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ARTICLE

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Anthropometric dataset for the German working-age population using 3D body scans from a regional epidemiological health study and a weighting algorithm

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ABSTRACT
For the ergonomic design of workplaces and products, a representative anthropometric dataset of the working-age population is needed. As body proportions are constantly changing and the latest publicly available dataset for Germany was published in 2004 (data collection period 1999–2002), the aim of this study was to create and publish an updated anthropometric dataset of the German working-age population. Within a regional epidemiological health study, 3D body scan data from 2313 subjects were collected and used to create an anthropometric dataset with a total of 39 ISO 7250-1 measures. To approximate the goal of generating representative values for Germany, the collected regional dataset was weighted with an algorithm, using values from a known nationally representative survey. Based on the weighted dataset, a gender stratified percentile table with values for the 5th, 50th, and 95th percentile was calculated.

Practitioner summary: Body proportions are constantly changing and the latest publicly available anthropometric dataset for Germany was published in 2004. A new dataset was created, using 3D body scans from an epidemiological health study and a weighting algorithm. Ultimately, percentile tables with values for the 5th, 50th, and 95th percentile are published.

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Anthropometry; data weighting; survey methodology; occupational safety and health

1. Introduction

In an ergonomic design process, it is necessary to consider the anthropometric characteristics of the user group. Accordingly, in the work environment, a representative anthropometric dataset of the working-age population is needed for the ergonomic design of products (e.g. tools) and workplaces (Dewangan, Owary, and Datta 2008; Ghaderi, Maleki, and Dianat 2014). Moreover, this anthropometric dataset needs to be up-to-date, because body measures and proportions of humans are constantly changing (Gordon and Bradtmiller 2012; Hanson et al. 2009). The latest publicly available dataset of the German working-age population was published in 2004 by the Federal Institute for Occupational Safety and Health (BAuA) (Jürgens 2004). The data collection period was between 1999 and 2002. The results of this research project served as a basis for the current DIN 33402-2 (DIN 2020) and ISO/TR 7250-2 (ISO 2013) values. A recent study by Castellucci et al. (2020) recommends the collection of anthropometric data in populations every decade. With this in mind, an update for the German working-age population seems reasonable.

Outdated anthropometric datasets are a common problem in the field of ergonomics (Garneau and Parkinson 2016). As mentioned in several studies (Pagano, Parkinson, and Reed 2015; Parkinson and Reed 2010; Vega et al. 2021), the generation and maintenance of accurate and comprehensive anthropometric data is time-consuming and expensive, which makes it difficult to ensure up-to-date data. The traditional method to gather an anthropometric dataset involves a qualified and experienced anthropologist, who uses various tools (e.g. anthropometer or beam caliper) to collect body measures from different subjects (this method is hereafter referred to as

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'manual measurement'). This method, described in ISO 7250-1 (ISO 2017), is a time-consuming procedure. The advancing technological development of 3D body scanners allows the collection of high-resolution three-dimensional images of the human body in a short time. Standards for handling and evaluating 3D body scans are documented in ISO 15535 (ISO 2012), ISO 15536 (ISO 2005, 2007), and ISO 20685-1 (ISO 2018). The advantages of 3D body scanners have been recognised by anthropometric surveys (Gordon et al. 2014; Treleaven 2004) and are increasingly used in the medical field (Haleem and Javaid 2019).

In 2013 the BAuA started a cooperation with an already existing epidemiological health study in north-east Germany to gather 3D body scan data. This kind of cooperation seems reasonable, as 3D body scan images are relevant for scientists from different research fields. From a medical perspective, the data can be used to identify health-related risk factors (Ng et al. 2016; Treleaven and Wells 2007). However, the same scan images can be used to generate anthropometric datasets for the utilisation in an ergonomic setting. Another advantage of this cooperation was the possibility to use the already available infrastructure from the epidemiological health study to gather a large amount of anthropometric measures from many subjects with only minor changes in their study design.

Different aspects and constraints which have to be considered in this type of study design have already been described in other publications: Bonin, Radke, and Wischniewski (2019) focussed on the data collection and processing methodology as well as the quality assurance process. The validity of anthropometric measures extracted from 3D body scans was investigated in the study by Bonin et al. (2020). The current publication addresses the fact that the epidemiological health study drew a regional sample. Consequently, the collected anthropometric dataset was not representative of the entire country.

The aim of this publication was to create and publish an updated anthropometric dataset of the German working-age population. Therefore, a weighting algorithm was utilised to approximate the goal of generating representative values for Germany. The weighted dataset was used to calculate a gender stratified percentile table.

2. Methods

2.1. Sampling method and subjects

The 3D body scans were collected within the Study of Health in Pomerania (SHIP). SHIP is a population-based epidemiological health study in north-east Germany, conducted by the University Medicine Greifswald (John et al. 2001; Völzke et al. 2011, 2015, 2022). Over the past 25 years, participants were examined in two longitudinal cohorts: SHIP and SHIP-Trend. Inclusion criteria were the reported main residence in the study region, an age between 20 and 79 years, and a German citizenship. The exclusion criterion for SHIP-Trend was the participation in SHIP. To ensure comparability, the quality assurance process, infrastructure, materials, and 3D body scan positions were identical in both cohorts. The SHIP study design was approved by the local ethics committee at the University Medicine Greifswald.

Table 1. Sample characterisation.

	Age groups (years)				
Gender	18–27	28–37	38–47	48–57	58–67
Women	0	104	325	382	341
Men	0	102	303	377	379
Total	0	206	628	759	720

For this study, the body scan data of 1600 subjects from the third SHIP follow-up (SHIP-3, 2014–2016) and 2393 subjects from the first SHIP-Trend follow-up (SHIP-Trend-1, 2016–2019) were available (To avoid misunderstandings, given the discrepancy between the collection period in SHIP and the actuality of the final weighted dataset, readers are reffered to section 2.5.1 at this point). As the scope of the current investigation was the working-age population, only subjects between 18 and 67 years were considered. Due to the follow-up character of both cohorts, the youngest subject was 28 years of age. Overall, 2981 out of the 3993 available subjects from SHIP-3 and SHIP-Trend-1 were within the defined age range.

Further, only subjects with a complete dataset were considered. Hence, an additional 668 subjects were excluded during the quality assurance process due to missing values, irregularities on the scan image, interfering medical aids, or implausible extreme values. Finally, $N = 2313$ subjects ($1152 = $ women, $1161 = $ men) within an age range of 28–67 years were eligible for this study (see Table 1).

2.2. Procedure

A Vitus Smart XXL Body Scanner (Avalution GmbH, Kaiserslautern, Germany) was used to gather the 3D body scans. The scanner fulfills the conditions of the evaluation protocol from Kouchi et al. (2012), which served as the basis for ISO 20685-2 (ISO 2015). A body scale (Seca 635, Seca GmbH & Co. KG, Hamburg, Germany) was integrated into the floor of the 3D

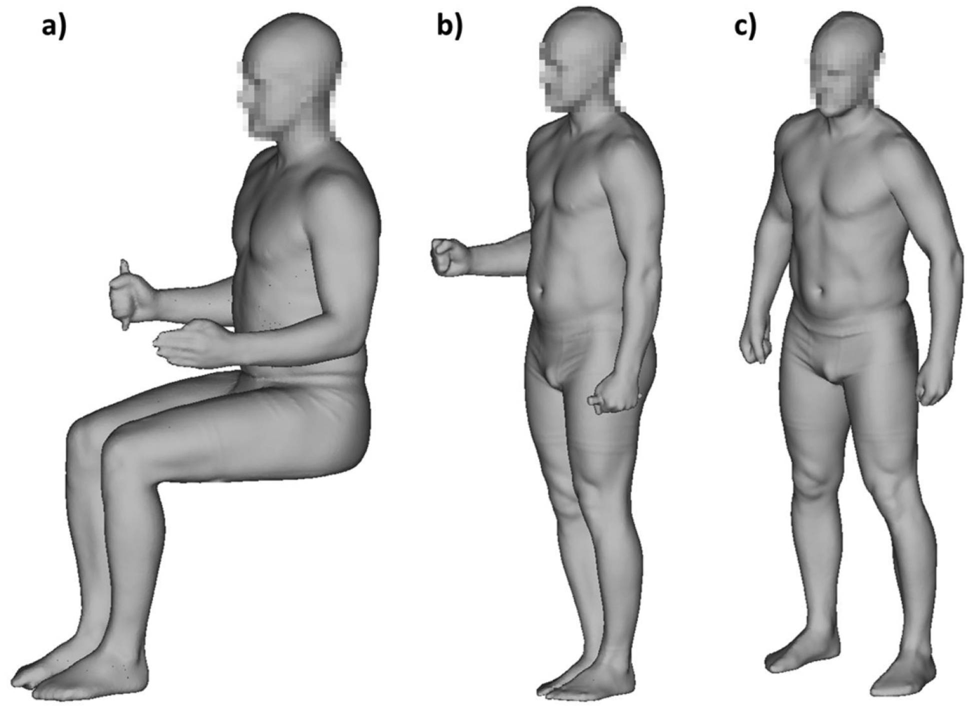

Figure 1. Anonymized sample scan image of the three different body postures (for better visualisation smoothed 3D scans are shown). Positions (a,b) are based on the recommendations, presented in ISO 20685-1; (c) is the standard scan position from the SHIP methodology.

scanner to determine body mass. The 3D whole-body scanner was calibrated daily. A precision test with calibrated weights was carried out every day to check the body scale. For the current study, three body scans per subject were necessary, one in a sitting position and two in different standing positions (see Figure 1). The subjects' clothing was ISO 20685-1 compliant.

