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A review of the methodology and applications of anthropometry in ergonomics and product design

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ABSTRACT
Anthropometry is a key element of ergonomic studies for addressing the problem of fitting the tasks/products to user characteristics, but there is a gap between anthropometric data and their application for designing ergonomic products and environments. This research was conducted to review the literature on the methodology and applications of anthropometry for the ergonomic design of products and environments, and to identify where further research is needed to improve its application and evaluation protocols. One hundred and sixteen papers meeting the inclusion criteria were reviewed. Although a number of anthropometric investigations have been conducted to improve the design of products/environments for different users, further research seems to be necessary, particularly for special groups, such as children, the elderly and people with disabilities. Different anthropometric measurement methods/techniques and fitting criteria are discussed regarding their applicability for various design applications. This review also highlights methodological issues (sampling considerations and prototype evaluation and testing) that should be considered in future research to ensure a user-centred approach of the design process.

Practitioner Summary: A literature review was conducted on the methodology and applications of anthropometry for the ergonomic design of products/environments. This review emphasises the need for anthropometric research to design for special groups, such as children, the elderly and people with disabilities, and methodological issues that should be considered in future research.

Abbreviations: 1D: one-dimensional; 2D: two-dimensional; 3D: three-dimensional; HF/E: Human Factors/Ergonomics; PCA: Principal Components Analysis; CA: Cluster Analysis; DHM: Digital Human Modelling

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Anthropometric data; designing; fitting criteria; user groups

1. Introduction

Ergonomics is the science of fitting a task to humans and products to users (Pheasant 2003). Designers of many products, environments and systems should consider the physical size and shape of target users—frequently referred to as designing for physical accommodation (Garneau and Parkinson 2016)—as it is essential that the workplace be suited to the body size and mobility of operators (Kroemer and Grandjean, 1997).

Anthropometry has many applications in a variety of fields, including ergonomics, product design, medicine, nutrition and engineering. Examples of the application of anthropometry in ergonomics generally include the design and layout of the spaces in which people live and work, with particular reference to anthropometric considerations, such as reach (e.g. the ability to grasp and operate controls, such as switches, buttons, knobs, etc.) (Bullock 1974; Nowak 1978; Sengupta and Das 2000; Das, Shikdar, and Winters 2007; Fathallah et al. 2009; Lin et al. 2016), clearance (e.g. adequate head room, elbow room, leg room, etc., which separate the body from hazards such as surrounding equipment) (Dianat et al. 2013; Hsiao 2013; Ghaderi, Maleki, and Dianat 2014), posture (e.g. relationship between the body dimensions and those of the workstation) (Wang et al. 1999; Das, Shikdar, and Winters 2007; Kushwaha and Kane 2016) and strength (e.g. the application and analysis of forces and torque in the operation of controls or in other physical tasks) (Eksioglu 2004; Dianat et al. 2017), as well as the characterisation of the differences in anthropometric characteristics among different occupational and ethnic groups (Hu et al. 2007;

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Hsiao et al. 2015a; Stewart, Ledingham, and Williams 2017) and changes over time in body dimensions (Tomkinson et al. 2017). Additionally, anthropometric data are essential for applying ergonomic principles to the design and improvement of a wide range of products for different users (Dewangan, Owary, and Datta 2008; Liu, 2008; Garneau and Parkinson 2011; Hsiao 2013; Ghaderi, Maleki, and Dianat 2014).

Based on the user-centred design approach, all products, including consumer products, clothes, living and working environments, etc., should be adjusted to user anthropometry to reduce negative health consequences, such as musculoskeletal pain and injuries. However, previous research has shown that the fit between different products, spaces or environments and users is not always optimal (Fathallah et al. 2009; Hanson et al. 2009; Dianat et al. 2013; Ghaderi, Maleki, and Dianat 2014; Brkić, Klarin, and Brkić 2015; Lacko et al. 2017).

Recent studies have reported an increasing prevalence of musculoskeletal problems in general and working populations in both developed and developing countries (Ahacic and Kåreholt, 2010; Hagen et al. 2011; Dianat et al. 2015). Poorly designed and ill-fitting products and workplaces that are not compatible with users' anthropometry are considered one of the factors that can increase the risk of developing musculoskeletal pain and discomfort (Spyropoulos et al. 2007; Hanson et al. 2009; Dianat and Salimi 2014; Kushwaha and Kane 2016). This increased risk might be explained by individual characteristics, such as anthropometric parameters, perhaps influencing the method of task performance and consequently affecting the amplitude and severity of exposure to awkward working postures, executed movements and the forces exerted (Buckle and Devereux 2002). Other researchers have also reported a high rate of occupational injuries due to inappropriate equipment design and have proposed anthropometric characteristic analysis to improve safety and to prevent injuries in the workplace (Davies et al. 1980; Brkić, Klarin, and Brkić 2015; Sutalaksana and Widyanti 2016). Therefore, anthropometric investigations can provide essential data for designing ergonomic equipment, tools, products or environments and therefore can have significant potential to improve work efficiency, productivity, usability, fit, comfort and safety (Hanson et al. 2009; Laios and Giannatsis 2010; Kushwaha and Kane 2016).

1.1. Rationale

The rationale for conducting this research originated from two issues related to anthropometry in design: methodological issue and application issue. To the authors' knowledge, there has been relatively little research into the methodology that should be used for the application of anthropometric data in the design of products and environments, and the existing published guidelines remain inadequate (methodological issue). As a result, and despite a large number of anthropometric investigations, very few attempts have been made to propose recommendations and guidelines to achieve user-centred products or environments, particularly when the design involves multivariate accommodation of anthropometric variability (application issue). Even with the advent of new technologies, such as three-dimensional scanning methods, there is still a gap between the anthropometric data and their applications for designing ergonomics products and environments. Therefore, the present research was conducted to review the literature on the methodology and applications of anthropometry for the ergonomic design of products and environments and to identify where further research is needed to improve its application and evaluation protocols.

2. Methodology

In the present review, research papers discussing different anthropometric approaches for the ergonomic design of products and environments were identified and selected, and then the published information was analysed to develop guidelines and recommendations in this regard. Two databases, SciVerse Scopus and PubMed, were used to find relevant published papers in the field studies of anthropometric surveys for specific purposes mentioned above. The following keywords were used to identify relevant papers: 'anthropometry' or 'anthropometric', 'dimensions' or 'characteristics' or 'sizes' or 'shapes' or 'measures' or 'measurements'. To avoid papers not relevant to the topic under study, the search was performed using the Boolean operator 'AND', together with the search terms 'ergonomics' or 'ergonomic', 'design' or 'designing' or 'redesign' or 'redesigning'. Articles resulting from the literature search were initially screened based on their titles and abstracts. If the title and abstract did not provide sufficient information to determine the eligibility, the full texts of potentially relevant articles were screened independently by two authors for inclusion. Moreover, authors reviewed references cited within all relevant retrieved papers to identify additional papers.

The following additional inclusion criteria were also adopted:

- Original and review articles written in English and published or in press in peer-reviewed journals;

- Articles published or in press between January 1971 and June 2017;
- Papers with ergonomic research/application (rather than merely pure, descriptive anthropometric studies) and
- Papers with specific approaches or criteria moving from anthropometric data to ergonomic/product design.

To be included in the review, the paper had to meet the above-mentioned inclusion criteria. Papers that did not present application in the ergonomics field and merely presented anthropometric data were excluded. In other words, the present paper differentiates between data collection studies and that research related to methodology or application of anthropometry for design. The application considered in this review is the use of different techniques such as percentiles, principal component analysis, regression models, etc. to design a specific workstation/work area or product. Examples of exclusions are Smith and Norris (2004), Pagano, Parkinson, and Reed (2015) and Vyavahare and Kallurkar (2016).

3. Results and discussion

Searches resulted in a total of 1609 records (984 from Scopus and 625 from PubMed) with different combinations of keywords, which was then reduced to 1068 after the removal of duplicate entries (Figure 1). After screening the title, abstract and keywords of each article, 184 papers were identified as being potentially relevant. After reviewing the corresponding full texts, 102 papers were selected based on the inclusion criteria. Finally, 14 additional papers were added after manual searches of the bibliography/reference lists were done from the 102 selected articles. The total number of articles to be reviewed comprises 116 papers.

