A systematic review on ear anthropometry and its industrial design applications

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Abstract

Ergonomics is extensively studied to provide a scientific understanding of humans' physical and cognitive use of products and workplaces. Ergonomics of the external ear is crucial for the industrial design of various ear-related products. For this review, 50 articles regarding ear anthropometry and its applications in product design that met determined inclusion criteria were selected after searching four databases, including Scopus, Web of Science, PubMed, and Science Direct. Previous anthropo- metric information acquired with traditional measurement, photogrammetric method, and three dimensional (3D) anthropometric techniques (photogrammetry, magnetic resonance imaging, computerized tomography, 3D scanning, and ear impression). Those studies demonstrated that demographic factors, including age, ethnicity, gender, and ear symmetry, should be considered when designing for specific markets. Ear sizes kept growth throughout the entire lifetime. Results also showed that males had larger ear sizes than females in most populations. Most of linear, area, and ratio dimensions showed a good symmetry between left and right ears, while angular dimensions tended to be nonsymmetric. Differences in anthropometric findings existed among Asian, Western, and African populations. Hence, there is a need to establish more universal anthropometric databases for different ethnicities to meet the development of product form and function. Furthermore, fit and comfort perception was important to be examined for product design, which can be studied through questionnaire on comfort perception, analysis online comments of consumers, and virtual fit analysis. With a comprehensive presentation of literature, future research opportunities were inspired from the perspective of industrial design.

KEYWORDS
ear anthropometry, ear modeling, ergonomic application, industrial design, systematic review

1 | INTRODUCTION

Ergonomic design is in high demand with increasing requirements from customers. Ear-related products, such as earphones, earmuffs, and different forms of hearing aids, are widely used in our everyday lives. These products were designed to fit different regions of the external ear, as shown in Figure 1. Ergonomic research for ear-related products has become crucial to achieving mass customization in this industry.

As a fundamental part of ergonomics, anthropometry can assist manufacturers in adjusting designs to cater to specific markets. Ear anthropometry contains studies on the size and shape of the external ear, as anthropometric reference for ear-related product design. The external ear, also named as auricle or pinna, includes helix, antihelix, tragion, antitragion, lobule, cymba concha, cavum concha, triangular fossa, intertragic incisure, and ear canal (Lee et al., 2018), as shown in Figure 2. Previous research mostly used traditional (Farkas, Posnick, & Hreczko, 1992; Kalcioglu, Miman, Toplu, Yakinci, & Ozturan, 2003; Sforza et al., 2009) and photogrammetric (Meijerman, Van Der Lugt, & Maat, 2007; Niemitz, Nibbrig, & Zacher, 2007) methods to measure selected ear dimensions.

The development of three dimensional (3D) data collection techniques has provided the opportunity to digitally model the human body for anthropometric research. Various techniques, including stereophotogrammetry, computed tomography (CT), Magnetic Resonance Imaging (MRI), and 3D scanning, have been used to collect data of the external ear (Chen, Chen, Chiu, Cheng, & Tsui, 2012; Coward & Scott, 2005). After data collection, the point clouds or triangular surfaces of the external ear can be processed and analyzed with 3D computer-aided design techniques or other modeling techniques. For example, ear impression was used to represent a more complete morphology of external ear when combined with the scanned ear data using an interactive closest point technique (Luximon, Martin, Ball, & Zhang, 2016). Also, ear dimensions were directly extracted from the 3D ear model in OnyxCeph software (Modabber et al., 2018). Examples of different measuring methods were presented in Figure 3. However, these measuring methods have their own characteristics when applied in ear anthropometry, which require addressing from a systematic view. For industrial design, anthropometric data were used to seek proper comfort and fit. Researchers have analyzed 3D models of human proportions for various industrial products, such as bras (Zheng, Yu, & Fan, 2007), footwear (Luximon, Goonetilleke, & Tsui, 2003; Sievanen & Peltonen, 2006), apparel (Istook & Hwang, 2001; Loker, Ashdown, & Schoenfelder, 2005), and head-related products (Luximon, Ball, & Chow, 2016; Skals, Ellena, Subic, Mustafa, & Pang, 2016). For ear-related products, selected ear dimensions were used to determine the corresponding dimensions of specific products, such as Bluetooth earphones and earplugs. (Chiou, Huang, & Chen, 2016; Chiu, Chiang, Liu, Wang, & Chiou, 2014). Researchers have also linked ear anthropometry with related product design via cluster analysis (Ji, Zhu, Gao, Bai, & Hu, 2018) and virtual fit analysis (Lee et al., 2016). However, applications of 3D ear anthropometry in industrial design have not been sufficiently studied due to the unique morphology and characteristics of the external ear.

FIGURE 1 Commercial products fitting with different regions of the external ear, including (a) earphone 1, (b) earphone 2, (c) headphone, and (d) bone conduction earphone

Ear anthropometry has seldom employed recent techniques for a systematic ergonomics-oriented review. Roebuck and Casali (2011) reviewed the terminology and research scope in selected ear anthropometric studies, pointing out several potential research gaps, with Roebuck (2015) particularly comparing the terminology used in the documentation. However, these studies focused on terminology and did not include a comprehensive interpretation of recent related techniques for industrial use.

The aim of this paper is to review systematically studies on ear anthropometry with different measuring methods, and also address the potential research gaps related to industrial design. Reviewing the literature is valuable to the summarization of the previous findings and revealing existing techniques so that designers, engineers, and scientists can obtain a comprehensive view of the previous work and future trends.

2 | METHODS

2.1 | Search strategy

In the review, research studies addressing anthropometric findings of external ear with potential or direct uses in ergonomic design were selected for further analysis. Regarding the research field of the

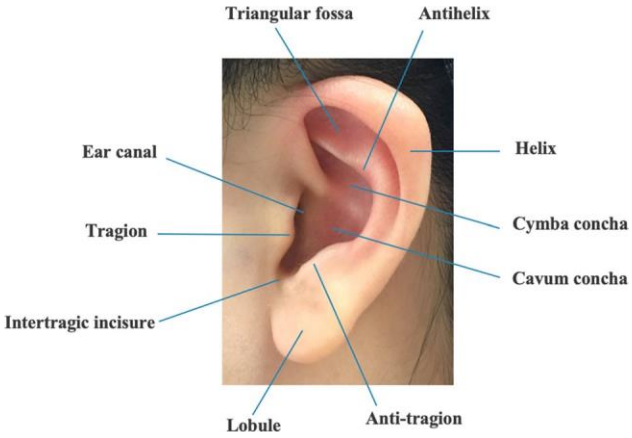

FIGURE 2 The anatomical structure of the external ear (Lee et al., 2018)