The scan positions (a) and (b) are based on the recommendations, presented in ISO 20685-1. From these scans, the anthropometric measures were extracted in a post-processing procedure by manually identifying landmarks on the scan image, using the proprietary software Anthroscan (version 3.0.7, Avalution GmbH, Kaiserslautern, Germany). This procedure is further referred to as 'reading' and the executing employees as 'reader'. Overall, six readers were certified for SHIP-3, three of them continued in SHIP-Trend-1 in addition to four newly certified readers. A more comprehensive explanation of the reading process can be found in Bonin, Radke, and Wischniewski (2019). Scan position (c) is the standard scan from the SHIP study design, with automatic measure extraction, using the Anthroscan software. A detailed description of all body scan positions can be found in Table 2. The employees who carried out the body scan examination on-site are hereafter referred to as 'examiners'. Five examiners were involved in SHIP-3, and four of them proceeded in SHIP-Trend-1.

2.3. Body measures

This study uses a 3D whole-body scanner to collect anthropometric data for ergonomic design processes in the work environment. Therefore, the selection of relevant measures was based on ISO 7250-1 and ISO 20685-1. Besides the demographic parameters of age and gender, 32 anthropometric measures, defined in ISO 7250-1, were extracted from body scan positions (a) and (b). Another seven measures were gathered from position (c). In addition, the measured body mass was included in the dataset. As recommended in ISO 20685-1, detailed measures of the hand, head, and foot were not considered. Three anthropometric measures, which can be collected with a 3D whole-body scanner according to ISO 20685-1, had to be excluded (see Table 3).

In summary, 40 anthropometric measures were considered in this investigation, 39 of them can be allocated to an ISO 7250-1 measure (see Table 4). In line with ISO/TR 7250-2, values from the right side of the body are presented in this paper, whenever it is possible.

2.4. Quality assurance

Standard operating procedures (SOP) were defined to ensure the highest possible degree of standardisation and data quality during the entire data collection,

Table 2. Detailed description of the different body scan positions.

Scan position	Description: Head	Arms	Trunk	Legs
(a)	- Frankurt horizontal plane	- Upper arms hanging relaxed at the side of the trunk - 90° elbow flexion in both arms - Palmar surface of both hands pointing inward - Wrists in a neutral position - Right hand grasps a measuring rod (grip axis vertical) - Fingertips of left hand extended and pointing forward	- Erect upper body - No rotation of the spine - Both shoulders in a horizontal plane and relaxed - Quiet respiration (normal breathing)	- 90° flexion in hip, knee, and ankle joints - Thighs in horizontal plane and parallel to each other - Toes pointing forward
(b)	- Frankfurt horizontal plane	- Upper arms hanging relaxed at the side of the trunk - 90° elbow flexion right - Left elbow extended, forearm hanging relaxed - Palmar surface of both hands pointing inward - Wrists in a neutral position - Right hand forming a fist - Left hand grasps a measuring rod (grip axis horizontal in sagittal plane)	- Erect upper body - No rotation of the spine - Both shoulders in a horizontal plane and relaxed - Quiet respiration (normal breathing)	- Extended hip and knee joints - Feet together - Toes pointing forward
(c)	- Frankfurt horizontal plane	- Moderate abduction in shoulder joints (∼20°) - Moderate flexion in elbow joints (∼20°) - Palmar surface of both hands pointing inward - Wrists in a neutral position - Both hands forming a fist	- Erect upper body - No rotation of the spine - Both shoulders in a horizontal plane and relaxed - Quiet respiration (normal breathing)	- Extended hip and knee joints - Feet placed shoulder-width apart on the floor - Toes pointing forward

The letters (a)–(c) in the first column refer to the labelling in Figure 1.

Table 3. Excluded anthropometric measures.

Reference number	Measure	Rationale for exclusion
6.1.7	Crotch height	ISO 7250-1 compliant measurement not possible, as the landmark 'perineum' is not identifiable on the 3D scan image. Calculation of a 'landmarking offset' (see section 2.4 for more information) was not feasible.
6.2.15	Thorax depth	Ventral landmark on the chest (men) or breast (women) was detected by a reader. Dorsal landmark on the back was detected by the Anthroscan software. Unfortunately, the dorsal landmark was frequently incorrectly identified, leading to a high number of missing or erroneous values.
6.4.10	Chest circumference	Calculated *via* Anthoscan's automatic measure extraction. Using a virtual tape measure, the algorithm sometimes included data points from other body parts (e.g. upper arms) or underestimated values, because of gaps in the scan surface. An automated detection of incorrect values was not possible in our study setting.

Reference numbers in the first column were selected in accordance with ISO 7250-1:2017.

processing, and analysis. Quality assurance involved several tasks, including the evaluation of inter- and intra-reader differences. To minimise errors, examiners and readers were trained and certified on a regular basis and readers had to attend body scan examinations at least during their initial training. Furthermore, time trends in the reading process were monitored. With the help of descriptive statistics, plausibility limits were defined to identify extreme values within the reading process. Values outside the plausibility limits were checked manually using the 3D scan images and subsequently declared as either erroneous and deleted or verified as plausible. In general, irregularities and abnormalities were documented in a standardised form using electronic case report forms. A more detailed description of the reading process and its evaluation can be found in Bonin, Radke, and Wischniewski (2019).

The body scan values were initially compared with values collected *via* manual measurements in a validation study. For this validation, a subsample of 44 subjects from SHIP-Trend-1 was utilised. The body scans were performed by the trained examiners. To avoid a reader effect, one single reader performed the reading process. The same reader was trained for the manual measurement and performed both examinations for the entire subsample. The manual measurement took place immediately after the body scan examination. A summary of the results can be found in Table 4 and Bonin et al. (2020).

During the validation study, systematic differences in the landmarking methodology between the SHIP SOP and ISO 7250-1 were analysed. In ISO 7250-1 the acromion is described as the most lateral point of the lateral edge of the acromial process and the olecranon as the rearmost point of the 90° flexed elbow. In the SHIP reading procedure, the acromion was identified as the most superior bony point, lateral from the mid-axillary line (often the acromioclavicular joint). Olecranon was identified as the rearmost point of the

Table 4. Anthropometric measures.

