# Study on multivariate analysis of anthropometric measures for upper body exoskeletons using archetypal analysis

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**Abstract:** The accurate fit of upper body exoskeletons is of importance for an efficient physical user support. However, there's a lack of multivariate data and adjustment ranges for proper upper body exoskeleton design. Therefore, the aim of this paper is to provide exoskeleton design-relevant body parameters of men and women as an input to suitable adjustment range for shoulder and back exoskeletons. We identified relevant body parameters for back and shoulder exoskeletons and calculated the upper and lower bounds for males and females by applying the archetypal analysis on a large anthropometric dataset from Mecklenburg-Vorpommern, Germany. Based on the archetypes, we identified minimum and maximum limits. These limits were checked for their accommodation level for the original as well as a weighted dataset, representing data for the whole of Germany. In addition, we compared the results of the limits with one dimensional percentile values. The results showed an accommodation for the identified multivariate limits between 87–94% for the different exoskeleton types and gender groups.

**Keywords:** upper body; anthropometry; design dimensions; percentiles; archetypal analysis; ergonomic; data set; measures; minimum and maximum limits.

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## 1 Introduction

The principles of a human-centred design and the consideration of the hierarchy of controls is most important for ergonomic design of workplaces (NIOSH, 2016) and, in many cases, body regions affected by occupational musculoskeletal disorders (MSD) can be relieved by ergonomically adapting the workplace. However, intervention approaches with exoskeletons as portable aids also offer a possible alternative solution with chances of reducing occupational MSDs and improving working conditions (Peters et al., 2019).

Effective adjustment and customisation options of shoulder and back exoskeletons are of particular importance for optimal support of the users (Smets, 2019; Baltrusch et al., 2020, 2021). Furthermore, the perceived comfort when wearing the exoskeleton that goes along with a proper fit is decisive for its use (Hensel and Keil, 2018). Knowledge of relevant anthropometric body parameters of the user group is central to the design of accurately fitting upper body exoskeletons. In this context, a representative anthropometric dataset is a prerequisite for calculating the anthropometric limits for the design and suitable adjustment range for shoulder and back exoskeletons (Dainoff et al., 2004; da Silva et al., 2018).

The Federal Institute for Occupational Safety and Health (BAuA) published the latest publicly available percentile dataset of the German working-age population in 2004 (Jürgens, 2004). The results of this research project are the basis for the current DIN 33402-2 (DIN, 2020) and ISO/TR 7250-2 (ISO, 2013) values, but do not offer all relevant parameters for shoulder and back exoskeleton design, as they only provide the most common parameters for workstation design (ISO, 2017). However, other values such as upper arm circumference, chest breadth and thigh length are important to ensure a good fit of exoskeletons to the body, because they ensure a good fixation of the exoskeleton and, as contact points between the exoskeleton and the body, can also be particularly prone to cause discomfort (Amandels et al., 2018; Theurel et al., 2018.). The current standards depict extremes of the distribution in the form of percentile values (e.g., 5th and 95th percentiles). The validity of percentile values for multiple, combined measures is often unclear, because they are not additive and do not allow multivariate analysis of the data (Robinette and McConville, 1981; Zehner et al., 1993). With respect to shoulder and back exoskeleton design, there are typically several exoskeleton-specific anthropometric measures (e.g., hip breadth, thighs length and upper arm circumference, etc.), that strongly or weakly correlated with each other (Poirson and Parkinson, 2014; Dianat et al., 2018). It is therefore necessary to choose a multivariate analysis approach to be able to cover a certain percentage of the user population by representative cases (e.g., archetypes).

To solve multivariate accommodation problems, there are several validated approaches. One common statistical technique bases on the use of principal component analysis (Zehner et al., 1993; Hudson et al., 1998; Brolin et al., 2012; Boyd and Parkinson, 2015; Reed and Park, 2017). Another is the archetypal analysis presented by Cutler and Breiman (1994). Archetype analysis assumes that there are several 'pure' cases or individuals located at the 'edges' of a dataset. All other individuals are considered 'mixtures' of these pure types. The theoretical individuals are generated to represent not only the size variance but also the proportional variability of the selected measures. Archetypal analysis is versatile and scientists use it in a wide variety of scientific fields. In the original work by Cutler and Breiman, 1994, a dataset on air pollution and another on the shape of soldiers' heads were analysed using archetypes. In further work, archetypal analysis was used in the field of market research (Li et al., 2003) and in the analysis of astronomy spectra (Chan et al., 2003). In addition, in the field of anthropometry, archetypal analysis is appropriated to generate boundary cases (Eugster and Leisch, 2009; Epifanio et al., 2013). However, provision of concrete design values, determined by archetypal analysis, does not exist yet. Therefore, with this work, we would like to test the applicability of archetype analysis as a possibility for generating anthropometric boundary cases for exoskeleton-specific parameters and present a new approach in this area.