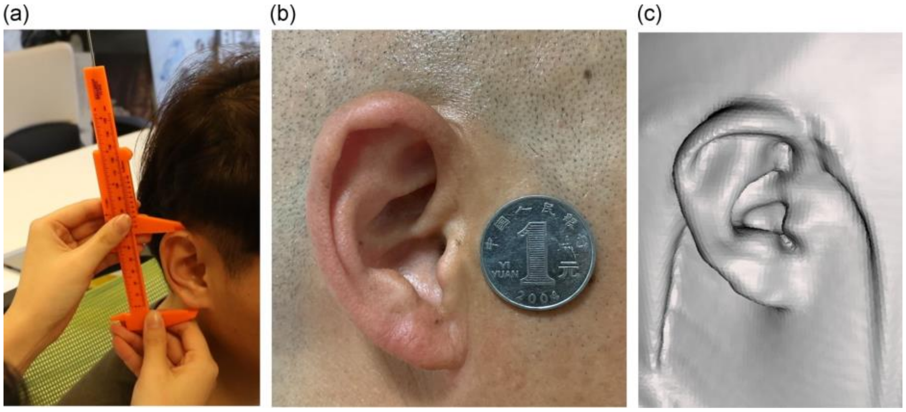

FIGURE3 Examples of (a) traditional measurement, (b) photogrammetric measurement (Ma et al., 2017), and (c) 3D scanning measurement

targeted topic, four closely related databases, Scopus, Web of Science, PubMed, and Science Direct, were searched to identify relevant published papers in recent and retrospective multidisciplin- ary studies. Peered-reviewed journal articles and conference proceedings published in English between January 1980 and December 2018 were included. Initial terms, including “ear” and “anthropometry”, were searched in the databases simultaneously.

2.2 | Inclusion criteria

After executing the search, the titles, abstracts, and full texts of identified papers were assessed to determine which articles satisfied the inclusion criteria. Inclusion criteria were determined as follows:

(a) anthropometry of the external ear instead of the middle and inner ear; (b) research concentrating on ear size and shape rather than auditory capability or genetic issues; (c) anthropometric results related to designing applications for uses other than medical purpose or personal identification, such as excluding abnormal ear growth and new-born subjects; and (d) original or reviewed studies written in English with full text available.

2.3 | Documentation categorization

Full texts of studies meeting the above inclusion criteria were reviewed for further analysis. According to the different focuses of these studies, papers were classified into three categories: (a) anthropometric data on ear-related product design, which directly presented the physical human variability of the external ear; (b) applications of ear anthropometry in product design, which transitioned anthropometric data to related product designs; and (c) review studies and recent techniques in ear anthropometry, which tested and examined existing techniques. Some of the research analyzed may contain content from more than one category.

3 | RESULTS

With the above search strategy, 566 papers in Scopus, 226 papers in Web of Science, 153 papers in PubMed, and 42 papers in Science Direct were identified individually. After deleting the duplicate and excluded articles, 50 articles were selected to be further reviewed. Based on the content, 37 articles were identified containing anthropometric data, 9 articles were found on design applications of ear anthropometry, and 12 articles were recognized as having an emphasis on review studies and recent techniques in ear anthropometry. During the documentation categorization, some articles were identified as containing both anthro- pometric data and applications in product design. The workflow of the systematic review process is demonstrated in Figure 4.

Thirty-seven papers containing anthropometric data that could be used in ear-related product design were identified. In previous ear anthropometric studies, researchers used different methods to measure the external ear, including traditional measurement, 2D photogrammetry, and 3D measuring methods. In most research, several ear dimensions were selected to analyze ear size and shape, and the statistical results were used as anthropometric references for related designs. Statistical findings were generated to describe the ear morphology for different populations, age groups, genders, and ear symmetry. For a certain population, the growth character- istics were found to vary upon specific dimension and gender. Farkas et al. (1992) revealed that ear length reached maturation size at 13 years of age in males and 12 years in females, while ear width achieved maturation size at 7 years in males and 6 years in females in the United States. Growth curves of males and females were illustrated for Turkish children (Kalcioglu et al., 2003) and Chinese children (Zhao et al., 2018). Ear growths throughout the whole lifetime were presented for Germans (Niemitz et al., 2007) and Italians (Sforza et al., 2009). When comparing populations, Alexander, Stott, Sivakumar, and Kang (2011) reported that Indians had larger ear length than Caucasians and African/Afro-Caribbean peoples, significantly in males and not significantly in females, Lee et al. (2018) found that Caucasians had wider but shorter ears than Koreans, and

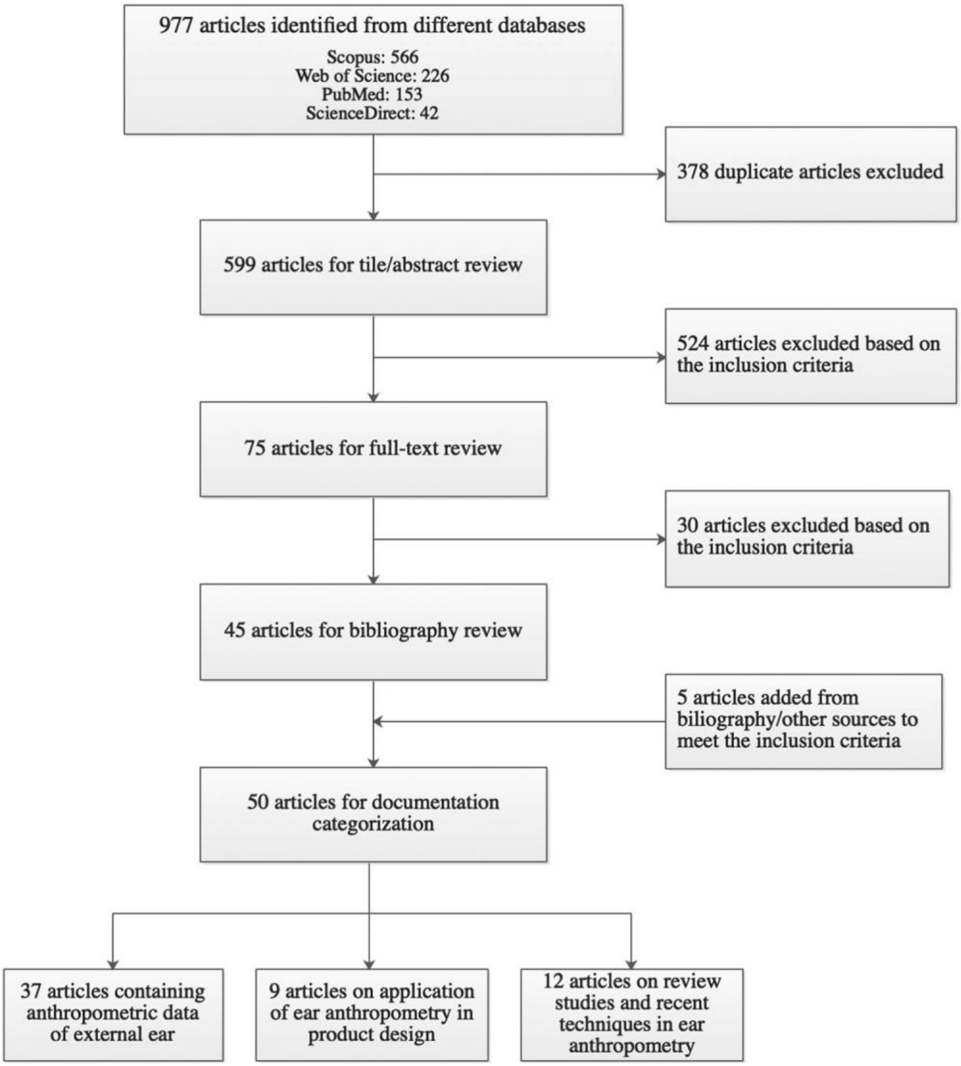

FIGURE 4 The workflow of the systematic review process

Hossein, Payam, and Masih (2018) determined that Hamadan men had significantly greater ear size than Caucasian men. In regard to gender differences, these investigations revealed that females have smaller ear length and width than males for Korean (Jung & Jung, 2003), Turkish (Barut & Aktunc, 2006; Tatlisumak et al., 2015), and Italian peoples (Sforza et al., 2009). Alexander et al. (2011) discovered that linear dimensions, including height and width, showed a higher symmetry, while angular measurements had less symmetry between the left and right sides. Tatlisumak et al. (2015) reported left ear length was significantly longer than the right length for the Turkish population while Jung and Jung (2003) concluded that Koreans have longer ear length on the right than the left side. These studies provided statistical findings of selected ear dimensions upon variables of population, age, gender, and symmetry. The overview of these results is demonstrated in Table 1.