Reference number	Measure	Scan position	Results from validation study: CI (mm) −95%	CI (mm) +95%	Within given tolerances
6.1.1	Body mass	–	–	–	–
6.1.2	Stature	(b)	0.5	5.1	no
6.1.3	Eye height	(b)	−14.2	−8.0	no
6.1.4	Shoulder height	(b)	−1.5	3.9	yes
6.1.5	Elbow height	(b)	−2.8	4.8	no
6.1.6	Iliac spine height, standing	(b)	−3.1	−9.1	no
6.1.8	Tibial height	(b)	−12.4	−3.6	no
6.1.9	Chest depth, standing	(b)	NA	NA	NA
6.1.10	Body depth, standing	(b)	NA	NA	NA
6.1.11	Chest breadth, standing	(b)	7.9	14.3	no
6.1.12	Hip breadth, standing	(b)	5.3	9.3	no
6.2.1	Sitting height (erect)	(a)	−6.3	0.5	no
6.2.2	Eye height, sitting	(a)	−5.0	−7.2	no
6.2.3	Cervicale height, sitting	(a)	−10.2	−3.6	no
6.2.4	Shoulder height, sitting	(a)	−8.2	0.0	no
6.2.5	Elbow height, sitting	(a)	−10.6	0.0	no
6.2.6	Shoulder-elbow length	(a)	−3.0	3.2	yes
6.2.7	Shoulder (biacromial) breadth	(a)	−4.6	5.6	no
6.2.8	Shoulder (bideltoid) breadth	(a)	9.3	14.9	no
6.2.9	Elbow-to-elbow breadth	(a)	27.3	50.1	no
6.2.10	Hip breadth, sitting	(a)	−4.5	3.3	no
6.2.11	Popliteal height, sitting	(a)	−10.1	9.7	no
6.2.12	Thigh clearance	(a)	−21.4	−14.8	no
6.2.13	Knee height, sitting	(a)	−3.7	2.5	yes
6.2.14	Abdominal depth, sitting	(a)	7.5	14.5	no
6.2.16	Buttock-abdomen depth, sitting	(a)	12.1	20.9	no
6.3.19	Arm circumference flexed	(c)	NA	NA	NA
6.3.20	Forearm circumference flexed	(c)	NA	NA	NA
6.4.3	Elbow-wrist length	(a)	−1.0	3.4	yes
6.4.4	Elbow-grip length	(a)	−12.7	−6.3	no
6.4.5	Fist (grip axis) height*	(b)	−20.0	−9.4	no
6.4.6	Forearm-fingertip length*	(a)	2.8	6.2	no
6.4.7	Buttock-popliteal length (seat depth)	(a)	−10.5	0.5	no
6.4.8	Buttock-knee length	(a)	−7.5	4.1	no
6.4.9	Neck circumference	(a)	2.4	7.4	no
6.4.11	Waist circumference	(c)	NA	NA	NA
6.4.12	Wrist circumference	(c)	NA	NA	NA
6.4.13	Thigh circumference	(c)	NA	NA	NA
6.4.14	Calf circumference	(c)	NA	NA	NA
–	Hip circumference	(c)	NA	NA	NA

Reference numbers in the first column were selected in accordance with ISO 7250-1:2017. The third column shows the utilised scan position to extract the measure [letters (a)–(c) refer to the labelling in Figure 1]. In the last columns the results from the validation study according to ISO 20685-1 are summarised (for more information see section 2.4).
CI: confidence interval; NA: not available (i.e. these measures were not analysed in the validation study).
*Measured on the left side of the body.

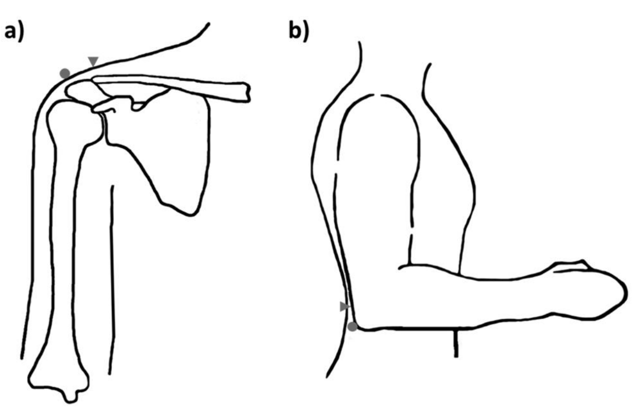

Figure 2. Visualisation (not true to scale) of different landmarking methodologies in ISO 7250-1 (dots) and the SHIP reading procedure (triangles) for the (a) acromion and (b) olecranon (own drawing).

90° flexed elbow, midline of the forearm, including soft tissue (see Figure 2).

Since it was not possible to change the landmark definitions in the SHIP SOP and seven anthropometric measures rely on these landmarks, offsets were calculated to approximate an ISO 7250-1 compliant landmarking (hereafter referred to as 'landmarking offsets'). In practice, these seven measures were gathered twice from each subject of the subsample: the first time in accordance with the landmark definition of ISO 7250-1, and the second time according to the landmark definition of the SHIP SOP. To account for different body sizes the landmarking offsets were calculated as the relative difference between the two landmark definitions, separately for women and men.

To clarify these landmarking offset calculation equations are presented below, using the measure shoulder height as an example. First, the anthropometric measure is collected from a subject $j\ (1 \le j \le n \mid j, n \in \mathbb{N})$, using an anthropometer and the ISO 7250-1 landmark definition. The acquired value is declared as SH^j_{ISO} in this example. Subsequently, the process is repeated, this time using the landmark definition of the SHIP SOP. The acquired value is declared as SH^j_{SHIP}. The difference between SH^j_{ISO} and SH^j_{SHIP} is calculated, relative to SH^j_{SHIP}:

$$\delta^j_{SH} = \frac{SH^j_{ISO} - SH^j_{SHIP}}{SH^j_{SHIP}} * 100.$$

This is repeated with n subjects of the validation study. Afterwards, the mean $\overline{\delta}_{SH}$ and standard deviation $s_{\delta_{SH}}$ can be calculated from the n subjects:

$$\overline{\delta}_{SH} = \frac{1}{n} * \sum_{j=1}^{n} \delta^j_{SH},$$

$$s_{\delta_{SH}} = \sqrt{\frac{1}{n-1} * \sum_{j=1}^{n} \left(\delta^j_{SH} - \overline{\delta}_{SH}\right)^2}.$$

The mean defines the landmarking offset value for the corresponding measure and gender. Given a subject $l\ (1 \le l \le \mathrm{N} \mid l, N \in \mathbb{N})$ from the study sample ($N = 2313$) with a value SH^l, an ISO 7250-1 landmark compliant measure is approximated using the following equation:

$$SH^l_{ISO} = SH^l + \left(\frac{SH^l * \overline{\delta}_{SH}}{100}\right).$$

This procedure was repeated for each subject ($N = 2313$), to calculate the percentiles of the offset corrected anthropometric measure afterwards (all corrected measures are marked with suffix '_off' in Tables 7 and 8).

In addition to the landmark definitions, there was a systematic difference between SHIP and ISO 7250-1 concerning the measuring rod. In ISO 7250-1 a diameter of 20 mm is defined. In SHIP the measures fist (grip axis) height and elbow-grip length were gathered, using a measuring rod with a diameter of 29 mm. This causes a systematic difference of 4.5 mm between a SHIP and an ISO 7250-1 compliant value. As the aim of this study was to collect ISO 7250-1 conform values, this difference was considered in all calculations and presented percentile values.

2.5. Data weighting

As the SHIP study represents a regional sample, the gathered dataset was weighted with data from a nationally representative survey to compensate for regional variations.

2.5.1. Reference dataset

The Study on the health of adults in Germany (DEGS), carried out by the Robert Koch Institute, provides a representative dataset of the German population (Scheidt-Nave et al. 2012). The target population includes adults aged between 18 and 79 years with a permanent residence in Germany according to local population registries. The first survey wave (DEGS1) was conducted between 2008 and 2011 and gathered data from 5626 subjects (2955 = women, 2671 = men) between 18 and 67 years. Accordingly, the actuality of the computed weighted SHIP dataset corresponds to this time period. Within the framework of DEGS1 a two-phase stratified (cluster) sample strategy was chosen and weighting coefficients were calculated to ensure the representativeness of the dataset (Kamtsiuris et al. 2013). The anthropometric measures of stature, body mass, hip circumference, and waist circumference were collected. Thus, DEGS1 provides publicly available and nationwide representative data for these four measures and is appropriate for the utilisation as a reference dataset. For the weighting algorithm employed in this study, the measures of stature, body mass, and body mass index (BMI) were considered as weighting parameters.

2.5.2. Weighting algorithm

An iterative proportional fitting (IPF) algorithm was used to determine optimised, cumulative weighting coefficients $k_i\ (1 \le i \le N \mid i, N \in \mathbb{N})$, based on predefined weighting parameters. The R package *survey* (Lumley 2020) with the *rake* function was utilised to perform this computation. Three input parameters are required for this function:

1. survey design object,
2. sample margins, and
3. population margins.

In the beginning, an unweighted survey design object was created for the calculations, which initially contained the unweighted SHIP dataset. Afterwards, all associated parameters and calculations were stored in this survey design object. The essential columns used for weighting were defined *via* the sample margins parameter. In this parameter, the relative frequency of occurrence of all values was determined and stored in a frequency table. The parameter population margins contained the relative frequency of occurrence of the weighting parameters from the reference dataset in the form of a frequency table.