In this section, different anthropometric measurement methods and techniques are discussed first (section 3.1), followed by a discussion of research in which anthropometry was collected and used for design. For this purpose, results from papers included in this review are grouped according to the designs/products for the specific user population (section 3.2) and are summarised in Tables 1 to 4. Such a classification can lead to a better understanding of the current situation and presents the direction for future research of each target group. This is particularly of interest as, from an anthropometric point of view, every user group has its own needs and requirements which should be considered in future research. The selected papers are also discussed in terms of their applicability (domain-specific or generic) (section 3.3) and sampling methodologies (section 3.4). Then, fitting criteria that maximise matches between products andenvironments and users are discussed in terms of their applicability for various design applications (section 3.5). The user-centred approach of the design process is discussed in the final part of the review (section 3.6). The two last parts address design practice more specifically.

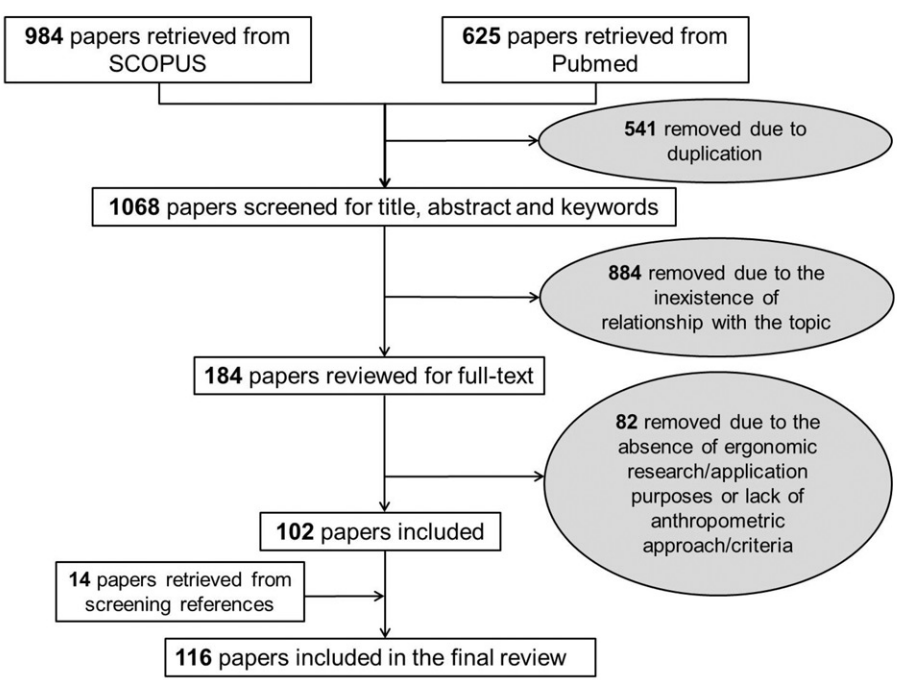

Figure 1. Flow diagram of the search strategy and exclusion criteria.

Table 1. Research related to designs/products for general population.

Study	Design/product	Application domain	Target group	Sampling plan	Sample size (n)	Age range (years)	Dimensions measured (n)	Anthropometric measurement/data	Fitting criteria
McClelland and Ward (1976)	Sanitary ware design (W.C. seat design)	D	General population	×	140	18–81	10	Photography	DS
Hira (1980)	Classroom desks	D	University students		40	NR	6	DMM	DS
Gazzuolo et al. (1992)	Garment pattern development	G	Women		50	19–50	35	DMM and photography	RM
Jung et al. (1998)	Passenger seats and coach layouts for trains	D	General population		NA	20–25	12	Anthropometric database	P
McCulloch, Paal, and Ashdown (1998)	Clothing design	G	General population		NA	18–51	5	ANSUR database	A nonlinear optimisation approach to maximise the quality of fit
Meunier et al. (2000)	Helmets	G	General population		30	NR	3	DMM and 3D scanning	Colour-coded illustrations to display matches between the head and helmet scans
Mochimaru, Kouchi, and Dohi (2000)	Shoe last design	G	Adult female population		56	18–59	4	3D scanning	CA
Jung and Jung (2003)	Ear-related products (earphones and earmuffs)	D	General/working population		600	17–89	7	DMM	P
Lee, Hong, and Kim (2004)	Brassieres	G	Women		37	NR	10	3D scanning	CA
Witana, Feng, and Goonetilleke (2004)	Footwear	G	Men		20	19–26	5	3D scanning	RM
Chou and Hsiao (2005)	Electric scooter	D	General population		60	18-25	9	2D anthropometer with laser pointer	Decision-making model based on the weighted generalised mean method
Vogt, Mergl, and Bubb (2005)	Interior layout design of passenger vehicles	D	General population		NA	18–70	2	Virtual design using RAMSIS software tool	Based on comfort angles for the joints of the human body
Gupta et al. (2006)	Garment sizing	G	Women		1900	18–35	20	DMM	Linear programming approach
Zheng, Yu, and Fan (2007)	Intimate apparel	D	Women		456	20–39	103	3D scanning	PCA, CA
Krauss et al. (2008)	Shoe design	G	Adult population		847	14–60	10	3D scanning	CA
Liu (2008)	Earphones, headphones, Bluetooth, cup earphones	G	General population		200	20-59	4	Photogrammetry	P
Tunay and Melemez (2008)	Classroom furniture	D	University students		1049	NR	13	DMM	P
Xiong et al. (2008)	Footwear	G	Adult population		50	19-24	3	3D scanning	Allometry

(continued)

Table 1. Continued.

Study	Design/product	Application domain	Target group	Sampling plan	Sample size (n)	Age range (years)	Dimensions measured (n)	Anthropometric measurement/data	Fitting criteria
Hanson et al. (2009)	Products and workplaces	D	General population	×	367	18-65	43	DMM and 3D scanning	DS, P
Högberg (2009)	Vehicle interior design	G	General population		NA	18-70	4	Virtual design using RAMSIS software tool	Adjustments based on H-point
Smardzewski (2009)	Furniture (sitting/ meal consumption)	G	General population		NA	NR	NR	Anthropometric database	P
Jung, Kwon, and You (2010)	Men's pants sizing system design	G	Males		NA	18–51	12	US Army male anthropometric data	RM
Thariq, Munasinghe, and Abeysekara (2010)	Chairs with mounted desktops	D	University students		385	20-28	15	DMM	Bivariate design (boundary cases)
Karuppiah et al. (2011)	Motorcycle lumbar support	D	Students		1032	18–24	11	DMM	P
Garneau and Parkinson (2011)	Bicycles	G	Men		NA	18–51	2	ANSUR database	Manikin-based population model and hybrid approaches
Hong et al. (2011)	Sports shoes	G	Adult population		2321	18–30	19	DMM and 3D scanning	CA
Krauss et al. (2011)	Shoe last designs	G	Adult population		287	18-65	5	3D scanning	CA
Osquei-Zadeh et al. (2011)	Library furniture	D	University students	×	267	18–26	11	DMM	Ranges, equations that covered the 5th–95th percentiles
Pandarum, Yu, and Hunter (2011)	Intimate apparel	D	Women		176	23–65	5	3D scanning	DS
Ismaila et al. (2013)	Furniture design	D	University students		720	17–27	12	DMM	P
Hoque et al. (2014)	Classroom furniture	D	University students		500	17–22	15	DMM	Ranges, equations that covered the 5th-95th percentiles
Dhara et al. (2015)	Vegetable cutter	D	Women		150	NR	3	DMM	P
Bhuiyan and Hossain (2015)	University hall furniture design	D	University students		88	19–28	35	DMM	P
Lee and Wang (2015)	Shoe lasts and footwear insoles	D	General population		3000	18-60	9	3D scanning	PCA
Wang et al. (2015)	Female urination device	D	Women		24	21–38	6	3D scanning	P
Hoque et al. (2016)	Bus passenger seats	D	General population		720	18–62	15	DMM	Ranges and equations that covered the 5th–95th percentiles
Zadry, Susanti, and Rahmayanti (2016)	Spinal board	D	General population		NA	15–64	9	Anthropometric database	P
Lacko et al. (2017)	Brain-computer interfacing headset	D	General population		13	20–25	4	3D anthropometry	PCA

CA: cluster analysis; D: domain-specific; DS: descriptive statistics; DMM: direct manual measurement; G: generic; NA: not applicable; NR: not reported; P: percentiles; PCA: principal component analysis; RM: regression models.