Nine articles were identified that studied the application of ear anthropometry in industrial design, as listed in Table 2. Stavrakos and Ahmed-Kristensen (2016) proposed a methodological framework on the application of 3D anthropometry in related design. In practice, most of the studies directly use anthropometric data as the size reference for product design with validation testing. Chiu et al. (2014) considered comfort perception by employing a questionnaire along with prototype testing. Jung and Jung (2003) and Ferguson, Greene, Repetti, Lewis, and Behdad (2015) combined anthropometric measurements with product reviews from online customers.

With the trend of 3D anthropometry, different techniques, including photogrammetry, MRI, computerized tomography (CT), laser scanning, and structured-light scanning, were applied in ear anthropometry for product design purposes. Twelve articles were identified containing review studies and recent techniques in ear anthropometry, as shown in Table 3. Four reviewed articles were found to systematically summarize related terminologies and applications from various literature. Five articles compared the reliability of these anthropometric methods from either medical or ergonomic perspectives, and two articles explored the combination of different scanned parts using computer-aided design for ear anthropometry. In addition, photogrammetry was applied in ear anthropometry as a quick method to extract ear dimensions.

TABLE 1 Studies on ear anthropometry providing statistical findings

Study	Population	Sample size[a]	Age (years)	Ear dimensions	Ear landmarks	Equipment and material	Ear symmetry	Main findings
Farkas et al.	North American	2590 (793M, 797F)	1–18	2 (ear width, ear length)	4 (sa, sba, pra, pa)	Caliper	Left	Provided growth curves and maturation age.
Tan et al. (1997)	American	100	21–98	4 (overall length, tragus height, lobe length, circumference)	/	String with scale	Both	Verified that ear keeps grow along with age.
Jung and Jung (2003)	Korean, Western	600 Koreans (300M, 30 Westerners	17–89	4 (pinna length, ear-connection length, length, lobule thickness)	/	Caliper	Both	Verified that ear keeps grow along Korean males have bigger ears than Western males, while Korean females have smaller ears.
Brucker et al. (2003)	American	123 (34M, 89F)	18–65	5 (total ear height, lobular height, lobular width, distance from the lateral palpebral commissure to the root of helix, distance the lateral palpebral commissure to the insertion of the lobule)	/	Caliper	Both	Suggested that earlobe is the only ear part that keeps change significantly with age.
Azaria et al.	Jews, Ethiopian, Asian and Arabs	547 (164M, 383F)	20–80	2 (earlobe length, line of balance)	/	Caliper	Both	Earlobe length changes under variables of age and gender; Ethnic origin had no significant influence on earlobe length.
Kalcioglu et al. (2003)	Turkish	1552	0–18	6 (length from superaurale subaurale, width from tragus to helix, width antihelix, conchal depth, height from helix to mastoid at superaurale level, height from helix to mastoid at tragal level)	2 (superaurale,	Direct measurement	Right	Provided growth curves and cut-off points of development.
Barut and (2006)	Turkish	153 (87M, 66F)	6–13	4 (ear height, ear width, height, lobule width)	5 (sa, sba, pra, pa, in)	Caliper	Both	Revealed the influences of gender and symmetry on ear dimensions for children.

(Continues)

TABLE 1 (Continued)

Study	Population	Sample size^a	Age (years)	Ear dimensions	Ear landmarks	Equipment and material	Ear symmetry	Main findings
Bozkir et al. (2006)	Turkish	341 (191M, 150F)	18–25	7 (total ear height, lobular height, lobular width, distance from tragus to antihelix, distance from tragus to helix, ear projection, ear width,)	/	Caliper	Both	Provided descriptive statistic results of ear dimensions for adult.
Purkait and Singh (2007)	Indian	415 (M)	18–70	9 (Length of the auricle, of the auricle, Lobular length, Lobular width, Conchal length, Conchal width, Auricular inclination Protrusion at the superaurale level, Protrusion at the tragal level)	10 (superaurale, preaurale, postaurale, concha superior, intertragica inferior, incisura anterior auris posterior, the strongest anthelical curvature, lobule anterior, lobule posterior)	Caliper	Both	Revealed the influences of age and symmetry on ear dimensions for males.
Meijerman et al. (2007)	Dutch Caucasian	1353 (919M, 434F)	18–99	5 (auricle length, auricle earlobe length, superior helix width, posterior helix width)	/	Digital camera	Both	Revealed the influence of age on ear dimensions.
Niemitz et al. (2007)	German	724	0–92	10 (greatest ear length, of ear base, length of ear cartilage, greatest length the earlobe, upper ear length, height of the Concha, of the Concha, width of Incisura intertragica, depth of the Incisura intertragica, greatest width of the	/	Digital camera	Both	Revealed the growth of ear throughout the entire lifetime.
Sharma, Sidhu, Sharma, Kapoor, and Singh (2007)	Indian	260 (M)	1–80	4 (length L_1L, breadth L_1B, thickness L_2T, root attachment)	/	Caliper	Both	Revealed the statistic dimensions for earlobe.
Liu (2008)	Taiwanese	200 (100M, 100F)	20–59	3 (earhole length, ear-connection length, pinna length)	/	Grid with scale + camera	Both	Revealed the influences of age and gender on ear dimensions.
Sforza et al.	Italian Caucasian	843 (497M, 346F)	4–73	4 (ear width, ear length, ear area, angle of the auricle)	5 (sa, sba, pra, pa, t)	Electromagnetic digitizer	Both	Revealed the influences of age, gender and symmetry on ear dimensions.
Ekanem et al. (2010)	Nigerians	217 (140M,	18–65	3 (total ear height, lobular height, lobular width)	/	Caliper	Both	Provided descriptive statistic results of ear dimensions for adults.

