligence (AI) methods, has been highlighted to achieve clothing based on 3D body data [27]. Olaru et al. presented an innovative approach for personalized pattern design using 3D scanning and CAD technology, providing accurate custom-fit body dimensions [28]. Later, Kim and Choi developed the corresponding measurement-based pattern-making (CMP) method for leggings by focusing on 3D body dimensions and material stretch characteristics to improve the fit and comfort [29].

These studies highlight the improvements in pattern-making techniques with 3D body scanning technology to meet the growing demand for customized and well-fitted clothing.

3.1.2. Fit and Size in Apparel

Three-dimensional body scanning technology in apparel design has significantly improved the size and fit of apparel, which is one of the critical factors in product development. This section addressed key findings from various studies showing how 3D scanning enhanced the sizing and fitting processes in the apparel industry.

The potential for a personalized fit in performance apparel has been highlighted by developing a smart EMG suit using 3D body scans to create tailored clothing patterns [30]. Ball et al. introduced a digital design method for wearable products by integrating 3D scanning and printing technologies, further advancing the field [31]. In terms of virtual fitting, how consumers interact and are satisfied with virtual fitting can be addressed through the emerging 3D scanning technique [32,33].

Three-dimensional body scanning-based anthropometric data were used to enhance the fit in specialized garments for the military and law enforcement sectors [34]. Kolose et al. analyzed the anthropometric data of military personnel in New Zealand to address gender-specific sizing systems that demonstrated how 3D body scanning reshapes the military uniform design by considering gender differences [35]. Hatch et al. addressed sizing inconsistencies in sports compression garments for women's athletic wear by addressing the existing size chart's issues in accommodating various body shapes [36]. In addition, the ease distribution in women's suits has been studied, highlighting how specific ease allowances significantly impact garment fit for women [37]. Romeo and Lee's research showed that there are significant fit issues faced by plus-size female teens struggling to find suitable options within standard sizing categories [38,39], highlighting the need for the industry to address specific market gaps. Kim et al. evaluated various pattern-drafting methods for women's bodies, highlighting the importance of precise measurements to enhance fit [40].

Fit and sizing are key issues in the apparel industry; the new 3D body scanning technology played a crucial role in addressing these issues, and its need has been continuously increasing in the apparel sector.

3.1.3. Footwear in Apparel

Three-dimensional scanning technology has improved the design and fit of footwear and socks. Dan et al. studied how the pressure exerted by men's socks is closely linked to fabric elasticity and stiffness using 3D foot scanning and assessed how this phenomenon impacted the lower leg [41]. This method can potentially be applicable to study other tight garments as well. For prosthetic socks' accurate fit and efficiency, Lindell et al. studied upper-limb amputees using 3D body scanning and reported that this approach was more precise than manual measurements [42]. Irzmańska and Okrasa used 3D scanning to analyze protective footwear fit across age groups, concluding that 3D-measured fit analysis can greatly prevent slips and falls among older adults [43]. The role of 3D scanning in creating well-fitted, inclusive, and practical footwear has been reported in these studies.

3.1.4. Functional Apparel

Regarding functional protective apparel, 3D body scanning technology was used to design and test garments for better fit, comfort, improved range of motion, and other functional features.

Li et al. analyzed compression pants for medical applications, using body scans to assess the pressure distribution on the lower limbs. They concluded that graduated compression pants can shape the body and improve blood flow, but they are less effective than specialized shapewear [44]. Conroy and Park focused on improving ballistic body armor by collaborating with police officers to address fit issues such as torso length and waist circumference and enhance comfort during physical tasks [45]. Kang and Kim developed a customizable bulletproof pad system based on individual chest measurements to enhance its coverage and ergonomic design [46]. Likewise, Wen and Shih redesigned bulletproof vests for Taiwanese soldiers by proposing a better fit and protection for vital organs [47]. Hobbs-Murphy et al. further focused on creating a Paralympic shooting jacket. The garment was redesigned to enhance fitness and movements based on users' feedback and 3D body scanning data, while some issues with arm movements were not resolved [48].