Table 2. Research related to designs/products for working population.

Study	Design/product	Application domain	Target group	Sampling plan	Sample size (n)	Age range (yr)	Dimensions measured (n)	Anthropometric measurement/data	Fitting criteria
Bullock (1974)	Aircraft cockpits (arm reach boundaries)	D	Pilots	×	110	NR	13	DMM	P
Das and Grady (1983)	Workplace layout designs	D	Industrial workers		NA	NR	14	Anthropometric database	P
Courtney and Wong (1985)	Bus driver cabs	D	Bus drivers		NA	20–55	56	Anthropometric database of the US military population	P
Nowak (1987)	Workstation designs	D	Industrial workers		430	18–65	22	DMM	P
Gite and Yadav (1989)	Hand tools and machinery	D	Agricultural workers		39	15–60	52	DMM	P
Coblentz, Mollard, and Ignazi (1991)	Protective equipment (military mask)	D	Military population		509	17–50	13	Stereophotogrammetry	DS
Das and Sengupta (1996)	Supermarket checkstand	D	Female cashiers		NR	NR	9	Anthropometric database	P
Sargent, Kay, and Sargent (1997)	Nuclear power plant console panels	G	Power plant operators		NR	NR	NR	Anthropometric database	P
Schultz et al. (1998)	Touch-screen displays	G	Working population		26	NR	2	Anthropometric database	P
Laing et al. (1999)	Protective clothing	D	Male firefighters		691	19–64	55	DMM	PCA, CA
Wang et al. (1999)	Work environment designs	D	Workers		1200	18-65	308	DMM and 3D scanning	DS
Yadav et al. (1999)	Tractor cabs	D	Tractor operators		105	NR	24	DMM	P
Sengupta and Das (2000)	Workstation designs (maximum reach)	D	Industrial workers	×	80	17–50	2	Potentiometric measurement	P
Hsiao, Bradtmiller, and Whitestone (2003)	Fall-protection harnesses	D	Construction workers	×	98	18-59	23	DMM	PCA
Hsiao et al. (2005)	Tractor cabs	D	Tractor drivers	×	100	18–76	33	DMM and 3D scanning	PCA
Hsu and Wang (2005)	Pant sizing	G	Army soldiers		610	NR	265	DMM	Decision tree method
Das, Shikdar, and Winters (2007)	Workstation designs for repetitive drill press operation	D	Drill operators		16	NR	NR	DMM	P
Parkinson et al. (2007)	Truck cabs	G	Truck drivers		NA	18–51	3	ANSUR database	Virtual fitting trial
Mehta et al. (2008)	Tractor seat designs	D	Male tractor operators		5434	15–67	9	DMM	P
Dewangan, Owary, and Datta (2008)	Agricultural hand tool designs	D	Agricultural workers	×	400	18–60	76	DMM	P
Hsiao et al. (2009)	Fall-arrest harness designs	D	Construction workers	×	216	NR	NR	3D scanning	PCA
Kwon et al. (2009)	Key dimensions for glove sizing system	D	US Army military personnel		NA	18–49	70	US Army hand anthropometric data	Correlation, RM
Dewangan, Owary, and Datta (2010)	Agricultural hand tools and equipment	D	Male agricultural workers	×	801	18–60	76	DMM	P
Guan et al. (2012)	Truck cab designs	D	Truck drivers	×	1950	20–65	35	DMM	PCA
Hsiao (2013)	Tractor roll-over protective structures, respirator test panels, fire truck cabs, and fall-arrest harnesses	D	Tractor operators, respirator users, firefighters and civilian workers	×	100, 3718, 951 and 816 subjects, respectively	18-76	11	DMM, 2D and 3D scanning	DS, probability modelling, PCA and Elliptic Fourier Analysis-based shape expression

(*continued*)

Table 2. Continued.

Study	Design/product	Application domain	Target group	Sampling plan	Sample size (n)	Age range (yr)	Dimensions measured (n)	Anthropometric measurement/data	Fitting criteria
Lee et al. (2013)	Helicopter cockpit design	D	Male pilots	×	94	20–49	21	DMM	DS, P
Mahmoudi and Bazrafshan (2013)	Carpet-weaver's chairs	D	Carpet weavers		47	18–58	12	DMM	P
Ghaderi, Maleki, and Dianat (2014)	Combine harvester seats	D	Agricultural machinery workers	×	200	19–70	9	DMM	P
Poirson and Parkinson (2014)	Cockpit seats	D	Male commercial pilots		NA	18–51	3	ANSUR database	Genetic algorithm
Yusoff et al. (2014)	Harvesting tools (chisels)	D	Harvesting workers	×	273	18–49	2	DMM	P
Hsiao et al. (2015a)	Protective gloves	D	Firefighters	×	951	18–65	14	2D hand scanning	PCA
Hsiao et al. (2015b)	Fire apparatus seat and seatbelt designs	D	Firefighters	×	951	18–65	14	DMM	P
Brkić, Klarin, and Brkić (2015)	Crane cabins	D	Crane operators		64	NR	9	DMM	P
Mahoney, Kurczewski, and Froede (2015)	Multi-user workstations	G	College-aged students		NA	NR	3	National Health and Nutrition Examination Survey (NHANES) and ANSUR data sets	Monte Carlo simulation
Syuaib (2015a,b)	Agricultural tools and equipment	D	Agricultural workers	×	141 and 371	NR	42 and 30	DMM	P
Zunjic et al. (2015)	Crane cabins	D	Crane operators		64	NR	9	DMM	P
Kushwaha and Kane (2016)	Workstation design of shipping crane cabins in steel industry	D	Crane operators		27	28–54	5	DMM	P
Mugisa et al. (2016)	Agricultural hand tool design	D	Female farmers		89	NR	28	DMM	P
Şenol (2016)	Cockpit designs	D	Male helicopter pilots		100	26–44	7	DMM	RM
Sutalaksana and Widyanti (2016)	Machinery and workstation designs	D	Roof tile workers		660	NR	17	DMM	P
Rhie et al. (2017)	Multi-function consoles used in Submarines	D	Navy personnel		NA	20–39	NR	Anthropometric database	P
Stewart, Ledingham, and Williams (2017)	Survival suit designs	D	Offshore workers	×	588	NR	19	3D scanning	CA

CA: cluster analysis; D: domain-specific; DS: descriptive statistics; DMM: direct manual measurement; G: generic; NA: not applicable; NR: not reported; P: percentiles; PCA: principal component analysis; RM: regression models.

Table 3. Research related designs/products for children.