(Continues)

TABLE 1 (Continued)

Study	Population	Sample size^a	Age (years)	Ear dimensions	Ear landmarks	Equipment and material	Ear symmetry	Main findings
Wang et al. (2011)	Chinese Han	485 (244M, 241F)	18–75	12 (Length of the auricle, Width of the auricle, Insertion length of the auricle, Length of tragus, Height of tragus, Lobular length, Lobular width, Conchal length, Conchal width, Protrusion at superaurale level, etc.)	16 (superaurale, subaurale, preaurale, postaurale, otobasion superius otobasion inferius, protragion, lobule anterior, lobule posterior, concha superior, strongest antihelical curvature, etc.)	Computed tomography	Both	Provided descriptive statistic results of ear dimensions for different age groups.
Alexander et al. (2011)	Caucasian , Afro-Caribbean, Indian, and mixed	228 (137M, 151F)	15–44	8 (ear length, ear axis, antihelix taken off angle, earlobe width, auricle concho-mastoid angle, conchal bowl depth, helical-mastoid distance)	/	Caliper + goniometer	Both	Revealed the influences of gender, age and on ear dimensions.
Deopa et al.	Indian	177 (93M,	17–25	4 (total ear height, ear lobular height, and lobular width)	6 (A, C, D, L, P, T)	Caliper	Both	Revealed the influences age and gender on ear dimensions.
Purkait (2013)	Indian	2147 (1163M, 984F)	0–18	11 (physiognomic ear physiognomic ear width, morphologic width; length, conchal width, conchal depth, lobular length, lobular width, tragal tragal height, etc.)	15 (superaurale, preaurale, postaurale, otobasion superius, otobasion inferius, superior, lobule lobule posterior, etc.)	Caliper	Right	Provided growth curves and maturation age.
Murgod, Angadi, Hallikerimath, and Kale (2013)	Indian	300 (150M, 150F)	18–30	5 (ear length, ear breadth, base of the auricle, lobe length, lobe width)	7 (sa, sba, pra, pa, most attachment of deepest point on the intertragic notch, posterior most point of the earlobe)	Digital camera +	Both	Provided descriptive statistic results and revealed the gender differences for ear dimensions.
Tatlisumak et al. (2015)	Turkish	400 (200M, 200F)	18–26	7 (Auricle length (AL), Distance from the highest point of the auricle to the bottom of the intertragic notch (TIN), Auricle width (AW), Distance from the tragus to helix (TH), Distance from the tragus to antihelix (TAH), Earlobe width (EW), Earlobe length (EL))	/	Digital camera + caliper	Both	Revealed the influences of gender and symmetry on ear dimensions.

(Continues)

TABLE 1 (Continued)

Study	Population	Sample size[a]	Age (years)	Ear dimensions	Ear landmarks	Equipment and material	Ear symmetry	Main findings
Yu et al. (2015)	Taiwanese	40 (20M, 20F)	M = 25.1	14 (height (ab) and width (cd) of ear canal opening, first bend canal length (aa_1, bb_1, cc_1, dd_1), and second bend canal length (aa_2, bb_2, cc_2, dd_2), total ear canal length (aa_3, bb_3, cc_3, dd_3)	/	Computed tomography	Both	Provided descriptive statistic results of ear canal dimensions.
Ahmed and Omer (2015)	Sudanese Arab	200 (100M, 100F)	18–30	6 (physiognomic ear length and width, lobule length and width, and conchal length and width)	10 (superaurale, preaurale, postaurale, concha superior, intertragica inferior, posterior point on the edge of incisura auris, strongest curvature, anterior posterior lobule.)	Caliper	Both	Provided descriptive statistic results of ear dimensions; Discovered the use of ear in gender estimation.
Shireen and Karadkhelkar (2015)	Indian	147 (77M,	18–25	4 (total ear height, ear lobular height and lobular width)	/	Caliper	Both	Provided descriptive statistic results and highlighted the differences in gender.
Lee et al. (2016)	Korean	100 (50M,	20–59	13 (ear length, ear breadth, ear protrusion, upper otobasion arc, cavum concha length, posterior concha to anterior cymba concha length, cavum concha width, cavum concha depth, ear canal length, ear canal width, etc.)	12 (superior auricle, inferior auricle, superius, posterior otobasion posterius, otobasion superius, tragion, posterior medical concha, incisura imtertrgica, etc.)	3D scanner + ear impression material	Right	Provided descriptive statistic results of ear dimensions.
Chiou et al.	Taiwanese	110	20–40	13 (Concha length, Concha width, Concha height, Ear canal opening length, Ear canal opening width, Anterior second bend Posterior second bend length, Superior second bend length, Inferior second bend length, Anterior second bend length, etc.)	19 (Tragus, Incisura anterior auris posterior, Incisura intertragica inferior, Crus-concha Center of crus, Concha peak,The superior points on the aperture,The inferior points on the aperture,The anterior points on the aperture, etc.)	3D scanner + ear impression material	Both	Provided descriptive statistic results of ear canal dimensions.

(Continues)

TABLE 1 (Continued)

Study	Population	Sample size[a]	Age (years)	Ear dimensions	Ear landmarks	Equipment and material	Ear symmetry	Main findings
Verma et al. (2016)	Indian	80 (33M, 47F)	18–25	9 (Total ear length, Ear length above tragus, Ear length below tragus, Tragus length, Ear breadth, Concha length, Concha breadth, Lobule	/	Caliper	Both	Compared ear dimensions under variables of gender and region in India.
Ma et al. (2017)	Chinese	12	M = 20.1	6 (ear height, ear width, ear length, the height of cavum conchae, the width of cavum conchae, earlobe	9 (pra, sa, pa, sba, incisura anterior auricle, t, in, ant, end of cavum conchea)	Coin + digital camera	Right	Provided descriptive statistic results.
Zhu et al. (2017)	Chinese	310 (169M, 141F)	18–28	12 (the total length of tragus, tragus length 1, tragus length 2, the total length of antitragus, the antitragus length 1, the antitragus length 2, the conchal width, The height of the ear canal opening, The width of the ear canal opening, the conchal depth, etc.)	7 (the most posterior point on the edge of the incisura anterior auris, the bump point of tragus, the deepest point in the incisura intertragica notch, the bump point of antitragus, the strongest antihelical curvature, the deepest point on the floor of auricular concha, the	3D scanner + ear impression material	Both	Provided description of ear canal dimensions under variables of gender and symmetry.
Zhao et al. (2018)	Chinese	480 (240M, 240F)	1–18	2 (ear length, ear width)	/	Direct measurement	Both	Provided growth curves and
Hossein et al. (2018)	Iranian and Hamadan	250 (125M, 125F)	18–30	2 (ear width, ear length)	4 (sa, sba, pra, pa)	Caliper	Both	Provided descriptive statistic results and differences upon gender and ethnicity.
Mououdi et al. (2018)	Iranian	153 (M)	24–59	3 (earhole length, pinna length, pinna width)	/	Mesh transparent screen + camera	Both	Revealed influences of age, ethnicity and symmetry on ear dimensions for
Japatti et al. (2018)	Indian	505 (225M, 280F)	18–64	9 (ear length, ear width, ear length above tragus, ear length below tragus, tragus length, concha length, concha breadth, lobule height, lobule	/	Mesh transparent screen + camera	Both	Revealed the influences of gender, age and symmetry on ear dimensions.