Three-dimensional scanning plays a critical role in firefighter gear development. Ciesielska-Wrobel et al. compared firefighter uniforms and found that different designs influenced comfort and perceived bulkiness [49]. Along those lines, Nawaz and Troynikov discovered that the micro-climate between the body and clothing greatly affected users' thermal comfort [50]. Wang and Wang studied firefighters' air gaps under load-bearing equipment to assess the mobility restriction [51]. Similarly, Mert et al. used 3D scans to investigate how body postures affected air gaps and contact areas, pointing out that these factors are crucial in ensuring thermal comfort and ease of movement in various garment designs [52]. Park and Langseth-Schmidt highlighted that female firefighters reported lower satisfaction with uniform pants than males due to the fit issues in lower-body dimensions, including waist and thigh girths [53].

Bogović et al. used 3D scanning to address the fit and functionality of anti-G suits for pilots, assuring dynamic posture adjustments for protection and comfort [54]. Similarly, virtual reality and 3D scanning have been used to improve the fit and functionality of wetsuits in various diving postures and redesign garments that can potentially adapt to body movements underwater [55]. Gorea and Baytar also applied 3D body scanning to sports bras, measuring compression before and after physical activity to provide even and consistent support during exercise [56]. Following this study, Gorea, Baytar, and Sanders put effort into designing moisture-responsive sports bras inspired by biomimicry that adapt to sweat levels and provide better comfort for mixed-use activities [57]. Digital dress forms created using 3D scans accurately reflect body dimensions in sitting and standing postures. Designers used these forms to consider dynamic anthropometry in product design [58]. For

instance, in children's face masks, Maher et al. applied 3D scanning and digital modeling to optimize mask fit for facial variability among children to improve comfort and fit for varied kids with different BMIs and ethnicities [59].

Rogina-Car and Bogović developed medical undershirts with microbial barriers by combining woven and knitted Tencel® fabrics to improve the fabric's adaptability to body shapes and microbial protection. They designed undershirts that comfortably align with various body shapes and provide an optimal microbial barrier (critical for patient recovery in medical settings) by using 3D body scanning techniques [60]. Similarly, Wang and Gu used 3D scanning to develop patient-specific medical compression stockings, achieving precise pressure distribution tailored to individual leg morphologies [61]. By combining data from 3D scans with mathematical modeling, researchers offered more comfortable and effective compression garments, distributing pressure across different leg zones. For lumbar support, Park and Kim used 3D scanning and printing to design a garment addressing obese women's needs, especially their unique lumbar requirements. By analyzing body measurements from obese participants, they created lumbar support with breathable materials that provided comfort and reduced abdominal pressure [62]. Alrasheedi et al. improved orthotic device design for disabled individuals using 3D body scanning [63]. Knee brace designs and evaluations were achieved by studying knee deformation and skin strain at different angles of knee bending. Their 3D scanning assessment showed great changes in knee shape and strain distribution [64]. Park and Lee developed a 3D-printed fall-impact protection pad, which is customized for older women [65]. By relying on anthropometric data from a 3D scanner, a flexible design for the fall protection pad was offered, which successfully absorbed over 79% of the impact force. Szkudlarek et al. studied the importance of using 3D scanning to study dimensional allowances in personal protective equipment (PPE) [66,67]. Their studies focused on optimizing the fit and comfort in their garments, and they concluded that body measurements influenced the PPE design for different professions (e.g., firefighters).