Study	Design/product	Application domain	Target group	Sampling plan	Sample size (*n*)	Age range (years)	Dimensions measured (*n*)	Anthropometric measurement/data	Fitting criteria
Evans, Courtney, and Fok (1988)	Classroom furniture	D	Primary and secondary schoolchildren		684	6–18	13	DMM	P
Jeong and Park (1990)	Classroom furniture	D	Secondary schoolchildren		1248	6–17	10	DMM	RM
Steenbekkers and Molenbroek (1990)	Cribs, playpens, toys and wheelchairs	D	Children	×	633	0–5.5	33	DMM	DS, P
Molenbroek, Kroon-Ramaekers, and Snijders (2003)	Classroom furniture	G	School students		above 3000	4–20	11	DMM	DS, P
Chung and Wong (2007)	Classroom furniture	D	Primary school children		214	10–13	13	DMM	Ranges and equations that covered the 5th–95th percentiles
García-Acosta and Lange-Morales (2007)	Classroom furniture	D	School students		NA	5–18	12	Anthropometric database	Ranges that covered the 5th–95th percentiles
Chung, Lin, and Wang (2007)	Clothing design	D	School children		7800	6–18	36	Anthropometric database	CA
Savanur, Altekar, and De (2007)	Classroom furniture	D	School students		225	10–14	42	DMM	P
Domljan and Grbac (2008)	Classroom furniture	D	Primary school children		556	6–14	4	DMM	P
Fathallah et al. (2009)	Farm tractor controls	D	Youth tractor operators		3900	12–16	10	Anthropometric database	Reach simulations using software and subsequent use of percentiles
Agha (2010)	Classroom furniture	D	Primary school children		600	6–11	5	DMM	Upper and lower bounds of the measured dimensions
Laios and Giannatsis (2010)	Children bicycles	D	Children		1247	NR	9	Anthropometric database	PCA
Oyewole, Haight, and Freivalds (2010)	Classroom furniture/ computer work stations	D	Primary school children		20	6–7	13	DMM	DS, P
Musa (2011)	Classroom furniture	D	Secondary school children		621	12–17	15	DMM	P
Agha and Alnahhal (2012)	Classroom furniture	G	Primary school children		600	6–11	4	DMM	Neural network, RM
Dianat et al. (2013)	Classroom furniture	D	Secondary school children		978	15–18	9	DMM	Ranges and equations that covered the 5th–95th percentiles
van Niekerk et al. (2013)	Computer workstations	D	School children	×	689	13–18	4	DMM	DS, P
Grozdanovic, Jekic, and Stojiljkovic (2014)	Playground equipment	D	Children		65	3–6	31	DMM	Ranges and equations that covered the 5th–95th percentiles
Ismaila et al. (2015)	Classroom furniture	D	Primary school children		200	5–14	8	DMM	P
Castellucci et al. (2016)	Classroom furniture	D	School children	×	3078	5–19	8	DMM	Ranges and equations that covered the 5th–95th percentiles

CA: cluster analysis; D: domain-specific; DS: descriptive statistics; DMM: direct manual measurement; G: generic; NA: not applicable; NR: not reported; P: percentiles; PCA: principal component analysis; RM: regression models.

Table 4. Research related to designs/products for elderly and people with disabilities.

Study	Design/product	Application domain	Target group	Sampling plan	Sample size (n)	Age range (years)	Dimensions measured (n)	Anthropometric measurement/data	Fitting criteria
Kenward (1971)	Wheelchair design	D	Young wheelchair users		66	5–16	13	DMM	DS
Goswami et al. (1986)	Tricycle design	D	Men with disabilities		61	NR	16	DMM	DS, P
Nowak (1989)	Workspace design	D	Disabled people		77	15–18	17	DMM	P
Hobson and Molenbroek (1990)	Design of seating and mobility devices	D	People with disabilities		133	2–55	94	DMM	DS, P
Jarosz (1996)	Workspace design	D	Wheelchair users		170	18–39	18	DMM	DS, P
Das and Kozey (1999)	Workstation design	D	Wheelchair mobile adults	×	62	20–64	16	Photogrammetry	DS, P
Kothiyal and Tettey (2001)	Office chairs and tables, storage shelves, and public transport bus seats	D	Elderly people		171	≥65	22	DMM	DS, P
Kozey and Das (2004)	Normal and maximum reach dimensions	D	Adult wheelchair users		62	20–64	2	Potentiometric measurement	DS, P
Paquet and Feathers (2004)	Input data for 3D human modelling	D	Manual and powered wheelchair users		121	22–94	31	3D data using an electromechanical probe	DS, P
Yu et al. (2013)	Pressure therapy gloves	G	Patients with hand problems		10	20–28	33	DMM, 2D and 3D scanning	DS
Chakrabortty, Asadujjaman, and Nuruzzaman (2014)	Hospital beds	D	Sensitive patients		103	NR	5	DMM	Fuzzy logic, analytical hierarchy process, RM
Dawal et al. (2015)	Domestic furniture and appliances	D	Elderly population		107	55–70	60	DMM	P
Hrovatin et al. (2015)	Kitchen furniture	G	Elderly population		NA	≥60	NR	Anthropometric database	P
Dawal et al. (2016)	Praying facilities	D	Elderly and disabled people		20	≥50	16	DMM	P
Lin et al. (2016)	Over bed table design	D	Bedridden patients		NA	18-25	10)	Anthropometric databases	DS, P

CA: cluster analysis; D: domain-specific; DS: descriptive statistics; DMM: direct manual measurement; G: generic; NA: not applicable; NR: not reported; P: percentiles; PCA: principal component analysis; RM: regression models.

3.1. Measurement methods

The basic anthropometric measurements of the human body include linear measurements (e.g. breadth, height and length measurements), angular measurements (e.g. measurements between planes and lines that cross the human body, such as flexion/extension on the sagittal plane), circumferences (e.g. head, neck and chest circumferences) and force measurements (e.g. grip, pinch and torque strength). Several anthropometric measurement methods and techniques have been developed over the years to maximise the level of accuracy and the repeatability of measurements. However, anthropometric data are subject to numerous sources of error, such as natural within-subject variation over time, posture, landmark identification, instrument position/orientation, pressure exerted by the measuring instrument, etc., which seem to be unavoidable. Nevertheless, it has been acknowledged that the level of accuracy and precision in anthropometric measurements depends on the application (Meunier and Yin 2000). Anthropometric measurement methods can be generally divided into one-dimensional (1D) direct manual measurements (Courtney and Wong 1985; Jeong and Park 1990; Das and Kozey 1999; Laing et al. 1999; Ghaderi, Maleki, and Dianat 2014), two-dimensional (2D) photogrammetric methods (Gazzuolo et al. 1992; Chou and Hsiao 2005; Yu et al. 2013; Hsiao et al. 2015a) and, more recently, three-dimensional (3D) scanning methods (Wang et al. 1999; Meunier et al. 2000; Paquet and Feathers 2004; Krauss et al. 2011; Stewart, Ledingham, and Williams 2017). These methods are described in more detail as follows.

3.1.1. Direct manual measurements

The direct measurement protocol is an easy and inexpensive method, in which traditional tools such as flexible measuring tapes, callipers, measuring boards and rulers are used to generate 1 D or univariate anthropometric data, such as distances and circumferences. This review indicates that most previous anthropometric research on designs or products have been devoted to 1 D data using traditional direct manual measurement methods. Almost all research on designs/products for children and those related to designs/products for the general and working populations have applied this method of anthropometric data collection (as seen in Tables 1 to 3). Nevertheless, the consistency and accuracy of the traditional direct manual measurements can be influenced by human error and subject variation (e.g. participants must remain still during the measurement period), and the measurement process is tedious and time consuming due to multiple direct measurements (Wang et al. 2007; Fourie et al. 2011; Poirson and Parkinson 2014; Lacko et al. 2017). Traditional methods of collecting anthropometric data can also represent some inherent limitations (e.g. locating the required body landmarks, skin deformation due to the application of measurement instruments and maintaining standard postures during measurement sessions) and errors, such as intra- and inter-observer errors (Feathers, Paquet, and Drury 2004; Hanson et al. 2009; Sims et al. 2012).

3.1.2. 2 D photogrammetric methods

Another method for collecting anthropometric data is based on the use of multi-camera photogrammetric systems that provide 2 D images. In 2 D photogrammetry, the surface data of the human body can be obtained by registering relatively simultaneous 2 D images from different viewing angles (Yu et al., 2013). These methods have been used in several previous anthropometric research to design workstations for wheelchair-mobile adults (Das and Kozey 1999), pressure therapy gloves for patients with hand problems (Yu et al., 2013) and protective gloves for firefighters (Hsiao et al., 2015a). Although digital cameras are relatively less expensive, the acquired images can be influenced by a number of factors, such as the number of registered images, viewing angle, distortion of a camera lens when capturing the images and lighting conditions (Lau and Armstrong 2011; Yu et al. 2013). Nevertheless, 2 D image-based anthropometric measurement systems compare favourably (in terms of reliability indices, such as Intraclass Correlation Coefficient [ICC] and Technical Error of Measurement [TEM]) with traditional 1 D measurement systems (Meunier and Yin 2000).