(Continues)

TABLE 1 (Continued)

Study	Population	Sample size[a]	Age (years)	Ear dimensions	Ear landmarks	Equipment and material	Ear symmetry	Main findings
Ji et al. (2018)	Chinese	310 (169M, 141F)	18–28	7 (AB, AC, AE, BC, CD, CE, DE)	5 (A:the most posterior point on the edge of the incisura anterior auricular, B: the bump point of tragus, C: the deepest point in the incisura intertragica notch, D: the bump point of antitragus, E: the strongest anthelical curvature)	3D scanner + ear impression material	Left	Determined the classification of concha shape for target population.
Lee et al. (2018)	Korean, Caucasian	230 Koreans (115M, 115F), 96 Caucasians (50M, 46F)	20–59	25 (ear length, ear breadth, ear protrusion, upper otobasion arc, cavum concha length, posterior concha to anterior cymba concha length, cavum concha width, cavum concha depth, ear canal length, ear canal width, etc.)	12 (superior auricle, inferior auricle, superius, posterior otobasion posterius, otobasion superius, tragion, posterior medical concha, incisura imtertrgica, etc.)	3D scanner + ear impression material	Right	Compared the between Korean and Caucasian.
Fu, Luximon, & Shah	Chinese	60 (30M, 30F)	5-13	4 (EL: ear length from superaurale to W1: ear width from postaurale to the ear base line, W2: the width from tragus to the strongest antihelical curvature, and FA: flipping angle from the base of the head to helix)	7 (Superaurale, Subaurale, Postaurale, Lobule anterior, Tragus, and Strongest antihelical curvature)	3D scanner	Both	Revealed the growth of ear dimensions Chinese children.
Modabber et al. (2018)	Caucasian	240 (120M, 120F)	21–65	11 (SubAu–SupAu, PreAu-PosrAu, Tra-PosrAu, Osup- Oinf, Ia-ITra, (SubAu–SupAu)-(PreAu-PostAu)(°), SupAu-L_1, L_1-L_2, L_2-L_3, L_3-SubAu, etc.)	9 (Tra, SupAu, SubAu, PreAu, PostAu, Osup, Oinf, Ia, ITra)	3D scanner	Both	Verified that Caucasian ear keeps grow during adulthood.

[a] F, female; M, male.

TABLE 2 Research on applications in ear-related product design

Study	Population	Sample size[a]	Products	Variables	Analysis techniques	Validation
Jung and Jung (2003)	Korean	600 (300M, 300F)	Earmuff, earphones, earrings	4 dimensions (pinna length, ear-connection length, earhole length, lobule thickness)	Mean, SD, percentile,	/
Chiu et al. (2014)	Taiwanese	198 (100M, 98F)	Bluetooth earphones	Gender, ear shape, product model, comfort perception by questionnaire.	ANOVA, *t* test, LSD test.	/
Ferguson et al. (2015)	Online consumers	100	Headphones	Consumer review content.	Frequency.	A case study of earbud headphones
Chiou et al. (2016)	Taiwanese, aged 20–40	110	Earplug	13 dimensions on ear canal (Concha length, Concha width, Concha height, Ear canal opening length, Ear canal opening width, Anterior second bend length, Posterior second bend length, Superior second bend length, Inferior second bend length, Anterior second bend length, etc.)	Mean, SD, percentile.	/
Lee et al. (2016)	Korean, aged 20–59	100 (50M, 50F)	earphone-head, ear- band, ear-tip	13 ear dimensions (ear length, ear breadth, ear protrusion, upper otobasion arc, cavum concha length, posterior concha to anterior cymba concha length, cavum concha width, cavum concha depth, ear canal length, ear canal width, etc.)	Mean, SD, percentile, correlation; virtual fit analysis	/
Stavrakos and Ahmed-Kristensen (2016)	Danish, aged 22–67	200	Proposed a methodological framework on application of 3D anthropometry with descriptive statistics and cluster analysis for ear-related product.			
Stavrakos et al. (2016)	Danish, aged 22–67	200 (100M, 100F)	in-the-ear Bluetooth headset	6 ear dimensions (ear length, ear breadth, ear height, concha X, concha Y, circumference)	Clustering analysis	Testing in-the-ear and behind-the-ear product on 20 subjects
Ji et al. (2018)	Chinese, aged 18–28	310 (169M, 141F)	earphone	7 dimensions on the concha (AB, AC, AE, BC, CD, CE, DE)	Classification based on 3 dimensions.	Testing earphone on 12 subjects
Mououdi et al. (2018)	Iranian, aged 24–	153 (M)	earmuffs and	3 dimensions (earhole length, pinna length, pinna width)	Mean, SD, percentile,	/

[a] F, female; M, male.

TABLE 3 Research on review studies and recent techniques in ear anthropometry

Study	Equipment and material	Techniques	Aim of the study	Application of the study
Coward and Scott (2005)	CT scanner, MRI scanner, laser scanner, casting material	CT, MRI, laser scanning, ear impression	To compare ear dimensions from CT, MRI, and laser	Rehabilitation use
Hunter et al. (2009)	/	/	To review the anatomy of ear and related terms for ear morphology.	Anthropometry
Liu et al. (2010)	Caliper, photocopier, camera	/	To compare the reliability of the three measuring	Product design
Roebuck and Casali (2011)	/	/	To review ear anthropometric terms and summarize practices for design.	Ergonomic design
Chen et al. (2012)	CT scanner, molding silicone	CT, ear impression	To compare dimensions of CT images and ear impression.	Hearing aids design
Mohamed et al. (2013)	Casting alginate	Ear impression	To compare ear dimensions between two impression techniques.	Auricular prosthesis
Roebuck (2015)	/	/	To review the documentation of anthropometry	Ergonomic design
Chen et al. (2015)	Caliper, 3Dmd^{TM} Cranial system	Stereophotogrammetry and structured-light techniques	To compare the reliability between traditional measurement and stereophotogrammetry.	Microtia reconstruction
Lee et al. (2016)	Artec Eva, Casting silicone	3D scanning, ear impression	To apply ear anthropometry in product design with 3D	Product design
Luximon, Martin, & Zhang (2016)	Cyberware 3030 scanner, aglinate	3D scanning, Iteratice Closest Point	To combine ear cast with scanned head using ICP method.	Product design
Ma et al. (2017)	Camera	Photogrammetry	To use photogrammetry in ear anthropometry as an method.	Industrial design
Lee et al. (2018)	3D scanner, casting silicone	3D scanning, ear impression	To review ear landmarks for product design use and several new landmarks and dimensions.	Product design

4 | DISCUSSION

Various ear anthropometric research has been conducted in recent decades. However, these individual studies have concentrated on specific dimensions with different anthropometric methods. The purpose of this paper is to provide a holistic view of previous ear anthropometry uses for product design. The following section summarizes the findings and contributions of previous studies and addresses the limitations and future opportunities on related topics.

4.1 | Anthropometric research on the external ear

Even though the number of anthropometric studies is not small, findings from these studies are difficult to converge due to their different anthropometric methods and various populations. Different measuring methods can be used in ear anthropometry, with advantages and disadvantages in each practice. The statistical findings in these studies have provided anthropometric knowledge of the morphological characteristics of external ears for specific populations.