Furniture design is another important product development category that uses 3D body scanning technology, from mattresses to protective equipment. Considering comfort and efficiency in design, Wu, Yuan, and Li studied sleep comfort by focusing on the body pressure distribution and spinal alignment in mattress designs. Their study compared the performance of different mattresses with different users by capturing the matter's deformity with a 3D scanner. They concluded that the latex foam/palm fiber mattress provided better comfort [68]. Similarly, Smulders et al. explored the application of 3D body scanning in aircraft seat design. They tried to optimize seat comfort and reduce seat weight by capturing participants' contours on seats through 3D scanners and sensors [69]. Similarly, Crytzer et al. [70] used 3D scanning to analyze back shapes in wheelchair users to enhance the fit of seating supports. Their findings indicated a great variation in back shapes and pelvic alignments that should be considered in wheelchair design.

These findings addressed how accurate anthropometric data are crucial to improve the safety and comfort in protective gear. Three-dimensional body scanning technology has been improving the design of furniture and protective equipment to make them safer and more comfortable.

3.2. Body Shape

Another interesting phenomenon studied using 3D body scanning technology was human body shapes. This technology guides industries like apparel, footwear, equipment, and medical wear to design products that consider the human 3D shape. A clear understanding of body shapes leads to better ergonomic products and increases user

satisfaction. Additionally, 3D scanning offers an understanding of how wearables influence body appearances, such as the effects of shapewear or bra design.

3.2.1. Size and Shape

Studies across various demographics reported that body shape variations and unique anthropometric characteristics impacted users' interaction with the product, directing the need to develop more adaptable and accurate sizing systems to accommodate diverse consumer profiles.

Demographic features are one of the dominant factors affecting body shape and posture. Makhanya et al. found significant shape differences among young African and Caucasian women in South Africa, leading to fit challenges caused by ethnicity [71]. Similarly, Park et al. concluded that unique body traits (e.g., pelvis tilt) among elderly Korean women could potentially complicate fit, especially in online shopping, highlighting the need for a more culturally diverse sizing system by studying varied body shapes [72]. Evenness in breast shape and asymmetry were studied, and the asymmetry index was used for more precise fit assessments for bras and apparel in younger, non-obese Caucasian women. This study also highlights the importance of updating the sizing system based on ethnic, age, and body-specific variations [73]. Later, Song et al. and Shin and Saeidi highlighted how aging and a high BMI lead to shape changes, such as posture shifts and abdomen prominence, and standard sizing is needed to address these issues [74,75].

Accordingly, varied body shapes are the main concern for the apparel industry since it needs to develop a comprehensive sizing system that addresses all body shapes. Chrimes et al. found that standard sizes inadequately serve body shapes, especially at the hips and thighs [76]. Shin and Saeidi as well as Hamad et al. identified specific body shapes among obese populations with unique fit challenges by clustering techniques. They addressed that the current sizing system is not comprehensive enough to include people with varied body shapes [77,78]. Following this study, Tan et al. introduced a prediction system using 3D body scans and clustering to enhance fit by recognizing distinct body shapes. It was successfully applied in uniform design [79].

Foot shapes, specifically, have attracted studies to assess footwear and their fit among different groups of people. Three-dimensional foot shape studies highlight the need for footwear that aligns with ethnic and age-related variations. Lee et al. found that Taiwanese women generally have a wider forefoot and straighter big toe than Japanese women [80]. Similarly, Alcacer et al. used archetypal analysis to categorize Spanish adult feet into three primary shapes based on their genders using detailed 3D landmarks [81]. Flat feet have also been analyzed using a 3D scanner to study midfoot and forefoot differences among different genders [82]. By understanding various foot shapes, footwear designs can be tailored to meet the needs of diverse populations. Stewart et al. analyzed the anatomical dimensions of 210 UK offshore workers, concluding that they are generally larger than the general population [83]. In fact, their size difference greatly impacts their ability to move through restricted spaces, especially while wearing personal protective equipment (PPE). This study further explored the egress capabilities of 404 offshore workers during simulated helicopter escapes. They identified key body dimensions that predict egress success, such as deltoid breadth and chest depth [84]. The research team further performed a cluster analysis on 588 male offshore workers to improve survival suit design. They found significant variations in body dimensions across workers with different weights. The study highlights the need for customized industrial clothing to enhance fitness and safety [85]. These studies addressed the vital role that 3D body scanning plays in studying body sizes and shapes to enhance equipment design for workspaces.