3.1.3. 3 D scanning methods

Three-dimensional anthropometry has been used for more than two decades, with methods ranging from manual collection of 3D locations of body landmarks using electromechanical probe or electromagnetic sensing systems to 3 D scanning of entire body surfaces (Feathers, Paquet, and Drury 2004). With the development of new technologies, human body dimensions can now be measured indirectly using a 3D scanning method. The 3D scanning method has been developed through advanced optoelectronic technologies (Stančić, Music, and Zanchi 2013; Lee and Wang 2015). The 3D scanner system involves a light source, sensors and a controller (Wang et al. 2007). Optoelectronic devices generally operate based on three different principles, including laser line scanners (Meunier et al. 2000; Chou and Hsiao 2005; Yu et al. 2013), structured light scanners (Wu et al. 2006) and multi-view camera systems (Jones et al. 1989; Starck, Hilton, and Illingworth 2001). 3D scanners capture several images of the body surface from various angles as a 3D point cloud. The individual point cloud data are then processed by fully or semi-automated software functions to produce meshes which can subsequently be transformed into solid objects (e.g. 3D virtual human model) for measurement (Wang et al. 2007). Anthropometric data could be extracted subsequently from these 3D images with the aid of a computer program (Wang et al. 2007; Kouchi and Mochimaru 2011), which seems to be the most effective method for obtaining 3D models, allowing a high sampling rate and rapid measurement (Stančić, Musić, and Zanchi 2013).

3.1.4. Comparison of methods

In recent years, indirect 3D anthropometric measurements have been adopted to design a variety of products or environments for general and working populations, and for the elderly and people with disabilities. These projects have included footwear designs (Mochimaru, Kouchi, and Dohi 2000; Witana, Feng, and Goonetilleke 2004; Krauss et al. 2008, 2011; Hong et al. 2011; Lee and Wang 2015), fashion and apparel designs (Lee, Hong, and Kim 2004; Gupta et al. 2006; Zheng, Yu, and Fan 2007; Jung, Kwon, and You 2010; Pandarum, Yu, and Hunter 2011), head-related product designs (Meunier et al. 2000; Lacko et al. 2017), workstations or work environment designs (Wang et al. 1999; Hanson et al. 2009), personal protective equipment designs (Hsiao et al. 2009, 2013; Stewart, Ledingham, and Williams 2017), tractor cab designs (Hsiao et al. 2005) and electric scooter designs (Chou and Hsiao 2005), as well as other products for special groups, such as the elderly and physically impaired individuals (Yu et al. 2013; Wang et al. 2015).

Computerised image-based systems can offer an alternative to overcome some of the problems of traditional anthropometric measurement methods, but they introduce their own sources of error, such as perspective distortion, camera resolution, camera calibration, landmarking errors, and modelling errors (Meunier and Yin 2000; Wang et al., 2007; Stančić, Musić, and Zanchi 2013). A number of investigations have evaluated the comparability of 3D scanned data with manually measured data (Feathers, Paquet, and Drury 2004; Weinberg et al., 2006; Wong et al., 2008; Sims et al., 2012), repeatability of scan-derived body dimensions (Weinberg et al., 2006; Robinette and Daanen 2006; Wong et al., 2008; Fourie et al., 2011; Bragança et al., 2017), and repeatability of scan-derived landmark locations obtained from the same image (Aldridge et al., 2005). However, there have been contradictory findings regarding the accuracy and precision of different anthropometric methods and techniques. Inadequacies in the required level of accuracy and the lack of a generally accepted quality evaluation protocol might be responsible for these contradictory results. This may be due to the fact that anthropometric protocols are generally defined in broad terms, which may lead to misinterpretation of fine measurement technique. Results of a recent review indicated that the accuracy, reliability and precision issues regarding manual anthropometric surveys are poorly addressed in the ergonomics literature (Viviani et al., 2018). It was shown that only 27 of the 79 reviewed papers mentioned at least one of the terms and none of the papers evaluated all of the terms. Only one paper mentioned and assessed precision and reliability of the measurement procedure, while none of the publications evaluated accuracy. It seems that the most difficult part of the issue is to establish the 'true value' of measurements (Viviani et al. 2018). In this regard, the International Society for the Advancement of Kinanthropometry (ISAK) (http://www.isak.global/) is an example which not only defines protocols precisely, but also conducts practical courses that quantify intra- and inter-measurer errors and offer 4 levels of measurement certificates. Although this can be considered as a best practice approach, it may not be feasible to adopt it in many ergonomics applications.

Results of this review reveal a relatively large contribution of traditional methods of measuring samples (69 of the 116 reviewed papers) with traditional instruments, such as anthropometers, tape and callipers (1D measurements). Outcomes of this research are generally presented as percentiles, means and standard deviations. In contrast, 3D scan-derived data are rare, and if used, data are mostly kept in commercial domains, such as Size China (Ball, 2009) and the CAESAR project (Harrison and Robinette, 2002; Robinette et al., 2002). Data about variations in the extracted dimensions are not published in the public domain but in scientific journals. Through some web sources (e.g. http://www.3dscanstore.com; http://3ddigitaldoubles.com, etc.), 3D scans are downloadable after a payment. However, when downloads are available, numerous dimensions can be extracted from 3D scans. Nevertheless, it should be noted that, in most cases, the extracted 1D data from the raw scans are not necessarily useful in design.

3.2. Target population

This section (and its subsections) is devoted to research in which anthropometric data were collected (or inferred) and then used for design. Anthropometric research related to the design of various products or spaces can be classified based on the specified target population. This research can generally be classified as designs/products related to (1) general populations, (2) working populations, (3) children and (4) the elderly and people with disabilities. These anthropometric design research and their findings to date for each category are described in the following sections.

Obviously, anthropometric measurements are an important consideration in the design process and a key element of successful design. Over the decades, considerable effort has been expended by researchers in establishing anthropometric databases for different groups, such as general (Jung et al. 1998; Jung and Jung 2003; Liu 2008; Hanson et al. 2009) and working populations (Wang et al. 1999; Dewangan, Owary, and Datta 2008, 2010; Syuaib 2015a); for children (Steenbekkers and Molenbroek 1990; Molenbroek, Kroon-Ramaekers, and Snijders 2003; Chung and Wong 2007; van Niekerk et al. 2013), the elderly and people with disabilities (Hobson and Molenbroek 1990; Das and Kozey 1999; Kozey and Das 2004). Of the reviewed papers, 32 presented data as a summary for the whole sample, 53 presented data by individual years of age, gender or race/ethnicity, and 2 presented data per individual in the survey.

3.2.1. Design for the general population

Anthropometric data are an important consideration in the design process, and are a key element in successful design. However, the main issue associated with design for the general population is the scarcity of comprehensive anthropometric databases. Either most of the available anthropometric data are based on military personnel, or the available data might not be representative of the general population (Pheasant 2003; Nadadur, Raschke, and Parkinson 2016). This problem is unlikely to be resolved unless comprehensive anthropometric studies in different countries are completed. Nevertheless, until then, numerous methods, such as proportionality constants, regression and neural network models, sum and difference dimensions and the method of ratio scaling, have been proposed to close the gaps (Pheasant, 2003; Dewangan, Owary, and Datta 2010; Agha and Alnahhal 2012; Poirson and Parkinson 2014). Results of published anthropometric research related to designs or products for general populations are presented in Table 1. Of the 116 papers in the review, 38 were related to the general population. These papers covered an age range from 18 to 81 y. However, this range in this present research was reffered as ‘general population’ as it was mentioned in the original investigations. It is, therefore, possible that the age range of this group might overlap with that of ‘elderly people’. As it is further discussed later in this review, it seems more appropriate to design specifically for elderly people (rather than a subset of the general population) due to elderly people’s special needs and anthropometric considerations. As can be seen in Table 1, investigations are generally related to the design of apparel and apparel-related products (clothing, intimate apparel and footwear), vehicle interiors and head-related products (helmets, earphones, headphones, headsets, etc.). Other types of products and designs (such as those requiring human muscular strength, reach and clearance dimensions, etc.) are also worth investigating.