4.1.1 | Measurement methods

With traditional measurement, specific ear dimensions are obtained directly with measuring tools, such as calipers, tape, and goniometers. This low-cost and convenient method was used for data collection in various studies (Alexander et al., 2011; Azaria, Adler, Silfen, Regev, & Hauben, 2003; Barut & Aktunc, 2006; Bozkir, Karakaş, Yavuz, & Dere, 2006; Brucker, Patel, & Sullivan, 2003; Deopa, Thakkar, Prakash, Niranjan, & Barua, 2013; Ekanem, Garaba, Musa, & Dare, 2010; Farkas et al., 1992; Jung & Jung, 2003; Kalcioglu et al., 2003; Purkait, 2013; Purkait & Singh, 2007; Tan, Osman, & Tan, 1997). These directly measured dimensions can be used to demonstrate the size of the external ear. However, the number of dimensions is limited, and particular dimensions, such as canal and angle dimensions, are difficult to acquire precisely using traditional measurement.

The 2D photogrammetric method was used along with image records of the external ear taken from a certain direction to determine ear size and shape. To extract ear dimensions, a scale reference, such as a measuring scale (Meijerman et al., 2007; Niemitz et al., 2007), a transparent grid with scale (Japatti et al., 2018; Liu, 2008; Mououdi, Akbari, & Mohammadi Khoshoei, 2018), and a coin (Ma, Tsao, Yu, & Zhou, 2017), was usually used to calculate the scale ratio. The 2D images provided selected ear dimensions and enabled the study on the size and shape of the auricle. Even though 2D photogrammetry can provide more information than traditional measurement, it is still difficult to gain ear canal data and some surface information through this method.

Recently, researchers have conducted ear anthropometry with 3D technologies. Different techniques have been applied to collect the external ear data, including stereophotogrammetry (Sforza et al., 2009), CT (Wang, Dong, Zhao, Bai, & Wu, 2011; Yu et al., 2015), and 3D scanning technology (Chiou et al., 2016; Ji et al., 2018; Lee et al., 2016; Lee et al., 2018; Modabber et al., 2018; Zhu, Ji, Gao, & Hu, 2017). Certain information, including specific dimensions and surface information, was extracted from 3D models for further analysis. To date, research on 3D anthropometry of the external ear is still at an exploratory stage, and the morphology is not completely understood. Different measuring methods had advantages and disadvantages from varying perspectives, which suggested that researchers could choose the related method based on the purpose and rationality of a specific study. Measurements taken with traditional measuring tools, including calipers, tape, and goniometer, were convenient to use in an anthropometric survey directly conducted by anthropometrists. However, some depth and angular dimensions were difficult to measure precisely because of the ear's complex structure. The photogrammetric measuring method used a camera to record the size and 2D shape of an external ear from a specific angle along with a scale reference, such as a transparent grid with measurements or a coin. The images were further analyzed based on researchers' needs. This method was easy to be conducted as long as the settings of the shooting angle and scale reference were consistent. Hence, the photogrammetric method provided an efficient way to extract ear dimensions, especially within a wide territorial scope. The obvious limitations of the method were difficulty remaining exactly at the same shooting angle for each individual measurement and that the extracted dimensions were limited by the selected shooting angle. As for 3D anthropometry, various data collection techniques, including stereophotogrammetry, CT, and 3D scanning, could be applied to obtain 3D model of an external ear. The ear model could be used to extract various anthropometric information including linear dimensions, angular measurement, and even a 3D surface of the external ear, which are valuable for different industrial uses. The challenges of the 3D anthropometric method were mainly limited by the application of current techniques. For example, hair around the ear region became an obstacle during data collection, and the ear canal was difficult to measure directly with a light-based scanner.

4.1.2 | Anthropometric dimensions

The statistical findings of anthropometric dimensions were compared among these individual studies, and design factors were suggested for future industrial products. However, different measuring methods, dimension definitions, and sample sizes might influence the discussion.

Niemitz et al. (2007) and Sforza et al. (2009) found that ear sizes kept growth throughout the entire lifetime for German and Italian Caucasians. Brucker et al. (2003) suggested that the earlobe is the only part of the ear that keeps growing along with age. Comparing with American children, the Chinese reached the maturation sizes at a later age for ear length, and at an earlier age for ear width. Specifically, Chinese reached the full growth of ear length at the age of 14 years for boys and girls, while American reached at 13 years for boys and 12 years for girls; Chinese achieved the maturation of ear width at 7 years in boys and 5 years in girls, whereas American achieved at 7 years for boys and 6 years for girls (Farkas et al., 1992; Zhao et al., 2018). Similar to German and Italian Caucasians, ear sizes including ear length and width kept growing during adulthood for different populations, such as Americans (Tan et al., 1997), Indians (Purkait & Singh, 2007), and Chinese Han (Wang et al., 2011). These results indicated the size growth of external ears with increasing age, which indicated that age should be considered in related industrial design.

Cross-sectional studies were conducted to examine the differences in ear dimensions among various ethnicities. Koreans had larger ear length and smaller ear width than Caucasians (Lee et al., 2018). Indians had the largest ear sizes on ear length and width, followed by Caucasians, and Africans (Alexander et al., 2011). Iranians had lager ear length and width than Caucasians (Hossein et al., 2018). Considering the differences among Asian, Western and African populations, products should be designed based on anthropometric dimensions in specific markets.

In addition to age and ethnicities, researchers have verified the effects of other demographic parameters on ear dimensions. Males tended to have larger ear sizes on ear length and width than females within the same population, such as Italian (Sforza et al., 2009), Indian (Alexander et al., 2011), Sudanese (Ahmed & Omer, 2015), and Chinese (Zhu et al., 2017). Regarding ear symmetry, most of linear, area, and ratio dimensions showed a good symmetry between the left and right ears, while angular dimensions tended to be not symmetric (Alexander et al., 2011; Sforza et al., 2009). Particularly, Italian Caucasians have a larger auricle angle of the left ear than the right ear for both males and females (Sforza et al., 2009). Turkish have larger ear width of the left ear, while ear height, lobule height, and lobule weight were examined to be symmetric (Barut & Aktunc, 2006). Taiwanese have larger earhole length, ear-connection length and pinna length for the right side (Liu, 2008). The studies provided valuable information on the influence of gender and symmetry; thus, these factors should be considered when designing for particular customers.

4.2 | Applications in ear-related product design

Guidelines for applying anthropometry in product design were systematically proposed by the HFES 300 Committee (2004). The structure of the design process was outlined as follows: defining the design problem, confirming the target population, constructing the anthropometric database, generating the human variability, and transitioning anthropometric data into products. For ear-related products, previous researchers have investigated the design problems in the current market, 3D anthropometry, and product design, and fit and comfort evaluation in ear-related product design.

4.2.1 | Design problems in current market

Simon (1988) referred design to a process of problem solving. To define the design problems of ear-related products, researchers have investigated the ear-related products in the current market. Among these studies, one major problem is that more anthropometric data is needed when designing various types of products, and another is the conflict between anthropometry and current product dimensions.