Apart from the functional applicability for body shapes, 3D body scanning technology was used to address how apparel in different bodies affects body appearances and shapes. Zhang et al. investigated the effectiveness of lower-body shapewear [86]. Their study involved scanning participants with and without high-waist thigh shapewear (HWTS), resulting in 42% noticeable changes in body shape (majorly transforming from spoon or rectangle shapes to an hourglass shape). Participants reported feeling more attractive when wearing shapewear. Similarly, Wang et al. focused on the impact of bra design on the appearance of women with larger breasts [87]. By involving participants through surveys related to their body scans from 3D scanning, the study identified preferences for minimizer bras that could represent smaller breast sizes. Findings showed that bras with a higher center and wider side panels flattened the breasts. These studies addressed and emphasized the role of 3D body scanning in assessing how clothing affects perceived body shapes and users' satisfaction.

3.2.2. Body Classifications

Body classification can be accurately studied by addressing diverse human shapes to improve product design. By employing 3D body scanning technology, recent studies have contributed to developing comprehensive classification systems across people with different demographic features. These accurate body classifications enhance the apparel industry to be inclusive of all people.

Yoon et al. focused on classifying male upper lateral somatotypes using 3D space vectors and standardized landmarks to categorize participants into distinct body types. The study found that most participants fell into the straight body type category, while swayback and bend-forward types were less common. This result highlights the great variability in upper body measurements among males [88]. Kousar et al. introduced a novel classification system for male body shapes that considers body curvature rather than relying solely on traditional measurements. They classified participants into three main shapes by focusing on angular measurements between the chest, waist, and hips. This study emphasized the importance of curvature in achieving a better fit in clothing [89]. Lower body shapes of obese men have also been studied and classified. This study reported three significant categories of male abdominal obesity. These classifications highlight the complexity of male body shapes and the necessity to study their varied body shapes [30].

Similarly, women's body classification has attracted studies to assess varied body shapes. Sun et al. developed a classification method for female upper body shapes. By extracting space vector blocks (SVBs) from 3D scans, they identified three distinct body shape categories that demonstrated improved garment fitting around critical areas like the waist and armhole [90]. Yu and Kim identified distinct body types for middle-aged women, reporting that the upper body mass increased while the lower body mass decreased with age [91].

3.3. Healthcare

In recent years, 3D body scanning technology has become a part of healthcare assessments. Several studies reported the application of 3D body scanning in varied healthcare settings, including muscular, skeletal, and body composition assessments. This theme explores the role of 3D body scanning in human healthcare.

3.3.1. Evaluation

Three-dimensional body scanning technology has been used as a diagnostic tool for multiple medical conditions, ranging from muscle mass estimation to scoliosis and chest deformities.

Kim et al. reported that a 3D body scanner effectively evaluates sarcopenia by measuring calf volume and the surface area. They suggested that a 3D body scanner is a reliable substitute for invasive methods such as bio-electrical impedance analysis (BIA) [92]. Roy et al. used 3D scanning to assess scoliosis in children by offering a non-invasive tool for mild to moderate case assessments. Köhler et al. showed that 3D scanning could predict cardiorespiratory fitness using lower limb measurements [93]. Also, Taniguchi et al. and Vitali et al. demonstrated the 3D scan's effectiveness in evaluating leg edema and lymphedema, respectively [94,95]. Liu et al. highlighted 3D body scanners' potential in pediatric biomechanical assessments, particularly in analyzing children's foot arches [96]. Kosilek et al. validated the 3D body scanner as a tool for evaluating abdominal obesity since it showed higher precision than traditional tape measurements [97].