To create reliable weighting coefficients, for each value within the frequency table of the sample margins parameter, there must be a corresponding equivalent within the frequency table of the population margins parameter. To obtain the best matching frequency tables, it was necessary to round the values of both datasets to the nearest integer values (in cm for length, breadth, and circumference measures; in kg for body mass). There is a possibility to activate the option *partial* = *True* within the *rake* function to ignore missing counterparts within the frequency tables. But in this case, those ignored entries would lead to a miscalculation of the weighted percentile tables. Therefore, this option was not used in this analysis. To execute the weighting algorithm despite gaps, the maximum range of corresponding values without gaps in both frequency tables was determined as boundaries for a confidence interval of reliable information. For values below and above these boundaries, a temporary 'cut-off' dataset was created, in which the values outside the confidence interval were substituted with the min and max values of the boundaries. It is important to note that due to this modification, the generated dataset and subsequent calculation of percentile values is only meaningful within the determined boundaries. To account for the limited data quality at the edges of the source data, only values between the 5th and 95th percentiles were recognised as reliable within the current study, even if the boundaries would allow a slightly wider percentile range.

The value of an individual weighting coefficient k_i is initially only limited by the condition:

$$\frac{\sum_i^N k_i}{N} = 1 \ .$$

Nevertheless, in case of very high or very low k_i values, it needs to be analysed if k_i still represents a reasonable value without overcorrecting the individual anthropometric value. Therefore, the *survey* package provides the *trimWeights* function for limiting the minimum and maximum value of k_i. If the value exceeds or undercuts the defined thresholds, k_i is set to the respective limit value. The difference between the limit value and the original calculated value is divided equally among the remaining weighting coefficients. After analysis of the relative distribution frequencies and isolated outliers, the threshold values for the *trimWeights* function were set to 0.01 and 5 $(0.01 \leq k_i \leq 5 \mid k_i \in \mathbb{Q})$. This corridor is comparable with the values used in DEGS1.

In numerous pre-tests different weighting parameters (stature and BMI or stature and body mass) and configurations (with or without *trimWeights* function) were evaluated. Weighting with the measures of stature and body mass with activated *trimWeights* function led to the best results (even distribution of weighting coefficients and lowest number of outliers) and was therefore used for the final weighting procedure (see sections 3.1 and 4.2).

2.6. Statistical analysis

All statistical analyses and plots were performed using R (R Core Team 2021). For the unweighted SHIP dataset, the basic function *quantile* was used to calculate the percentile values. To compute percentile values of the weighted SHIP dataset, the function *wtd.quantile* from the R package *Hmisc* (Harrell 2020) was used. In accordance with ergonomic and anthropometric standards, the 5th, 50th, and 95th percentiles were calculated for each anthropometric measure.

3. Results

3.1. Data weighting

To approximate the goal of generating a representative dataset for Germany, the regional SHIP dataset was weighted with an algorithm. Table 5 shows the minima, maxima, means, and sums of the weighting coefficients k_i for different weighting parameters and configurations evaluated in the pre-tests.

Figure 3 shows the relative frequency distribution of the weighting coefficients k_i for the aforementioned combinations.

Table 6 shows the comparison of matching anthropometric measures from DEGS1, the unweighted SHIP dataset, and the weighted SHIP dataset. Thus, this table enables a qualitative evaluation of the weighting algorithm.

3.2. Percentile table

3.2.1. Unweighted results

Table 7 shows the calculated percentile values for the unweighted SHIP dataset, including the measures calculated *via* landmarking offsets to compensate for systematic methodological differences in landmarking between ISO 7250-1 and SHIP. Consequently, the

Table 5. Descriptive parameters of the weighting coefficients k_i, calculated within the algorithm for different weighting parameters and configurations.

		Women				Men			
Weighting parameters	Trimmed weights (0.01–5)	Min	Max	Mean	Sum	Min	Max	Mean	Sum
Stature + BMI	No	0.13	7.68	1.00	1152	0.35	7.16	1.00	1161
Stature + body mass	No	0.10	8.99	1.00	1152	0.20	6.91	1.00	1161
Stature + BMI	Yes	0.14	5.00	1.00	1152	0.36	5.00	1.00	1161
Stature + body mass*	Yes	0.11	5.00	1.00	1152	0.21	5.00	1.00	1161

BMI: body mass index.
*Used for final weighting procedure.

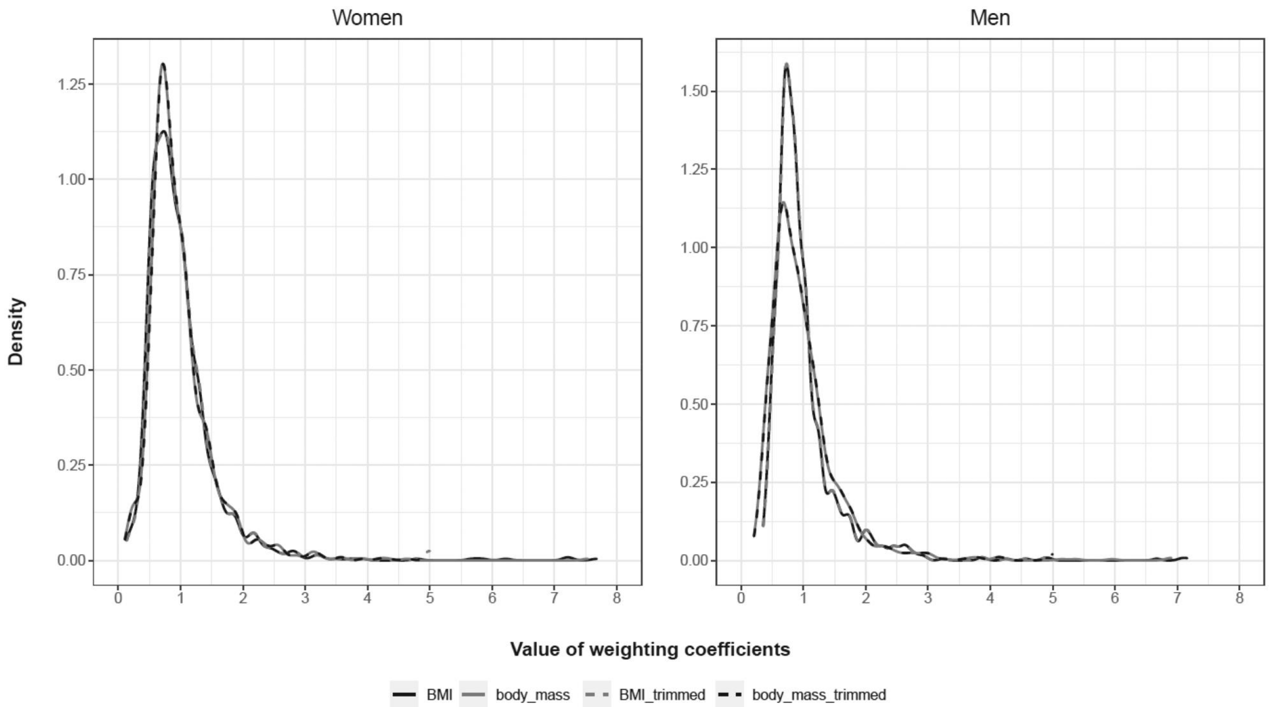

Figure 3. Density plots of the weighting coefficients k_i, calculated within the algorithm. Comparison between different weighting parameters and configurations. Combination options: BMI = Stature + body mass index without trimmed weights (black solid line); body_mass = Stature + body mass without trimmed weights (grey solid line); BMI_trimmed = Stature + body mass index with trimmed weights (grey dashed line); body_mass_trimmed = Stature + body mass with trimmed weights (black dashed line).

Table 6. Comparison of the 5th (P5), 50th (P50), and 95th (P95) percentile values between the DEGS1 dataset (D1), the unweighted SHIP dataset (S), and the weighted (Sw) SHIP dataset (all measures in mm, except for body mass given in kg; all measures rounded to the nearest 10 mm or 1 kg value to ensure comparability with the weighted SHIP dataset).

	P5			P50			P95		
	S	Sw	D1	S	Sw	D1	S	Sw	D1
Women									
Stature	1560	1540	1540	1660	1640	1640	1770	1750	1750
Body mass	54	52	52	69	67	67	95	99	99
Waist circumference	700	700	660	840	840	800	1060	1090	1080
Hip circumference	850	850	900	990	990	1020	1190	1220	1220
Men									
Stature	1680	1660	1660	1780	1780	1780	1900	1900	1900
Body mass	68	63	63	87	84	84	112	112	112
Waist circumference	830	800	760	990	970	940	1190	1200	1170
Hip circumference	880	850	900	1010	990	1010	1200	1200	1150

Table 7. Percentile table of the unweighted SHIP dataset with values for the 5th (P5), 50th (P50), and 95th (P95) percentile (all measures in mm, except for body mass given in kg; all measures rounded to the nearest 1 mm or 0.1 kg value).