Different ear dimensions are essential as anthropometric references for different product designs. In individual studies, ear dimensions were statistically analyzed for designing specific products. Jung and Jung (2003) separately investigated ear length for earmuffs, ear-connection length for ear-cup earphones, earhole length for earphones, and lobule thickness for earring pins. Chiou et al. (2016) surveyed 13 concha dimensions for hearing protection earplugs, including concha length, width, and height. Lee et al. (2016) investigated concha dimensions, such as concha length, concha width, canal length, and canal width, for earphone-head design. Moreover, Lee et al. (2016) revealed that ear dimensions selected in previous studies could not provide sufficient data for earphone design. For example, curvatures of the ear root were considered as an important factor for holding ear-band products, such as ear-band earphones, headphones, and glasses design (Lee et al., 2016). These studies highlighted the importance of different ear dimensions when designing different products, and addressed the requirements of the market to explore more ear anthropometric information for the design.

Several studies have been conducted to compare ear anthropometry of the target population with product dimensions in the market. These comparisons can identify whether the proper fit is provided for the current market. When designing for Korean, Jung and Jung (2003) proposed to change the sized of the earmuff, ear-cup earphones, and earphones, while earring pins was reported to remain the current size in the market. Mououdi et al. (2018) examined the differences between the anthropometric data and current products, which recommended redesigning earplugs based on anthropometric data for Iranians. These findings verified the need to improve current product sizes and shapes for specific target populations.

4.2.2 | 3D anthropometry and product design

As a research trend in ergonomic design, 3D anthropometry was also used to model the external ear for related product design. However, the relationship between 3D ear anthropometry and product design has not been sufficiently studied to provide a comprehensive generalization of its application in ergonomic design. Stavrakos and Ahmed-Kristensen (2016) proposed a methodological framework by applying 3D anthropometry to product design, which included discussion on various ear-related products, such as over-the-ear headphones and in-the-ear headsets. Archetypes were used to represent the target population, which was validated with in-the-ear and behind-the-ear products (Stavrakos, Ahmed-Kristensen, &

Goldman, 2016). Nine clusters were distributed to represent the ear database of 200 Danes, which were based on six ear dimensions, including ear length, breadth, and height, as well as concha X, Y, and circumference (Stavrakos et al., 2016). With similar statistical analysis, Ji et al. (2018) classified, within an ear database, the concha shape into 27 groups based on three dimensions extracted from the 3D point clouds, later verifying the results with prototypes of earphones. With cluster analysis, ear anthropometric data in a database of a specific population can, in turn, be classified into subgroups (Ji et al., 2018; Stavrakos et al., 2016), which could be used to generate archetypes for related industrial designs catering to the corresponding consumable market.

4.2.3 | Fit and comfort evaluation in ear-related product design

After anthropometric information was chosen, physical fit and comfort perception were studied to link anthropometric data with industrial design. Lee et al. (2016) examined the physical fit between product and ear anthropometry. In the study, a virtual fit analysis was conducted when the designed ear-tip earphones were placed on 3D ear models. To further study comfort perception for ear-related products, prototype testing, and online review methods were used. Chiu et al. (2014) investigated the influences of model character- istics, gender, and ear shape on comfort perception for Bluetooth earphones, suggesting that more measurements should be taken, and elastic material and adjustable structure should remain, if possible, for a better fit. Instead of analyzing user experience through specific surveys or questionnaires, Ferguson et al. (2015) presented an efficient method to combine anthropometric measurements with consumer preferences from online reviews to validate the results using earbud headphones. In these studies, researchers have explored different methods to investigate physical fit and comfort perception for ear-related products through questionnaires on comfort perception (Chiu et al., 2014), by reviewing online consumer content (Ferguson et al., 2015), and via virtual fit analysis (Lee et al., 2016). These studies were valuable for improving the fit and comfort of current ear-related products.

4.3 | Review studies and recent techniques in ear anthropometry

Even though traditional measurement has been widely used for data collection, 2D and 3D methods have also been applied in ear anthropometry to provide further details of size and shape. However, when applying these modern methods in ear anthropometry, challenges occur due to the complex morphology and variability of the external ear. This section summarizes recent techniques in ear anthropometry, with a discussion of potential uses in industrial design.

In most studies, ear anthropometry has been conducted by analyzing selected dimensions determined by anatomical landmarks. However, the definitions of these landmarks and dimensions have not been consistent among previous studies. Hunter et al. (2009) standardized the ear anatomical features and term definitions in ear morphology, while Roebuck and Casali (2011) compared terminology in current ear anthropometric studies related to design use. Based on the objectives of different studies, researchers selected different ear dimensions for analysis. Beyond the landmarks and dimensions mentioned above, Stavrakos et al. (2016) and Lee et al. (2018) organized the previous terminology and defined new landmarks and dimensions particularly for product design use. Selected landmarks and dimensions are shown in Figure 5. These basic dimensions can be further analyzed to demonstrate the characteristics of ear size for comparison among different populations.

Photogrammetry is proven to be a very efficient method for measuring ear dimensions of an enormous target population. An efficient method was proposed to extract ear dimensions with a one- yuan coin as the scaling reference, with the aim of developing a sizing

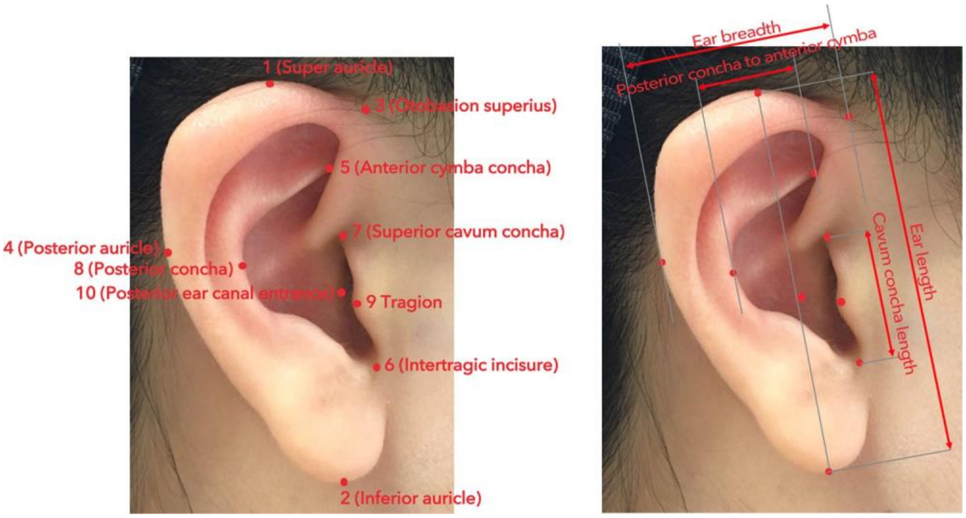

FIGURE 5 Selected landmarks and dimensions in the literature (Lee et al., 2018)

system for industrial use (Ma et al., 2017). The reliability of ear anthropometry has been compared utilizing direct measurement, photocopier scanning, and photogrammetry (Liu, Tseng, & Chia, 2010). These 2D techniques have obvious limitations in accuracy, since it is difficult to ensure the projection of each photo is from exactly the same angle.