In treatment evaluations, Wong et al. used 3D scanning to track pectus carinatum patients' progress with orthotic bracing due to its reliability and non-invasive monitoring capability [98]. Uemura et al. also assessed chest wall elevation after the Nuss procedure for pectus excavatum using 3D body scanning, finding prominent elevation and symmetry improvements. This study recommended that the 3D body scanner is a reliable and non-invasive tool for assessing surgical outcomes [99]. Grünwald et al. highlighted its effectiveness in scoliosis monitoring, reducing reliance on X-rays [100]. Similarly, Kurzydło et al. found the capability of 3D scanning in assessing posture correction [101], while DeBaun et al. showed its sensitivity in assessing shoulder asymmetry after clavicle fractures [102]. Three-dimensional scanners were instrumental in assessing the effects of gender-affirming hormone treatment on facial features in transgender individuals, finding notable changes in facial geometry and improvements in self-reported satisfaction and self-esteem [103].

For body composition, Sager et al. and Cavegn et al. discussed that 3D body scanners could be useful in measuring fat and muscle mass in young Swiss men by showing a high correlation with traditional anthropometric data [104,105]. Tinsley et al. compared different 3D body scanners and demonstrated their efficiency for clinical evaluations [106]. Other body composition studies have assessed the importance of this anthropometric data, from body compositions to the design of medical garments such as scoliosis braces and the evaluation of changes in the spine. Lu et al. evaluated body geometry and symmetry for adolescent idiopathic scoliosis using 3D body scanning [21]. They indicated this tool as an accurate and non-invasive body measurement to design accurate scoliosis braces for more efficient treatments.

3.3.2. Prediction

The 3D body scanner technology can play a vital role in various health metrics, not only for assessments but also for predictions in healthcare.

Conkle et al. evaluated the AutoAnthro system's potential for nutritional assessments in children, concluding that 3D imaging could provide a more comfortable experience than traditional methods. Despite the cost of this method, the AutoAnthro system can effectively capture critical body measurements for evaluating nutritional status with a more user-friendly approach [107]. In another context, Dathan-Stumpf et al. assessed the use of 3D body scanning for predicting successful vaginal breech deliveries, providing another option to traditional MR pelvimetry [18]. Their results showed that outer pelvic measurements from 3D scans could effectively predict delivery outcomes.

Similarly, Choppin et al. explored the torso shape measurements from 3D scanning to predict body fat distribution [108]. Their study found that combining shape and size measurements improved the accuracy of predicting body fat and its distribution, which is crucial for assessing cardio-metabolic risk. This study highlighted the important role

of 3D body scanning techniques in body composition assessments and aligned with the results by Conkle et al. [107]. Furthermore, Guarnieri Lopez et al. studied the associations between 3D surface scanner-derived measurements and body composition. Their research concluded that specific combinations of 3D measurements and demographic and lifestyle factors improved body fat and muscle mass predictions, validating the important role of 3D body scanners in predictions [109].

Later, Morse et al. utilized machine learning algorithms to predict injuries among army recruits based on 3D body shape data. Their models showed a better performance in comparison to traditional metrics like BMI. This study elaborated on how 3D scanning can be applied beyond body composition to predict health-related outcomes [110]. Tian et al. also used a 3D scanning model to estimate pediatric body composition. Their study indicated that 3D optical scans could accurately predict total and regional adiposity, offering a non-invasive option to traditional methods like DXA [20].

Three-dimensional body scanning also plays a crucial role in healthcare for assessing morphological changes. Kwon et al. used 3D photogrammetry to study age-related facial changes in Korean females. Their study showed reductions in upper-facial volume and some changes in the nasal and eyelid parts of the face due to aging [111]. Similarly, Rauter and Simenko studied body asymmetries in cyclists, finding that high-performing athletes had more symmetrical bodies, particularly in calf girth, which can lead to better performances [112]. Loeffler-Wirth et al. used 3D scanning to classify body types in children and adolescents. They showed how body shapes changed with age, especially in overweight individuals [113]. These three studies addressed the effectiveness of 3D scanning in tracking morphological variations across ages.