		Women ($n = 1152$)			Men ($n = 1161$)		
Reference number	Measure	P5	P50	P95	P5	P50	P95
6.1.1	Body mass	53.6	69.3	95.2	68.5	87	111.6
6.1.2	Stature	1559	1661	1772	1678	1784	1903
6.1.3	Eye height	1438	1539	1647	1554	1660	1777
6.1.4	Shoulder height*[a]	1285	1379	1480	1392	1490	1595
6.1.4	Shoulder height_off*[b]	1273	1367	1467	1378	1475	1579
6.1.5	Elbow height	945	1022	1104	1020	1100	1184
6.1.6	Iliac spine height, standing	835	915	1001	899	984	1076
6.1.8	Tibial height	373	413	453	410	450	493
6.1.9	Chest depth, standing	191	226	269	226	263	305
6.1.10	Body depth, standing	270	320	395	287	343	412
6.1.11	Chest breadth, standing	291	328	373	329	373	417
6.1.12	Hip breadth, standing	334	375	428	337	369	407
6.2.1	Sitting height (erect)	823	879	933	869	929	988
6.2.2	Eye height, sitting	705	757	810	744	802	860
6.2.3	Cervicale height, sitting	591	638	683	634	684	734
6.2.4	Shoulder height, sitting*[a]	552	598	643	588	633	684
6.2.4	Shoulder height, sitting_off*[b]	541	586	630	574	618	668
6.2.5	Elbow height, sitting	199	242	284	197	244	289
6.2.6	Shoulder-elbow length*[a]	325	357	387	357	390	423
6.2.6	Shoulder-elbow length_off*[b]	308	338	367	339	370	401
6.2.7	Shoulder (biacromial) breadth†[a]	256	301	343	303	350	397
6.2.7	Shoulder (biacromial) breadth_off†[b]	300	352	402	354	409	464
6.2.8	Shoulder (bideltoid) breadth	413	451	500	462	507	552
6.2.9	Elbow-to-elbow breadth	453	528	619	515	599	680
6.2.10	Hip breadth, sitting	359	409	482	361	404	456
6.2.11	Popliteal height, sitting	373	407	448	404	443	480
6.2.12	Thigh clearance	123	146	174	136	157	182
6.2.13	Knee height, sitting	464	501	547	500	545	593
6.2.14	Abdominal depth, sitting	221	280	366	246	308	388
6.2.16	Buttock-abdomen depth, sitting	241	297	388	244	307	383
6.3.19	Arm circumference flexed	253	291	343	281	319	358
6.3.20	Forearm circumference flexed	229	258	299	268	299	333
6.4.3	Elbow-wrist length*[a]	238	262	285	265	288	316
6.4.3	Elbow-wrist length_off*[b]	220	243	264	252	274	301
6.4.4	Elbow-grip length*[a]	309	337	369	343	373	404
6.4.4	Elbow-grip length_off*[b]	286	312	341	323	352	381
6.4.5	Fist (grip axis) height	694	762	829	744	816	888
6.4.6	Forearm-fingertip length*[a]	414	445	480	454	490	527
6.4.6	Forearm-fingertip length_off*[b]	398	427	461	444	480	516
6.4.7	Buttock-popliteal length (seat depth)	460	503	547	463	507	553
6.4.8	Buttock-knee length	553	601	656	573	620	672
6.4.9	Neck circumference	321	357	405	378	420	472
6.4.11	Waist circumference	699	844	1059	832	994	1186
6.4.12	Wrist circumference	151	168	191	172	188	209
6.4.13	Thigh circumference	499	574	675	501	566	636
6.4.14	Calf circumference	327	373	437	345	390	439

Reference numbers in the first column were selected in accordance with ISO 7250-1:2017. Suffix '_off' marks measures with offset corrected percentile values.
*Calculated landmarking offset value is smaller than SHIP value. It is recommended to consider a context sensitive worst-case scenario. See section 4.4 for further discussion.
†Due to abnormalities, identified in the quality assurance process, these measures should be viewed with caution (see section 4.3.4).
[a]Value measured in SHIP.
[b]Approximation of ISO 7250-1 measure *via* landmarking offset calculation. See section 2.4 for more information.

percentile values presented in this table are based on the measured values from the regional SHIP sample.

3.2.2. Weighted results

Table 8 shows the calculated percentile values for the weighted SHIP dataset, including the measures calculated *via* landmarking offsets to compensate for systematic methodological differences in landmarking between ISO 7250-1 and SHIP. Accordingly, the values presented in this final percentile table aim to approximate nationally representative values.

4. Discussion

The cooperation with an ongoing regional epidemiological health study and the utilisation of a 3D body scanner provided an efficient way to gather

Table 8. Percentile table of the weighted SHIP dataset with values for the 5th (P5), 50th (P50), and 95th (P95) percentile (all measures in mm, except for body mass given in kg; all measures rounded to the nearest 10 mm or 1 kg value).

		Women ($n = 1152$)			Men ($n = 1161$)		
Reference number	Measure	P5	P50	P95	P5	P50	P95
6.1.1	Body mass	52	67	99	63	84	112
6.1.2	Stature	1540	1640	1750	1660	1780	1900
6.1.3	Eye height	1420	1520	1630	1540	1650	1770
6.1.4	Shoulder height*[a]	1270	1360	1460	1370	1480	1590
6.1.4	Shoulder height_off*[b]	1260	1350	1450	1360	1470	1580
6.1.5	Elbow height	930	1010	1090	1000	1090	1180
6.1.6	Iliac spine height, standing	820	900	980	890	980	1070
6.1.8	Tibial height	370	410	450	400	450	490
6.1.9	Chest depth, standing	190	220	270	220	260	300
6.1.10	Body depth, standing	270	320	400	280	330	410
6.1.11	Chest breadth, standing	290	330	380	320	370	420
6.1.12	Hip breadth, standing	330	370	430	330	360	410
6.2.1	Sitting height (erect)	820	870	930	860	930	990
6.2.2	Eye height, sitting	700	750	810	740	800	860
6.2.3	Cervicale height, sitting	590	630	680	630	680	730
6.2.4	Shoulder height, sitting*[a]	550	590	640	580	630	680
6.2.4	Shoulder height, sitting_off*[b]	540	580	630	570	620	670
6.2.5	Elbow height, sitting	200	240	280	190	240	290
6.2.6	Shoulder-elbow length*[a]	320	350	380	350	390	420
6.2.6	Shoulder-elbow length_off*[b]	300	340	360	340	370	400
6.2.7	Shoulder (biacromial) breadth†[a]	250	300	340	300	350	400
6.2.7	Shoulder (biacromial) breadth_off†[b]	290	350	400	350	410	460
6.2.8	Shoulder (bideltoid) breadth	410	450	500	450	500	550
6.2.9	Elbow-to-elbow breadth	450	530	620	500	590	680
6.2.10	Hip breadth, sitting	360	410	490	350	400	460
6.2.11	Popliteal height, sitting	370	400	440	400	440	480
6.2.12	Thigh clearance	120	140	180	130	160	180
6.2.13	Knee height, sitting	460	490	540	500	540	590
6.2.14	Abdominal depth, sitting	220	280	380	240	300	390
6.2.16	Buttock-abdomen depth, sitting	240	300	400	240	300	390
6.3.19	Arm circumference flexed	250	290	350	270	320	360
6.3.20	Forearm circumference flexed	230	260	300	260	300	330
6.4.3	Elbow-wrist length*[a]	240	260	280	260	290	320
6.4.3	Elbow-wrist length_off*[b]	220	240	260	250	270	300
6.4.4	Elbow-grip length*[a]	310	330	370	340	370	400
6.4.4	Elbow-grip length_off*[b]	280	310	340	320	350	380
6.4.5	Fist (grip axis) height	690	750	820	740	810	880
6.4.6	Forearm-fingertip length*[a]	410	440	480	450	490	520
6.4.6	Forearm-fingertip length_off*[b]	390	420	460	440	480	510
6.4.7	Buttock-popliteal length (seat depth)	450	500	540	460	500	550
6.4.8	Buttock-knee length	540	600	660	570	620	670
6.4.9	Neck circumference	320	360	410	370	410	470
6.4.11	Waist circumference	700	840	1090	800	970	1200
6.4.12	Wrist circumference	150	170	190	170	190	210
6.4.13	Thigh circumference	490	570	690	490	560	630
6.4.14	Calf circumference	320	370	440	340	380	440

Reference numbers in the first column were selected in accordance with ISO 7250-1:2017. Suffix '_off' marks measures with offset corrected percentile values.
*Calculated landmarking offset value is smaller than SHIP value. It is recommended to consider a context sensitive worst-case scenario. See section 4.4 for further discussion.
†Due to abnormalities, identified in the quality assurance process, these measures should be viewed with caution (see section 4.3.4).
[a]Value measured in SHIP.
[b]Approximation of ISO 7250-1 measure *via* landmarking offset calculation. See section 2.4 for more information.

anthropometric data. Using the existing infrastructure, it was possible to acquire data from many subjects with only minor changes in the SHIP study design. In total, the time required for the body scan examination was ∼15 min per subject. An additional 10 min were needed for the manual reading process. Taking into account the number of extracted anthropometric measures, this measurement procedure was most likely less time-consuming than a manual measurement, especially for the subjects, as they did not have to be present during the manual reading process.