3.2.2. Designing for working populations

A summary of published anthropometric research related to designs or products for working populations is presented in Table 2. Results of this review indicate that a larger number of anthropometric research with a greater diversity of designs have been devoted to the working population, compared with other population groups. Of the 116 reviewed papers, 43 were related to the working population. These investigations were generally related to workstations or workplace layout designs (optimum clearance and reach dimensions, improved working postures, etc.), hand tools and equipment, personal protective equipment (protective clothing, gloves, fall-arrest harnesses and seatbelts), aircraft and helicopter cockpit designs (arm reach boundaries) and agricultural machinery (tractors, combine harvesters, etc.). There are many other instances in which anthropometry can be employed advantageously to improve design in the workplace. However, it is worth noting that, when the design involves working populations, there might be some body size differences between professional working groups and general population that should be considered when defining the target population. Such differences might be due to a variety of factors, such as job requirements, the nature and culture of the work environment and years of employment (Hsiao et al. 2015a; Stewart, Ledingham, and Williams 2017).

3.2.3. Designing for children

Anthropometric data from children play an important role in the design of a variety of products and environments for this age group. These data are particularly important from accident prevention and safety promotion points of view (Steenbekkers and Molenbroek 1990; Grozdanovic, Jekic, and Stojiljkovic 2014). Additionally, poorly designed and ill-fitting products and environments that do not meet children's dimensional requirements can lead to increased pain and discomfort, and may tend to increase the risk of the development of musculoskeletal problems amongst children (Milanese and Grimmer 2004; Murphy, Buckle, and Stubbs 2007). In the study of Castellucci et al. (2017); all the studies reviewed emphasised that changes in school furniture dimensions (for better fit or match) would result in postural improvements, less muscular effort and less reported discomfort/pain. These outcomes are also of particular interest since the presence of musculoskeletal symptoms in children who are at earlier stages of their development, is a significant risk factor for experiencing such symptoms in adulthood (Harreby et al. 1995; Siivola et al. 2004). In addition, rapid changes in children's body sizes and shapes present a particular challenge for human factors/ergonomics (HF/E) specialists and designers. As a result, a number of investigators have suggested that a 'one-size-fits-all' design solution might not be applicable for children (García-Acosta and Lange-Morales 2007; Dianat et al. 2013; van Niekerk et al. 2013). Table 3 summarises the results of published anthropometric research related to designs/products for children. Of the 116 papers in the review, 20 were related to this target population. As can be seen in this table, major work in this area has focused on the design of classroom furniture or computer workstations, while far less attention has been paid to the design of other products or environments specifically for this population group. In addition, one enduring challenge is to design for both adults and children (e.g. seats in trains and buses).

3.2.4. Designing for the elderly and people with disabilities

For the design of universally convenient environments and products, accurate structural anthropometric measurements for both able-bodied individuals and people with disabilities are required (Das and Kozey 1999). Results of published anthropometric research related to designs/products for the elderly and people with disabilities are presented in Table 4. This review emphasises that there has been limited anthropometric research done specifically to special groups, such as the elderly or disabled population, as most of them to date have focused on non-disabled individuals. Only 15 of the 116 papers reviewed were related to this group of users, despite the need for 'inclusive design' approaches (also referred to as 'design for all' or 'universal design'), emphasising the importance of the integration of older and disabled people into the mainstream of society (Clarkson and Coleman 2015). Including people who are older or who have physical disabilities into designs, following this approach, has the potential to increase the market for the products or systems being designed (Sims et al. 2012). This outcome is particularly critical from the design point of view because some investigators have pointed out differences in structural and functional anthropometric dimensions between able-bodied people and people with disabilities (Kozey and Das 2004). Similarly, anthropometric data derived from adult populations also might not be applicable to the elderly as the ageing process involves significant changes in anthropometric variables (Hu et al. 2007). As a consequence, lack of anthropometric data from the elderly or people with disabilities limits the ability of designers to create safe and effective products or environments for a wide range of users (Hobson and Molenbroek 1990; Paquet and Feathers 2004). With a rapidly ageing population, it is therefore apparent that further research is needed to design products and environments specifically for this population.

3.3. Application domain

Another point of interest in anthropometric surveys is to understand whether the intended application is domain specific or generic. While domain-specific data provide solutions to specific situations and are relatively easy to apply (e.g. the reach envelope of a driver sitting in a car seat), generic results (e.g. the angle of shoulder rotation) seem to be more difficult to apply to real-world problems. Nevertheless, it is important to note that there is not a simple dichotomy between domain-specific and generic data, but a continuum which ranges from highly specific to fully generic data. Although most papers in this review (91 of 116) were characterised as being domain-specific, both the domain-specific and generic data sets are equally important from the design standpoint. While research with domain-specific applications address design solutions for specific contexts of use, generic data can be used to develop guidelines and recommendations for a broader variety of applications.

3.4. Sampling issues

An appropriate sampling plan seems to be necessary to ensure that anthropometric data from a research accurately represent the target-user population. For anthropometric research, a good sampling plan involves determining the sample size, as well as determining the sample structure in terms of age, gender, race/ethnicity or occupational group. An effort should also be devoted to sampling additional individuals at the extremes of the target population (e.g. oversample the tails of the distributions of relevant parameters) to make sure that data collected or applied to a problem be appropriate for a target-user population. Nevertheless, the application of such an approach requires that the designer has a good understanding of the design requirements and population in question. Of the 116 papers reviewed, only 24 considered sampling strategies in their surveys. It is also of concern that several papers even used military anthropometric data, such as the US Army anthropometric survey known as ANSUR (Gordon et al., 1989), to propose anthropometric design guidelines for general or working populations (see Tables 1 and 2). This presents a problem since anthropometric dimensions of military personnel differ (e.g., by being taller or heavier) from those of the general or working populations. In contrast, general or working populations may represent a greater variation in their range of body dimensions (Hsiao, Long, and Snyder 2002; Rhie et al., 2017). It, therefore, appears that more attention must be paid to the issue of sampling strategies in future research. The ISO 15535 standard can be consulted for more detailed information (ISO, 2012). The variability of sample sizes in the reviewed papers was considerable, ranging from 10 to 5434 samples. This review also showed a large variation in the number of anthropometric dimensions measured in these papers (ranging from 2 to 308 body dimensions). Nevertheless, the required number of body dimensions in anthropometric research largely depends on their objectives.

3.5. Fitting criteria

In anthropometric design research, fitting of the products/environments to users should be undertaken using appropriate criteria. Fitting criteria that maximise matches between products/environments and users are rarely based on a single, nonadjustable design solution but are based on methods such as sizing systems and adjustability, which are generally adopted by HF/E specialists and designers (McCulloch, Paal, and Ashdown 1998; Schultz et al., 1998; Jung, Kwon, and You 2010; Hsiao et al. 2015a). While anthropometric data in most of the reviewed papers have been generally published in the form of descriptive statistics and percentiles, a number of researchers have emphasised that standard anthropometric tables, based on one or several dimensions, could not adequately address the variability of complex body dimensions (Zheng, Yu, and Fan 2007; Jung, Kwon, and You 2010; Hsiao 2013; Poirson and Parkinson 2014).

It is worth noting that effective utilisation of anthropometric data requires a thorough analysis of the inherent design problems faced by HF/E professionals or designers. In some design applications, the design involves a single parameter related to only one anthropometric dimension of the user (univariate); therefore, the 'design for extremes' approach (or 'boundary cases') could be applied in these cases. The design of lintel or beam height in interior door frames, which is related to stature, is a typical example. In such cases, different approaches, such as regression analysis, percentiles or ranges, could be used as criteria to determine the level of match/mismatch between products/environments and users or to convert anthropometric data into design recommendations (Jeong and Park 1990; Steenbekkers and Molenbroek 1990; Molenbroek, Kroon-Ramaekers, and Snijders 2003; Dianat et al. 2013; Ghaderi, Maleki, and Dianat 2014). In 76 of the 116 papers, authors used percentiles or ranges as fitting criteria, while regression models were used in six papers.