To overcome the problems encountered in the photogrammetric method, 3D anthropometry can provide more information on the size and shape of the external ear. Different data collection techniques, such as MRI, computerized tomography (CT), and 3D scanning, can be used to conduct 3D anthropometry. Coward and Scott (2005) compared selected dimensions collected through different techniques, including traditional measurement, MRI, CT, and laser scanning, with no statistical differences amongst these measuring methods. Additionally, an MRI cannot provide surface and contour dimensions of good quality for stone casts of the external ear. Chen, Albdour, Lizardo, Chen, and Chen (2015) compared the reliability between traditional measurement and stereophotogrammetry with structured light, which suggested 3D stereophotogrammetry provided a relatively higher precision than traditional measurement, even though a high precision of measurement was found for both methods. Comparisons of ear length and ear width using these different measuring techniques were presented in Table 4. These studies provided scientific comparisons of direct measurement and various 3D techniques, even though these results were only discussed from a medical perspective. Relevant applications in industrial design still need to be explored along with additional size and shape information for a larger target population.

As a widely used industry technique for 3D anthropometry, the application of 3D scanning for analysis of the external ear can be different than for other aspects of the body. Certain challenges occur due to the optical principles, including (a) difficulty of collecting data on a complex surface structure; (b) problems when directly scanning the ear canal; and (c) the obstacles of hair or other excretions. To mitigate these challenges, researchers have tested different techniques to model the external ear. Ear impression is an option for collecting detailed information of both the ear canal and pinna. The stone casting was used to acquire almost a full representation model of the auricle, except for the ear canal (Coward & Scott, 2005; Mohamed, Mani, Seenivasan, Vaidhyanathan, & Veeravalli, 2013). Silicone molding was applied to represent the surface of the ear canal particularly (Chiou et al., 2016; Ji et al., 2018). To achieve a full illustration of the external ear, including its location on the head, researchers further tried to merge the 3D point cloud of ear impressions with a head model. Luximon, Martin, Ball, & Zhang (2016) applied an iterative closest point method to merge the point cloud with a 3D head model for a stone casting, while Lee et al. (2016) combined the digital model for silicone molding with a scanned head. To date, 3D anthropometry of the external ear still needs to be explored to gain a complete generalization of ear size and shape for the representation of a large population for industrial use.

Previously, anatomical terminology was reviewed for ear anthropometry (Hunter et al., 2009; Roebuck & Casali, 2011), which provided references for researchers to select and define consistent landmarks and dimensions. Recent computer-aided design techniques provided opportunities to conduct ear anthropometry efficiently and effectively. Ma et al. (2017) proposed an efficient photogrammetric method to gather ear dimensions, although the accuracy was difficult to control. On the whole, 3D anthropometry was tested to improve ear anthropometry with higher precision results than traditional measurement (Chen et al., 2015). Different data collection techniques, including MRI, CT, and laser scanning, were compared, and the results did not reveal statistical differences among these techniques (Hunter et al., 2009). As a widely used technique in industry, 3D scanning can be used in ear anthropometry effectively, despite resulting challenges still needing to be explored in future research.

4.4 | Limitations and future opportunities

There are limitations in the existing research that need to be addressed for future research regarding ear anthropometry and its application in industrial designs. Future opportunities were proposed but not limited in the section.

First, the findings in the literature revealed the influences of age, gender, symmetry, and ethnicity on ear dimensions. These demographic factors should be considered to represent the variation of external ears when defining the target population for industrial design. Previously, most findings from these studies contained limited ear dimensions that could only assist in specific product designs. However, previous ear dimensions were not sufficient to support current industrial products (Lee et al., 2016), especially with more and more varied products that need fitting within different ear regions. For each new design, an anthropometric survey has to be conducted if the required dimensions are not included in previous studies. For instance, curvatures of the ear root were important when designing ear-band products, which were not sufficiently studied in the literature (Lee et al., 2016). Even within a similar product appearance, the product sizes still needed to be redesigned for different populations (Mououdi et al., 2018). Regarding these situations, numerous anthropometric studies should be taken for innovative products and different populations. Hence, if a more comprehensive ear anthropometric database can be established for a target population, various industrial products can be designed for the population with related anthropometric data extracted from the same database, instead of starting a new survey.

As an effective and efficient measuring method, 3D anthropometry could provide a complete 3D model of an external ear. Anthropometric information could be extracted from the 3D ear models to assist the improvement of current, and even future, products. More related studies need to be conducted to overcome the challenges that arise during the application of 3D ear anthropometry. The inconsistency of terminology and definitions among individual studies made it difficult to systematically compare the

TABLE 4 Comparisons between different measuring techniques for ear anthropometry

Measuring technique	Device	Dimension	Precision (mm)	Reliability (mm)	Other notes
Direct measurement	Caliper	Ear length	0.64 (Chen et al., 2015)	0.60 (Liu et al., 2010); 0.73 for natural ear and for ear cast (Coward & Scott, 2005)	The external ear was impressed into a plaster ear cast.
		Ear width	0.54 (Chen et al., 2015)	0.34 (Liu et al., 2010); 0.82 for natural ear and for ear cast (Coward & Scott, 2005)	
Photogrammetry	Digital camera	Ear length	/	0.37 (Liu et al., 2010)	/
		Ear width		0.29 (Liu et al., 2010)	
MRI	MRI scanner	Ear length	/	0.56 (Coward & Scott, 2005)	MRI cannot be used to scan cast model with good quality. (Coward & Scott, 2005)
		Ear width		1.17 (Coward & Scott, 2005)	
CT	CT scanner	Ear length	/	0.59 (Coward & Scott, 2005)	Data was acquired from ear cast since CT scanning was invasive to human body. (Coward & Scott, 2005)
		Ear width		0.68 (Coward & Scott, 2005)	
Laser scanning	Laser scanner	Ear length	/	0.40 (Coward & Scott, 2005)	/
		Ear width		3.39 (Coward & Scott, 2005)	
Structured-light scanning	Structured-light scanner	Ear length	0.30 (Chen et al., 2015)	/	/
		Ear width	0.28 (Chen et al., 2015)		

anthropometric findings in the literature for more generalized applications. Technically, 3D anthropometric applications still have to be explored to overcome challenges during practical usage, including difficulty in directly scanning the ear canal and the obstacles of hair and other excretions. Until now, researchers have tried different techniques to acquire the ear model, with related limitations discussed in the literature. Future research can be conducted to solve these technical problems.

Another research gap is related to a comprehensive exploration of the relationship between anthropometric data and related product design. In conjunction with user experience, related products can be designed with consideration of physical fit and comfort perception. Results in the review showed that most relevant studies focused on specific products or the contradiction between human variability and current product characteristics. Specific studies can assist in a particular product design, but there is no sufficient research systematically linking ear anthropometry with related product design. Therefore, there is still a need to study relevant fit issues both physically and psychologically to guide holistic, user-centered design for ear-related products.

5 | CONCLUSIONS

To conclude, 3D anthropometry can provide more thorough and accurate information on size and shape compared to traditional measurement and photogrammetry. However, direct applications of 3D scanning in ear anthropometry are still quite challenging, considering the ear's complex structure and variability among individuals. This paper systematically reviewed previous ear anthropometry research and its application in ergonomic use, summarized methods and results of ear anthropometry in individual studies, and suggested establishing a universal reference to represent human variability using 3D anthropometry with con- siderations of different demographic factors. The paper also examined the application of ear anthropometry in related product design, thus addressing the potential research opportunities for user-centered design. Recent techniques in ear anthropometry were compared in the paper, which included a discussion of potential use for further research.

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