3.4. Anthropometry Measurements

The anthropometric measurements theme is a more general and broad theme addressing all studies that focused on improving the accuracy of anthropometric data with 3D body scanners. The assessed studies in this thematic analysis highlighted the importance of accurate 3D-based anthropometric data for possible future studies. By capturing detailed body dimensions, 3D scanning technology proves to be a more precise measurement tool for body measurements of diverse groups, such as children, athletes, pregnant women, and aging populations.

For children, 3D body scanning provides a more comprehensive understanding of their growth patterns, a crucial element for designing products like ventilation masks [114] or understanding ethnic differences in head and face dimensions [115]. For adult populations, such as male laborers in Taiwan [116] and the German working-age population [117], the use of 3D body scanning provides the accurate estimation of body volume and dimensions necessary for improving the comfort and safety of workplaces and garments. Cultural and regional variations in anthropometric data were also assessed in different studies, such as the Almousa study which studied the importance of cultural and regional variations in anthropometric data in Saudi Arabia [118].

Special populations, such as athletes, can also take advantage of 3D body scanning by understanding the impact of their training on their body composition. For instance, Simenko et al. found asymmetries in judokas. Hence, some strategies could be proposed to prevent injuries and enhance their performance [22]. Similarly, as shown by Balasubramanian and Robinette, pregnant women experience dynamic changes in their body shapes and dimensions, which is essential for designing maternity wear that adapts to their changing bodies [119]. Studies on body changes among women are not just limited to pregnancies. How women's body changes in different positions (i.e., seated and standing) is of interest to anthropometric studies such as Griffin et al. [120]. Their study concluded significant

changes in the waist, hip, and thigh areas, with some bold contractions at the midline front and expansions at the midline back.

Three-dimensional body scanners played a vital role in enhancing the accuracy of anthropometric measurements for diverse applications, as discussed under this theme.

3.5. Avatar Creation

Avatar creation, primarily through 3D body scanning technology, is another important theme of 3D body scanning applications in various fields such as animation, fashion, and product design. Although this theme contains relatively few studies identified through this systematic literature review, it highlights the importance of 3D body scanners in creating avatars for specific purposes and possibly creating realistic and functional virtual representations of the human body. From a practical perspective, Brownridge and Twigg focused on creating avatars for analyzing ballet performances [121]. They combined motion capture and body scanning data to produce realistic avatars. Luximon et al. studied head-specific avatar creation by developing 3D head templates for product design using high-resolution scans from the SizeChina survey. Their tool combined 3D scan data with traditional anthropometric measurements to create templates categorized by size to improve the fit and design of head-fitting products like helmets and facemasks [122]. Whether for fashion, performance analysis, or product design, these studies highlight how 3D body scanning technology and avatar creation can practically facilitate product design for the human body.

3.6. Body Image

Body image is an individual's perception, thoughts, and feelings about their body's appearance. Humans' body images can be influenced by various factors such as psychological conditions, societal norms, and influential interventions, including technological effects. Three-dimensional body scans can measure body images and assist clinicians in addressing psychological conditions.

Mölbert et al. explored the body image distortion (BID) experienced by individuals with anorexia nervosa (AN). They reported a disconnection between their physical reality and internal body image perceptions. It showed the challenges in treating BID, even among those receiving treatment [123]. Similarly, Park noted that women, especially those with a higher BMI and social physique anxiety, experienced negative emotions after viewing their 3D avatars [124]. Rahman and Navarro found that shorter men struggled to meet societal expectations but became more accepting as they aged [125]. For women, Grogan et al. used 3D body scanning to measure the influence of clothing sizing and reported a decrease in body satisfaction, with adverse effects persisting weeks after the scan period [126].