In other design applications, two (bivariate) or more (multivariate) parameters must be considered since two/multiple anthropometric dimensions are relevant to the function of a product. In such cases, standard anthropometry tables could not adequately address the design applications involving bivariate or multivariate applications. Examples of bivariate anthropometric procedure are the design of helmets, which requires head length and head breadth dimensions (Meunier et al. 2000), and the design of respirators require face length and face width dimensions (Hsiao 2013). The design of fall-arrest harnesses, which requires multiple dimensions of the human torso, is an example of a multivariate anthropometric method (Hsiao 2013). Generally, the greater that the number is of involved dimensions, the more complex that the product design process is.

A number of statistical approaches have been used as fitting criteria in research involving multivariate applications to transform anthropometric data into design parameters. Principal components analysis (PCA), which groups a large number of measurement variables into a small set depending on their significance of correlation or covariance, is the most commonly used approach. This criterion was used only in 11 of the 116 reviewed papers. The PCA method has been used in a number of anthropometric investigations for establishing sizing systems for apparel and apparel-related products (Zheng, Yu, and Fan 2007; Lee and Wang 2015) and personal protective equipment (Laing et al. 1999; Hsiao et al. 2009, 2015a), as well as for the design of tractor and truck cabs (Hsiao et al. 2005, 2013; Guan et al 2012), children's bicycles (Laios and Giannatsis 2010) and brain-computer interfacing (BCI) headsets (Lacko et al. 2017). Cluster analysis (CA), which involves finding similar groups of data, is another commonly used multivariate statistical method (Mochimaru, Kouchi, and Dohi 2000; Lee, Hong, and Kim 2004; Chung, Lin, and Wang 2007; Krauss et al. 2008, 2011; Hong et al. 2011; Stewart, Ledingham, and Williams 2017). Individual clusters in this analysis may be of a specific absolute dimension, but also have unique body proportions (e.g. the leg-length to stature, or shoulder-to-hip breadth ratios). Of the 116 papers, 9 used this fitting criterion.

Results of this review reveal that there is still limited knowledge about the appropriate fitting criteria that define the level of match/mismatch between products/environments dimensions and anthropometric characteristics of users. This seems to be the case for both univariate (e.g. seat depth of a chair) and multivariate (e.g. design of a respirator or gas mask) design applications. Therefore, further studies are required to evaluate the applicability of different fitting criteria for various design applications.

3.6. Methods for physical accommodation considering anthropometry

3.6.1. Guidelines and standards

To date, several guidelines and standards, such as HFES 300-2004 (HFES, 2004), ANSI/HFES 100-2007 (HFES, 2007), ISO 7250-2008 (ISO, 2008), BIFMA G1-2013 (BIFMA, 2013) and ISO 6385-2016 (ISO, 2016), have been developed addressing design issues based on anthropometric principles.

3.6.2. Anthropometric-based design approach

According to anthropometric principles, all products and spaces (living and working places) should be designed to accommodate the largest percentage possible of the user population (HFES 300, 2004; Jung, Kwon, and You 2010). Several anthropometric-based design procedures proposed in the literature are summarised in Table 5 as an example. However, from these data, it would be difficult to propose a complete procedure. A more accurate and effective means of describing an anthropometric-based design procedure is to consider several levels of procedures for capturing/applying anthropometric data as discussed below.

- *Univariate/1D approaches using 5th–95th percentile values*

The simplest approach is measuring several 1D anthropometric dimensions and presenting them independently as 5th and 95th percentile values, and finally using them directly to design a specific workstation/work area or product. The design of school furniture and workstations are examples (Molenbroek, Kroon-Ramaekers, and Snijders 2003; Das, Shikdar, and Winters 2007; Kushwaha and Kane, 2016). Though this method is very simple, it is very limited in application. As noted earlier, most reviewed papers applied such an approach in their surveys.

- *Population-based approaches*

Another approach is measuring several anthropometric dimensions of individuals, and storing these data in a database. Then, a set of criteria can be defined to determine whether individuals can be included or excluded. For this, it is necessary to apply these criteria to a database to predict the number of people excluded or included (see for example Nadadur, Raschke, and Parkinson 2016). The aforementioned inclusive design (see, for example, http://calc.inclusivedesigntoolkit.com) and multivariate design approaches are examples. While none of the papers in this review explicitly proposed their design solutions based on inclusive designs, there are several papers, as noted above, involving multivariate anthropometry (see for example Laing et al. 1999; Hsiao et al. 2005; Laios and Giannatsis, 2010), which is clearly an area requiring further investigation, particularly from an inclusive design point of view.

- User-centered approach

Table 5. Anthropometric-based design procedures proposed in the literature.

Source	Procedure
Das and Sengupta, 1996	• Obtaining relevant information (e.g. task performance, equipment, working posture and environment) • Identifying the appropriate user population and obtaining the relevant anthropometric measurements or using the available statistical data from anthropometric surveys • Developing a mock-up of the design and conducting trials with participants • Constructing a prototype model based on the final design
Jung et al., 1998	• Survey and analysis of design requirement (e.g. postural analysis, product design variables and target user anthropometry) • Product design based on the analysis (e.g. relationship of design variables, anthropometric variability, comfort sensitivity, etc.) • Prototyping and evaluation • Arrangement and layout
Pheasant, 2003	• Obtaining the anthropometric characteristics of the users • Determining the ways in which these characteristics might impose constraints upon the design (e.g. product, space, etc.) • Selecting the criteria that define an effective match between the design and the user
HFES 300, 2004	• Defining the problem (e.g. relevant design parameters and anthropometric measures) • Defining the target population • Identifying the database and relevant considerations • Selecting the cases • Applying the cases to the design
Garneau and Parkinson 2012	• Careful consideration of the target user population • Modelling actual user behaviour • Performing virtual fitting trials • Simultaneous consideration of multiple dimensions of variability
Hsiao, 2013	• Determining the body dimensions that are of essential importance for the design • Determining the population to be considered • Selecting the population percentage to be accommodated • Obtaining the necessary reference data/materials to determine the appropriate statistics • Calculating the specific dimensions • Adjusting as necessary (for shoes, clothing and other gear)
Rhie et al., 2017	• Clarification by task analysis • Analysis of HF/E factors • Design and simulation • Evaluation with mock-up

The collection and application of anthropometric data would, in themselves, seem to be valuable goals for anthropometric research. Another important to be considered is that the user-centred approach of ergonomics for design necessitates the evaluation of design proposal by end-users. This consideration is very important, and it will add value to such research because it has been shown that products designed using ergonomics criteria related to anthropometry are not necessarily preferred more by users than the available alternatives (Kolich 2003). Other investigators have also acknowledged that anthropometry might not be the sole determinant of preferred product settings (Dekker et al. 2007).

- *Approaches considering additional (subjective) factors*

Some investigators have acknowledged that consideration of both user anthropometry and anthropometry-independent effects (e.g. user preferences and comfort), also known as hybrid approaches, might improve the effectiveness of the proposed designs (Christiaans and Bremner 1998; Garneau and Parkinson 2011). Therefore, experimental trials with representative samples of users testing prototype versions of products/environments under controlled conditions seem to be necessary to evaluate the effectiveness of proposed designs. To consider this possibility, both objective (e.g. performance, time, error, etc.) and subjective assessments (e.g. user assessments such as preference, comfort/discomfort, usability, etc.) that provide valuable information about the design are recommended. Molenbroek, Mantas, and deBruin (2011) proposed a unique user-centred design approach for the application of a smart toilet for elderly people in the EU-Friendly Restroom Project (Figure 2). In this FRR project, a prototype was tested in several places in Europe, and during the development process, it was tested three or four times while the design was increasingly evolving towards a real adjustable toilet that could