The fundamental methodological approach of this study could be transferred to other populations in other countries. Considering the fact that conducting a nationwide anthropometric survey is expensive and time-consuming, the current study provides an alternative approach to generate a comprehensive anthropometric dataset with less cost and less effort. Cooperating with a (regional) public health study is beneficial for both sides, as the 3D scans can be used in the medical field for a variety of research questions (Ng et al. 2016; Treleaven and Wells 2007). Moreover, many countries conduct some kind of nationwide public health survey (e.g. the 'National Health and Nutrition Examination Survey' in the USA), collecting the anthropometric measures of stature and body mass. Such data can be used as a reference within the weighting algorithm and thus, the prerequisites for the methodological approach of this study are reachable in many cases.

4.1. 3D body scan measurement vs. manual measurement

Although the body scanner fulfilled the conditions of the evaluation protocol from Kouchi et al. (2012) and the inter- and intra-reader reliability throughout the digital reading process was on a high level (Bonin, Radke, and Wischniewski 2019), the differences in values between 3D body scanner and the manual measurement exceeded the ISO 20685-1 validation tolerances for the vast majority of anthropometric measures (see Table 4). The subject's clothing was ISO 20685-1 compliant and body postures, as well as breathing conditions during the scanning procedure, were based on recommendations from ISO 20685-1.

Besides several other known issues like slightly different posture or compressed hair underneath the bathing cap, the most likely main cause for the results of the validation study is the different identification of anatomical landmarks. Landmarking errors are known to have a large impact on comparability (Kouchi and Mochimaru 2011) between measures in general. This is particularly evident in the comparison of manual measures *vs.* scan-derived measures as the palpation of prominent anatomic landmarks (e.g. spina iliaca anterior superior) is not possible during the landmark identification on a computer. Moreover, the body scanner used in this study was not capable of detecting colourised landmarks on the subject's skin and the limited timeframe within the SHIP methodology restricted the application of physical markers for each landmark.

Eventually, the calculated differences between the 3D body scan measurement and the manual measurement are comparable with the results from other validation studies (Han, Nam, and Choi 2010; Koepke et al. 2017).

4.2. Data weighting

In numerous pre-tests, several weighting options with different weighting parameters and configurations were tested to ensure the best possible results (see Table 5 and Figure 3). Evaluating the relative frequency distributions of the calculated weighting coefficients k_i and performing an extreme value analysis led to the final combination. An even distribution of the weighting coefficients paired with the lowest number of outliers was achieved with the weighting parameters stature and body mass with activated *trimWeights* function. The qualitative evaluation of the weighting algorithm, based on comparable anthropometric measures between DEGS1 data, unweighted SHIP data, and weighted SHIP data (see Table 6), showed plausible changes, indicating an already good composition of the sample structure in SHIP and a reasonable performance of the algorithm.

However, it is remarkable that the weighting coefficients count equally for all measures of a subject. Thereby, the influence of the weighting coefficients on the respective percentile values differs, due to different body compositions. While some measures show a clearly visible effect after the weighting procedure, other parameters only show effects within the range of rounding inaccuracies (see Tables 7 and 8).

4.3. Limitations

This study has several limitations that must be taken into account when using the percentile data.

4.3.1. Exclusion of anthropometric measures

ISO 7250-1 defines basic human body measures for technological designs in the ergonomic field. However, in accordance with the recommendations of ISO 20685-1, only body measures suitable for the collection with a 3D whole-body scanner were gathered in this study. Detailed measures of the hand, head, and foot were not calculated. Furthermore, crotch height, thorax depth, and chest circumference had to be excluded from the dataset.

This leads to a limited usability for practitioners whenever these anthropometric measures are required in a design process. Nevertheless, 39 essential measures from ISO 7250-1 could be gathered, which is sufficient for many important use cases [e.g. seated office workstation with visual display terminals (Gordon 2002)].

4.3.2. Data collection in an ongoing epidemiological follow-up study

Because SHIP-3 and SHIP-Trend-1 are follow-up examinations, it was not possible to influence the composition of the sample, resulting in the youngest subject being 28 years of age (see section 2.1). Concerning the anthropometric measures, the predefined sample led to gaps at the distribution edges. In addition, due to the follow-up character of SHIP-3 and SHIP-Trend-1, the sample size could not be influenced.

Moreover, inclusion criteria in SHIP could not be changed. Hence, inclusion criteria in SHIP and DEGS1 were not the same and the composition of the populations differed, concerning the inclusion of people from other nations. Overall, 27% of people in Germany have a migration background and approximately half of them have German citizenship (Demographie Portal 2020). Only the proportion with a German citizenship was included in SHIP. Therefore, SHIP provides a good basis but since people with other citizenships work in Germany as well, this inclusion criterion was a limitation for the current study. However, persons of other nations are generally considered in the final weighted dataset, as the inclusion criterion in DEGS1 was only a permanent residence in Germany (see section 2.5.1). Consequently, people with a migration background and other citizenship [∼13% of the population in Germany (Statista 2021)] were considered within the weighting procedure.

4.3.3. Data weighting

For the used weighting algorithm, the anthropometric measures were rounded to the nearest 10 mm or 1 kg value to enable reliable weighted data. Due to data gaps at the edges of the distribution in the predefined SHIP sample, only data between the 5th and 95th percentile were defined as reliable. This limitation is necessary unless supplementary data are available. Further, DEGS1 was conducted between 2008 and 2011. Therefore, the approximation to the given body proportions of the German working-age population is currently only valid for this time period, unless newer DEGS survey data is available.

4.3.4. Offset calculation

SHIP values of the measured shoulder (biacromial) breadth were systematically lower than expected, due to different landmarking methodologies in SHIP SOP and ISO 7250-1 (see section 2.4 and Figure 2). However, even when adding the calculated landmarking offset, the values were still substantially low compared to nearby measures, e.g. shoulder (bideltoid) breadth. Because the measured shoulder (biacromial) breadth showed also quality-relevant abnormalities in the quality assurance process, this measure should not be used and instead be substituted by surrounding measures.

4.4. Percentile table for the German working-age population and comparison with latest dataset

The weighted SHIP dataset, presented as percentile table (see Table 8), aims to provide an approximation of nationally representative values. Despite the limitations mentioned above, the percentile table seems acceptable for the integration in the ergonomic design process of workplaces and products. However, it is necessary to check whether the maximum errors (e.g. the differences from the validation study) could influence the design measures to an extent that would result in safety-relevant deviations. For example, if the calculated safety ranges for arm reach erroneously turn out to be smaller than required in reality. Regarding this topic, special attention must be paid to the seven measures with a landmarking offset calculation (see section 2.4 and Figure 2). These measures have two values for each percentile, a SHIP value and an offset value (see Tables 7 and 8). If one of those seven measures is used in a safety-relevant context, a worst-case scenario should be considered. For example, for safety ranges the greater value should be used, for the positioning of an emergency stop switch, the smaller value.

The ISO 20685-1 validation tolerances were exceeded for the vast majority of anthropometric measures within the validation study. Thus, a longitudinal comparison with previous anthropometric datasets (e.g. Jürgens 2004), which used the manual measuring method described in ISO 7250-1, to investigate time trends for individual anthropometric measures is problematic. Differences could be due to anthropometric changes in the population or due to differences between the measuring methods.