Both improving people's self-esteem and mediating the effect of the 3D avatar on body image were also studied by Park and Ogle [127]. They explored how viewing a virtual avatar created from one's anthropometric data impacts self-body perception. Their study found that participants showed improved self-esteem and self-compassion after participating in a body positivity program. However, seeing their 3D avatars made some people feel less satisfied with their ideal body image. Uniforms are another mediator between body images and 3D body avatars, which are created using 3D body scanning. Nemeth et al. reported that female athletes were not satisfied with uniforms that did not represent their muscular physical body, even when satisfied with their bodies for their sport [128]. Thus, from treating psychological conditions to assessing body images, 3D body scanners can be implemented.

4. Conclusions and Future Recommendations

Three-dimensional body scanning technology facilitates academic research and industries by improving accuracy, rapid prototyping, customization, and understanding. This review highlighted its application in six key areas: product development, body shape, healthcare, anthropometry, avatar creation, and body image. In product development, 3D scanning has been used predominantly for apparel products to improve the clothing fit without compromising the range of motions by estimating dynamic anthropometry, thereby augmenting the traditional approaches in enhancing user–product interactions. Studies on body shape highlight how scanning can track physical changes over time, especially for athletes, aging populations, and pregnant women. Capturing the 3D shape of the body and the volume helps various fields to understand the nature of growth and the spatial occupancy. Next to product development, the main applications of the technology were prominent in the healthcare sector. In this sector, the technology supports non-invasive assessments for diagnostics, treatment monitoring, and predictive modeling. Anthropometric measurements focus on collecting body dimensions and creating databases of different populations with 3D models, supplementing human-centered design and population-specific studies in public health, evolutionary biology, and obesity trends, to name a few. In addition, the 3D data have been useful in developing safety protocol standards for workspaces and public infrastructure. Regarding virtual avatar creation, 3D scanning technology produces high-resolution, realistic virtual models for animation, gaming, and even personalized online shopping. In the area of body image, it helps study how people view themselves, affecting self-esteem and the acceptance of their body.

While the technology has widespread applications, it is not without deficits or shortfalls. Tracing back to the evolution of 3D body scanners, the early versions were purely hardware-dependent [6], as the concept of software and computational signal processing was nonexistent. As technology evolved, software processing began to offload the computational requirements from the hardware part of 3D body scanning. Since then, there has been a racing condition between the hardware and software elements of 3D body scanning. Faster computational capacity and compact electronics contributed significantly to handling the correspondence problem of photogrammetry and optimizing the triangulation process to generate the 3D cloud, but they are not eliminated in total. The time-of-flight scanners, though suitable for real-time applications, are still prone to errors in scanning darker surfaces and regions of objects closer in proximity [12]. They also lack texture identification. Stereo vision technology is relatively cheaper in terms of hardware, but it requires sophisticated post-processing of images from multiple cameras. On the other hand, laser-based scanners are less computationally intensive devices, are suitable for hand-held scanners, and are capable of generating high-resolution figurines. The structured light approach offers larger fields of view and can be faster and more accurate than their single-beam counterparts. However, it is prone to shadowing error, warranting the synchronous use of multiple cameras.

The existing error tolerance may be adequate for applications such as avatar creation and body image. However, the remaining areas would benefit from improved speed and accuracy. Local errors may not be devastating since the former two areas need a holistic representation of 3D figurines. However, tight tolerances may be preferred for medical product development and other anthropometry-based applications. In addition, a key ingredient in estimating error tolerances and accuracies is the ground truth, which is often unavailable when scanning a human body. The accuracies reported by the manufacturers have to rely on solid stationary objects, while 3D body scanning for humans involves muscles that are not absolutely solid or stationary, resulting in soft tissue artifacts [129,130].