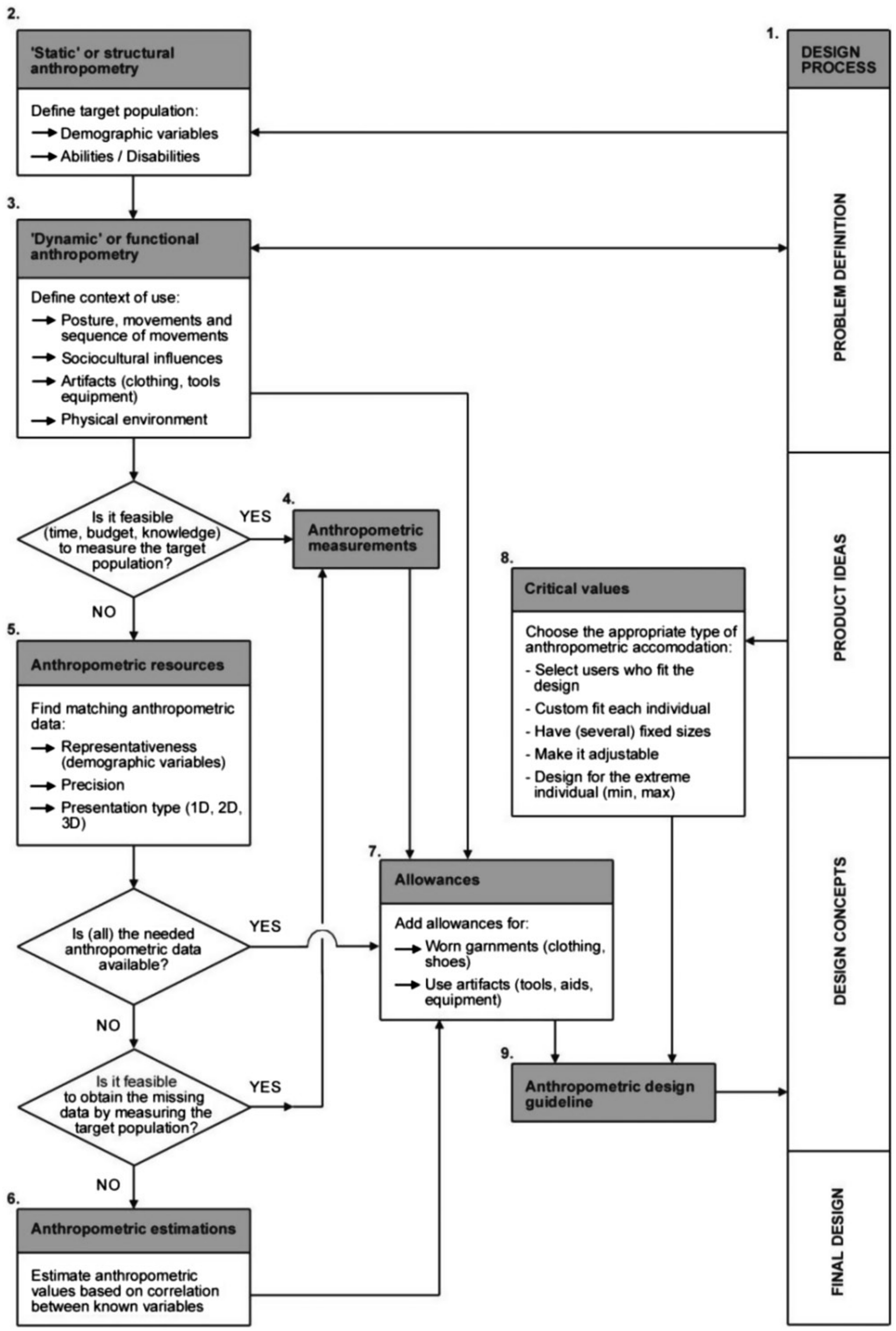

Figure 2. Anthropometric design process, adapted from Molenbroek, Mantas, and deBruin (2011).

be remote controlled either by voice or small physical controls. In Molenbroek and Goto (2015), it was described that education is necessary to realise such a user-centred design approach.

- *Use of prototypes*

This review demonstrates that only 8 of the 116 reviewed papers have considered prototype evaluation and testing. The design of supermarket checkstand workstations (Das and Sengupta 1996), passenger seats and coach layouts for high-speed trains (Jung et al. 1998), electric scooter designs (Chou and Hsiao 2005), upright stationary bicycles (Garneau and Parkinson 2011), a motorcycle's lumbar support (Karuppiah et al. 2011) and multi-function consoles used in submarines (Rhie et al. 2017) are examples. Chou and Hsiao (2005) conducted an anthropometric investigation among scooter riders using 2D measurements and proposed an electric scooter design based on the anthropometric data of users, and then they evaluated their prototype design based on subjective assessments from actual users (e.g. appearance presentation, stability and comfort). A relatively similar approach was used by Karuppiah et al. (2011) for the design of a motorcycle's lumbar support. Garneau and Parkinson (2011) compared different methods of user accommodation including manikin-based approaches (e.g. using proportionality constants, databases and digital human models [DHMs]), population model approaches and hybrid approaches in a case study involving the prototype design of an upright stationary bicycle, and they discussed advantages and disadvantages of each method through its application. Rhie et al. (2017) proposed design specifications for multi-function consoles used in submarines based on percentile values, and then they evaluated their proposed design using a full-scale mock-up considering subjective comfort and reaction times (e.g. monitoring and detecting stimuli given through the mock-up). However, most papers in this review either focused only on anthropometric measurements or only design dimensions for a particular product/environment without prototype testing.

- *Digital human modelling (DHM)*

There are two other examples, in which authors evaluated their proposed designs based only on virtual reality and not actual users (Vogt, Mergl, and Bubb 2005; Laios and Giannatsis 2010). Vogt, Mergl, and Bubb (2005) attempted to improve the interior layout designs of passenger vehicles using virtual design (e.g. DHMs in RAMSIS software). Authors developed their design ideas based on comfort angles for joints of the human body. Laios and Giannatsis (2010) also tried to improve designs of children bicycles, and they evaluated the proposed re-designed model using 3D virtual modelling techniques. DHMs have been utilised to analyse and improve the physical ergonomics of different designs (Chaffin 2005). DHMs are effective design tools for visualisation and ergonomic evaluation of the interactions between users and workstations/products, particularly in terms of reach, clearance, visibility and comfort (Jung, Kwon, and You 2009). Although the ergonomic design process using DHMs seems to be rapid and economical, there are some concerns regarding the validity of existing DHM tools (e.g. valid and realistic posture and motion prediction models for various populations) that should be addressed to improve their functionality (Chaffin 2005). Furthermore, all these tools only consider the physical dimensions of users and not their preferences (Mahoney, Kurczewski, and Froede 2015).

3.7. Practical implications and recommendations for future research

This review highlights the scarcity of anthropometric data on the target-user population and identifies the current gap in methodology and application of anthropometry for design by HF/E professionals and designers. Thus, implications for ergonomic practice may be to develop comprehensive anthropometric databases for the population of interest and to design a wider range of products using multivariate design approaches. More specifically, the following research issues are recommended to be addressed in future research:

- More attention to the 3D scan-derived data or even 2D anthropometry as they have applications in various areas such as head-related product designs, DHM, etc. Specifically, the emphasis should be placed on the use of 3D scans alone (not the extracted dimensions) in design.
- Research for better understanding of the anthropometric differences among occupational groups. Of interest here is to determine whether such differences are due to recruitment stipulation or the nature and culture of work environment;
- Comparison of different populations changes over time in body dimensions (secular changes).
- Additional attention to the issue of sampling strategies in future anthropometric research;
- Inclusive design and multivariate design approaches, particularly design for special groups such as the elderly and people with disabilities, pregnant women, children, etc.
- Applicability of different fitting criteria for various design applications.
- Consideration of kinematic/biomechanic approaches: It is suggested to measure several anthropometric dimensions of humans and, in addition, to generate a 'human behaviour' model that can manipulate degrees of freedom of human joints to achieve various postures (e.g. to determine whether a required posture for a task can be adopted successfully). Manipulating human degrees of freedom to achieve task success is complex and challenging (in terms of both data collection and application), but worth further investigation. In this regard, the ideal would be a personalised avatar that shows the tasks that can

be performed virtually before being asked of actual users.

- It also seems that, in the near future, virtual testing with one's own avatar (virtual human) will be more common. An individual will have the right to give permission to web-based retail outlets to use avatars to perform virtual fit-mapping before the 'buy' button is hit, and he/she is certain about the colour and fit to decrease the current large percentage of cases of 'return to sender'.
- Further attention to the user-centred approach of ergonomics for design through prototype evaluation and testing (using both objective and subjective assessments).

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