Since a calibrated body scale was used in SHIP (see section 2.2), at least a comparison for body mass is feasible. Compared to the values presented in Jürgens (2004), the changes are mainly located in the upper percentiles starting from the 50th percentile upwards, in both genders. A weight gain of 12 kg for women and men at the 95th percentile can be observed, which corresponds to a relative change of 13.8% for women and 12% for men. Notwithstanding the abovementioned uncertainty, some changes are discernible, which are in line with the increase in body mass and cannot be based exclusively on deviations between the individual measurement methods. The new data show a noteworthy increase in breadth, depth, and circumference measures (which exceed the maximum observed methodical error from the validation study by far). The values of the 5th percentile show the smallest changes for both genders, followed by moderate changes in the 50th percentiles and an over-proportional increase of the values within the 95th percentiles. This leads to the assumption, that designers should take these changes into account when designing products and workplaces.

From a user perspective, on the one hand, the error values from the validation study and the measures with a landmarking offset calculation hinder the usability of the presented percentile values to a certain degree, as the user needs to consider these aspects in the design process. On the other hand, the newly generated dataset is substantially more up-to-date, and the changes in width, depth, and circumference measures are noticeably increased—even under consideration of possible measuring errors—which promotes the usability in design processes.

5. Conclusion and future directions

This publication provides a percentile table with anthropometric data for the German working-age population. Moreover, the methodology for a weighting algorithm was presented, which allows the approximation of nationally representative values, based on a regional sample. For this study representative values from DEGS1 were used (data collection between 2008 and 2011). While addressing the limitations, the calculated percentile table should be incorporated into the ergonomic design process of products and workplaces.

In a follow-up project, the BAuA continues to collect 3D body scan data, especially to close the gaps at the partially incomplete distribution edges, to be able to weight the data in a meaningful higher level of detail, even below the 5th percentile and above the 95th percentile. Moreover, a new 3D whole-body scanner now offers the possibility to capture colourised landmarks on the subject's skin, which can be identified in the subsequent manual reading process. Thus, a major source of error (landmarking errors; Kouchi and Mochimaru 2011) might be eliminated within the future project.

In addition to the univariate utilisation of datasets *via* percentile tables, multivariate analyses can be performed using anthropometric datasets with raw data. These analyses are capable of considering several combined anthropometric measures simultaneously (Dianat, Molenbroek, and Castellucci 2018; OPEN Design Lab 2021). However, the raw data from SHIP cannot be published due to data usage regulations. Therefore, the authors developed an algorithm that allows the synthesis of a virtual dataset (Wischniewski, Bonin, and Grötsch 2015; Wischniewski et al. 2017). Compared to the original dataset the virtual dataset is statistically almost identical but can be used without any privacy concerns. Hence, another publication is in progress, which will describe the methodology for the synthesis and a subsequent multivariate validation extensively. Furthermore, the virtual raw data will be presented to ensure a more holistic utilisation of the SHIP dataset.

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References

Bonin, D., D. Radke, and S. Wischniewski. 2019. "Gathering 3D Body Surface Scans and Anthropometric Data as Part of an Epidemiological Health Study – Method and Results." Paper Presented at the Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018). Volume V: Human Simulation and Virtual

Environments, Work With Computing Systems (WWCS), Process Control, Florence, August 26–30. doi:10.1007/978-3-319-96077-7_14.

Bonin, D., S. Wischniewski, M. Peters, and D. Radke. 2020. "Anthropometric Measure Extraction and Offset Calculation for 3D Body Scan Data, Obtained from an Epidemiological Health Study." Paper Presented at the Proceedings of the 6th International Digital Human Modeling (DHM) Symposium, Skövde, August 31–September 2. doi:10.3233/ATDE200004.

Castellucci, H., C. Viviani, P. Arezes, J.F. Molenbroek, M. Martínez, V. Aparici, and I. Dianat. 2020. "Applied Anthropometry for Common Industrial Settings Design: Working and Ideal Manual Handling Heights." *International Journal of Industrial Ergonomics*. 78: 102963. doi:10.1016/j.ergon.2020.102963.

Demographie Portal. 2020. "Bevölkerung mit Migrationshintergrund." Accessed August 9, 2022. https://www.demografie-portal.de/DE/Fakten/bevoelkerung-migrationshintergrund.html

Dewangan, K., C. Owary, and R. Datta. 2008. "Anthropometric Data of Female Farm Workers from North Eastern India and Design of Hand Tools of the Hilly Region." *International Journal of Industrial Ergonomics*. 38 (1): 90–100. doi:10.1016/j.ergon.2007.09.004.

Dianat, I., J. Molenbroek, and H.I. Castellucci. 2018. "A Review of the Methodology and Applications of Anthropometry in Ergonomics and Product Design." *Ergonomics* 61 (12): 1696–1720. doi:10.1080/00140139.2018.1502817.

DIN. 2020. *33402-2:2020 Ergonomics – Human Body Dimensions – Part 2: Values*. Berlin: Beuth.

Garneau, C.J., and M.B. Parkinson. 2016. "A Survey of Anthropometry and Physical Accommodation in Ergonomics Curricula." *Ergonomics* 59 (1): 143–154. doi:10.1080/00140139.2015.1052853.

Ghaderi, E., A. Maleki, and I. Dianat. 2014. "Design of Combine Harvester Seat Based on Anthropometric Data of Iranian Operators." *International Journal of Industrial Ergonomics* 44 (6): 810–816. doi:10.1016/j.ergon.2014.10.003.

Gordon, C. 2002. "Multivariate Anthropometric Models for Seated Workstation Design." In *Contemporary Ergonomics*, edited by P.T. McCabe, 582–589. Taylor & Francis.

Gordon, C.C., C.L. Blackwell, B. Bradtmiller, J.L. Parham, P. Barrientos, S.P. Paquette, B. Corner, J. Carson, J. Venezia, B.M. Rockwell, M. Mucher, and S. Kristensen. 2014. "2012 Anthropometric Survey of US Army Personnel: Methods and Summary Statistics." Accessed March 29, 2021. https://apps.dtic.mil/sti/citations/ADA611869

Gordon, C.C., and B. Bradtmiller. 2012. "Anthropometric Change: Implications for Office Ergonomics." *Work* 41: 4606–4611. doi:10.3233/WOR-2012-0076-4606.

Haleem, A., and M. Javaid. 2019. "3D Scanning Applications in Medical Field: A Literature-Based Review." *Clinical Epidemiology and Global Health* 7 (2): 199–210. doi:10.1016/j.cegh.2018.05.006.

Han, H., Y. Nam, and K. Choi. 2010. "Comparative Analysis of 3D Body Scan Measurements and Manual Measurements of Size Korea Adult Females." *International Journal of Industrial Ergonomics* 40 (5): 530–540. doi:10.1016/j.ergon.2010.06.002.

Hanson, L., L. Sperling, G. Gard, S. Ipsen, and C.O. Vergara. 2009. "Swedish Anthropometrics for Product and Workplace Design." *Applied Ergonomics* 40 (4): 797–806. doi:10.1016/j.apergo.2008.08.007.

Harrell, F.E. 2020. *Hmisc: Harrell Miscellaneous*. R package version 4.5-0.

ISO. 2005. *15536-1:2005 Ergonomics – Computer Manikins and Body Templates – Part 1: General Requirements*. Geneva: International Organization for Standardization.

ISO. 2007. *15536-2:2007 Ergonomics – Computer Manikins and Body Templates – Part 2: Verification of Functions and Validation of Dimensions for Computer Manikin Systems*. Geneva: International Organization for Standardization.

ISO. 2012. *15535:2012 General Requirements for Establishing Anthropometric Databases*. Geneva: International Organization for Standardization.

ISO. 2013. *7250-2:2010 + Amd 1:2013 Basic Human Body Measurements for Technological Design – Part 2: Statistical Summaries of Body Measurements from National Populations*. Geneva: International Organization for Standardization.

ISO. 2015. *20685-2:2015 Ergonomics – 3-D Scanning Methodologies for Internationally Compatible Anthropometric Databases – Part 2: Evaluation Protocol of Surface Shape and Repeatability of Relative Landmark Positions*. Geneva: International Organization for Standardization.

ISO. 2017. *7250-1:2017 Basic Human Body Measurements for Technological Design – Part 1: Body Measurement Definitions and Landmarks*. Geneva: International Organization for Standardization.

ISO. 2018. *20685-1:2018 3-D Scanning Methodologies for Internationally Compatible Anthropometric Databases – Part 1: Evaluation Protocol for Body Dimensions Extracted from 3-D Body Scans*. Geneva: International Organization for Standardization.

John, U., B. Greiner, E. Hensel, J. Lüdemann, M. Piek, S. Sauer, C. Adam, G. Born, D. Alte, E. Greiser, U. Haertel, H.W. Hense, J. Haerting, S. Willich, and C. Kessler. 2001. "Study of Health in Pomerania (SHIP): A Health Examination Survey in an East German Region: Objectives and Design." *Sozial- Und Praventivmedizin* 46 (3): 186–194. doi:10.1007/BF01324255.