Most scanners use sophisticated software implementations to overcome the deficits and errors in 3D acquisition. For example, statistical approaches are being used to remove outlier data points. The interpolation of missing data points resulting from occlusion, a lack of local variation, unintended movements, and darkness are also being addressed at the software layer of the 3D scanning technology. Recently, AI incorporation into the software has been a promising approach to deal with the deficits of 3D technology.

As AI has become widely available for several applications, its contribution to 3D body scanning technology is emerging to provide improvements in both apparel/fashion and healthcare sectors. In apparel, 3D body scanning applications use AI-powered landmark detection and machine learning to extract precise body dimensions for personalized garment selection and virtual try-on features. AI integration helps address the retailer's long-standing challenges, such as improper fit and high return rates, by providing consumers with AI-driven size recommendations. Additionally, digital body-size libraries store anthropometric data from 3D scans, enabling AI-driven virtual try-ons and personalized sizing. This approach increases personalization, reduces manual customization efforts, and minimizes clothing returns [131–133]. Recently, companies like Alvanon have aimed to standardize sizing across the fashion industry by matching consumer bodies to industry sizing standards to ensure better-fit consistency and reduce production waste. This shift toward industry-specific AI solutions is crucial for sustainability, enabling apparel companies to produce the correct goods at the right time and quantities [134]. In product development, AI and 3D body scanning work together to predict dynamic body measurements. Instead of relying on static scans, AI helps analyze body movements and shape variations in real time and predicts key measurement points, helping designers improve the ergonomic fit for gloves, protective gear, and other wearables [135].

In the healthcare domain, the current state-of-the-art AI-enabled diagnostics are proving useful in 2D image analyses and interpretation with speed and accuracy, predictive analyses and patient-specific diagnosis, and clinical decision support [136]. However, AI's application for whole-body health analysis is still in its early stages but is emerging. AI-powered 3D body volume scanning has been employed to assess metabolic syndrome risk by integrating body volume data with demographic factors. Researchers demonstrated that body volume indices (BVIs) derived from AI analysis outperformed traditional measures like BMI and waist-to-hip ratio in predicting metabolic syndrome severity [133]. Apart from the whole-body data, AI-based deep networks are used in computing 3D representations of skeletal orientation and the position of multiple humans in an environment [137]. These advancements show the future potential of AI-integrated 3D body scanning for medical diagnostics, fitness tracking, preventive healthcare, and other interdisciplinary areas such as pose estimation and wearable technologies.

Future studies on this technology can focus on global standards for 3D body scanning measurements and procedures to increase data consistency and reliability across different industries worldwide. Newer 3D databases focusing on underrepresented ethnic populations and differently abled people should be created to maximize the inclusive design approach. Combining technology with AI could also improve predictions, like identifying early signs of injuries in athletes or tracking possible health risks related to weight. The digital modality of 3D body scanning lends itself to parametric training of AI models. By incorporating hardware-enabled AI technology, the 3D scanning technology can be extended towards estimating 3D objects along the time dimension, making them viable for 4D approaches. In addition to developing faster and high-fidelity hardware and software, there is a need for sensing technologies that are immune to errors related to soft tissue and viscoelastic objects while retaining the non-invasive feature. Furthermore, multidisciplinary research of technologists with healthcare providers and social scientists can deepen

our understanding and expand use cases, such as proposing 3D scanning systems for specific cultural and demographic variations for inclusive product design or even medical diagnostics. Three-dimensional body scanning can serve as a powerful tool to improve human-centric product development and health monitoring.

5. Study Limitation

This study has limitations that should be accounted for. First, the database search was limited to Scopus and Web of Science, excluding relevant studies from other databases. Furthermore, restricting the search to English-language articles might have restricted this study from accessing valuable research published in other languages, especially considering the global adoption of 3D body scanning technology. Focusing on studies published between 2014 and 2024 further excluded initial studies, which might have provided practical information related to technological developments. Additionally, the exclusion of conference abstracts, opinion pieces, and editorials may have limited the scope of the analysis. Eliminating these limitations might generate additional themes in this domain.

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