Jürgens, H.W. 2004. *Erhebung Anthropometrischer Maße Zur Aktualisierung Der DIN 33 402. Teil 2*. Bremerhaven: Wirtschaftsverlag NW Verlag für neue Wissenschaft GmbH.

Kamtsiuris, P., M. Lange, R. Hoffmann, A.S. Rosario, S. Dahm, R. Kuhnert, and B.-M. Kurth. 2013. The First Wave of the German Health Interview and Examination Survey for Adults (DEGS1). *Bundesgesundheitsblatt, Gesundheitsforschung, Gesundheitsschutz* 56 (5–6): 620–630. doi:10.1007/s00103-012-1650-9.

Koepke, N., M. Zwahlen, J.C. Wells, N. Bender, M. Henneberg, F.J. Rühli, and K. Staub. 2017. "Comparison of 3D Laser-Based Photonic Scans and Manual Anthropometric Measurements of Body Size and Shape in a Validation Study of 123 Young Swiss Men." *PeerJ* 5: e2980. doi:10.7717/peerj.2980.

Kouchi, M., and M. Mochimaru. 2011. "Errors in Landmarking and the Evaluation of the Accuracy of Traditional and 3D Anthropometry." *Applied Ergonomics* 42 (3): 518–527. doi:10.1016/j.apergo.2010.09.011.

Kouchi, M., M. Mochimaru, B. Bradtmiller, H. Daanen, P. Li, B. Nacher, and Y. Nam. 2012. "A Protocol for Evaluating the Accuracy of 3D Body Scanners." *Work* 41 (Supplement): 4010–4017. doi:10.3233/WOR-2012-0064-4010.

Lumley, T. 2020. *Survey: Analysis of Complex Survey Samples*. R package version 4.0.

Ng, B., B. Hinton, B. Fan, A. Kanaya, and J. Shepherd. 2016. "Clinical Anthropometrics and Body Composition from 3D Whole-Body Surface Scans." *European Journal of Clinical Nutrition* 70 (11): 1265–1270. doi:10.1038/ejcn.2016.109.

OPEN Design Lab. 2021. "Multivariate Accommodation Calculator 2.0." Accessed March 29, 2021. https://www.openlab.psu.edu/

Pagano, B.T., M.B. Parkinson, and M.P. Reed. 2015. "An Updated Estimate of the Body Dimensions of US Children." *Ergonomics* 58 (6): 1045–1057. doi:10.1080/00140139.2014.1000392.

Parkinson, M.B., and M.P. Reed. 2010. "Creating Virtual User Populations by Analysis of Anthropometric Data." *International Journal of Industrial Ergonomics*. 40 (1): 106–111. doi:10.1016/j.ergon.2009.07.003.

R Core Team. 2021. *R: A Language and Environment for Statistical Computing*. Vienna: R Foundation for Statistical Computing.

Scheidt-Nave, Christa, Panagiotis Kamtsiuris, Antje Gößwald, Heike Hölling, Michael Lange, Markus A. Busch, Stefan Dahm, Rüdiger Dölle, Ute Ellert, Judith Fuchs, Ulfert Hapke, Christin Heidemann, Hildtraud Knopf, Detlef Laussmann, Gert B M. Mensink, Hannelore Neuhauser, Almut Richter, Anke-Christine Sass, Angelika Schaffrath Rosario, Heribert Stolzenberg, Michael Thamm, and Bärbel-Maria Kurth. 2012. "German Health Interview and Examination Survey for Adults (DEGS)-Design, Objectives and Implementation of the First Data Collection Wave." *BMC Public Health* 12 (1): 730. doi:10.1186/1471-2458-12-730.

Statista. 2021. "Anteil der ausländischen Bevölkerung an der Gesamtbevölkerung in Deutschland von 1991 bis 2021." Accessed August 9, 2022. https://de.statista.com/statistik/daten/studie/14271/umfrage/deutschland-anteil-aus-laender-an-bevoelkerung/

Treleaven, P. 2004. "Sizing us up." *IEEE Spectrum* 41 (4): 28–31. doi:10.1109/MSPEC.2004.1279190.

Treleaven, P., and J. Wells. 2007. "3D Body Scanning and Healthcare Applications." *Computer Magazine* 40 (7): 28–34. doi:10.1109/MC.2007.225.

Vega, G.R., U.Z. Colado, X.P.Z. Colado, D.A.R. Vega, and E.J.V. Bustillos. 2021. "Comparison of Univariate and Multivariate Anthropometric Accommodation of the Northwest Mexico Population." *Ergonomics* 64 (8): 1018–1034. doi:10.1080/00140139.2021.1892832.

Völzke, Henry, Dietrich Alte, Carsten Oliver Schmidt, Dörte Radke, Roberto Lorbeer, Nele Friedrich, Nicole Aumann, Katharina Lau, Michael Piontek, Gabriele Born, Christoph Havemann, Till Ittermann, Sabine Schipf, Robin Haring, Sebastian E. Baumeister, Henri Wallaschofski, Matthias Nauck, Stephanie Frick, Andreas Arnold, Michael Jünger, Julia Mayerle, Matthias Kraft, Markus M. Lerch, Marcus Dörr, Thorsten Reffelmann, Klaus Empen, Stephan B. Felix, Anne Obst, Beate Koch, Sven Gläser, Ralf Ewert, Ingo Fietze, Thomas Penzel, Martina Dören, Wolfgang Rathmann, Johannes Haerting, Mario Hannemann, Jürgen Röpcke, Ulf Schminke, Clemens Jürgens, Frank Tost, Rainer Rettig, Jan A. Kors, Saskia Ungerer, Katrin Hegenscheid, Jens-Peter Kühn, Julia Kühn, Norbert Hosten, Ralf Puls, Jörg Henke, Oliver Gloger, Alexander Teumer, Georg Homuth, Uwe Völker, Christian Schwahn, Birte Holtfreter, Ines Polzer, Thomas Kohlmann, Hans J. Grabe, Dieter Rosskopf, Heyo K. Kroemer, Thomas Kocher, Reiner Biffar, Ulrich John, and Wolfgang Hoffmann. 2011. "Cohort Profile: The Study of Health in Pomerania." *International Journal of Epidemiology* 40 (2): 294–307. doi:10.1093/ije/dyp394.

Völzke, H., T. Ittermann, C.O. Schmidt, S.E. Baumeister, S. Schipf, D. Alte, R. Biffer, U. John, and W. Hoffmann. 2015. "Prevalence Trends in Lifestyle-Related Risk Factors: two Cross-Sectional Analyses with a Total of 8728 Participants from the Study of Health in Pomerania from 1997 to 2001 and 2008 to 2012." *Deutsches Arzteblatt International* 112 (11): 185–192. doi:10.3238/arztebl.2015.0185.

Völzke, H., J. Schössow, C.O. Schmidt, C. Jürgens, A. Richter, A. Werner, N. Werner, D. Radke, A. Teumer, T. Ittermann, B. Schauer, V. Henck, N. Friedrich, A. Hannemann, T. Winter, M. Nauck, M. Dörr, M. Bahls, S.B. Felix, B. Stubbe, R. Ewert, F. Frost, M.M. Lerch, H.J. Grabe, R. Bülow, M. Otto, N. Hosten, W. Rathmann, U. Schminke, R. Großjohann, F. Tost, G. Homuth, U. Völker, S. Weiss, S. Holtfreter, B.M. Bröker, K. Zimmermann, L. Kaderali, M. Winnefeld, B. Kristof, K. Berger, S. Samietz, C. Schwahn, B. Holtfreter, R. Biffar, S. Kindler, K. Wittfeld, W. Hoffmann, and T. Kocher. 2022. "Cohort Profile Update: The Study of Health in Pomerania (SHIP)." *International Journal of Epidemiology* dyac034. doi:10.1093/ije/dyac034.

Wischniewski, S., D. Bonin, and A. Grötsch. 2015. "Virtual Anthropometry – Synthesis and Visualisation of Virtual Anthropometric Populations for Product and Manufacturing Engineering." Paper Presented at the Proceedings of the 19th Triennial Congress of the International Ergonomics Association, Melbourne, August 9–14.

Wischniewski, S., A. Grötsch, D. Bonin, and M. Parkinson. 2017. *Synthesis and Validation of a Virtual Anthropometric User Population of German Civilians Based on an up-to-Date Representative Dataset (Series Title: Baua: Focus)*. Dortmund: BAuA.