The aim of this paper is to provide a specific dataset of body parameters for men and women with a fixed accommodation level (>90%) relevant to the development of suitable adjustment ranges of upper body exoskeletons, which are identified by archetypal analysis, using a large regional anthropometric dataset from Germany.

## 2 Method

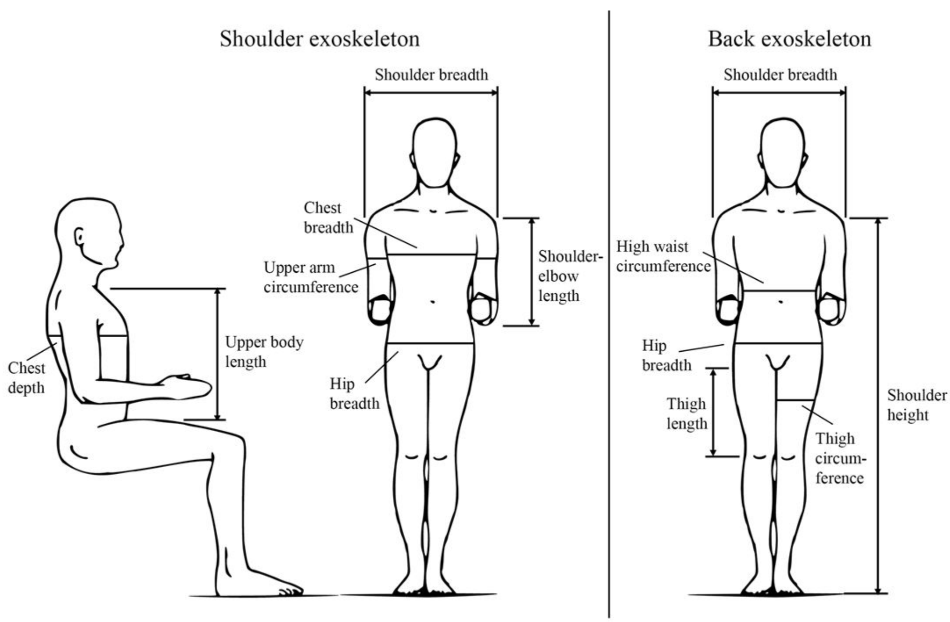
As data base, we use a large regional sample for Germany, derived from 3D body scans, taken as part of our research project on Digital Ergonomics in cooperation with the University of Greifswald and the Study of Health in Pomerania (SHIP). The dataset used consists of 2015 3D body scans and according anthropometric parameters (923 women and 1,092 men). It is an age- and gender-stratified random sample drawn from the centralised registry data of Mecklenburg-Vorpommern (Völzke et al., 2011). Inclusion criteria were reported primary residence in the study region, age range from 20 to 79 years, and German nationality. As the study represents a regional sample, Bonin et al. (2021) used data from a nationally representative survey for Germany (Scheidt-Nave et al., 2012) to compensate for regional variations with a weighting coefficient. As we considered the working-age population, we selected subjects between 18 and 67 years. More information can be found in the publication of Bonin et al. (2021).

Based on the dataset described above, we selected body parameters, relevant for the design of back as well as shoulder exoskeletons, and performed an archetypal analysis of the original data. We generated limits by choosing minimum and maximum from the archetype values for the chosen parameters for males and females and verified the accommodation level. If we achieved the appropriate level of accommodation, we applied the limits to the weighted data and checked the coverage.

### *2.1 Selection of the parameters*

Because we are focussing on back and shoulder exoskeletons in this study, and both models typically require different body contact points with different relevant body parameters, we also focus our evaluation separately on the combinations of parameters for the respective exoskeleton models. We are not determined on a specific model or manufacturer of exoskeletons in this article. Therefore, we try to cover as much as possible of existing models with the chosen parameters and also to provide possible parameters for future exoskeleton developments. First we selected the body parameters relevant for back and shoulder exoskeleton design, based upon the essential anthropometric dimensions listed in DIN EN ISO 7250:2017. We based our selection of body parameters firstly on the parts of the exoskeleton that are adjustable for the user (e.g., upper body length to adjust the length of the fasteners on the back for the back exoskeleton models or upper arm circumference for the attachment of the shoulder exoskeleton). We also selected other parameters that might be relevant to the design process.

**Figure 1** Relevant body parameters for shoulder exoskeletons (S), and back exoskeletons (B)




Seven relevant body parameters were determined for shoulder exoskeletons (S), and six relevant parameters for back exoskeletons (B) as shown in figure 1 and table 1. The selection of the dimensions considered the attachment points of the two exoskeleton-models and the body areas where the exoskeletons run along the body. In addition to the body parameters given in Table 1, we also used the body parameters ‘sitting thigh clearance’ and ‘sitting shoulder height’ as well as ‘standing crotch height’ and ‘sitting popliteal height’ to generate the values for the body parameters ‘upper body length’ respectively ‘thigh length’. This was necessary because the data basis did not provide values for these body parameters.

**Table 1** Relevant body parameters for shoulder and back exoskeletons

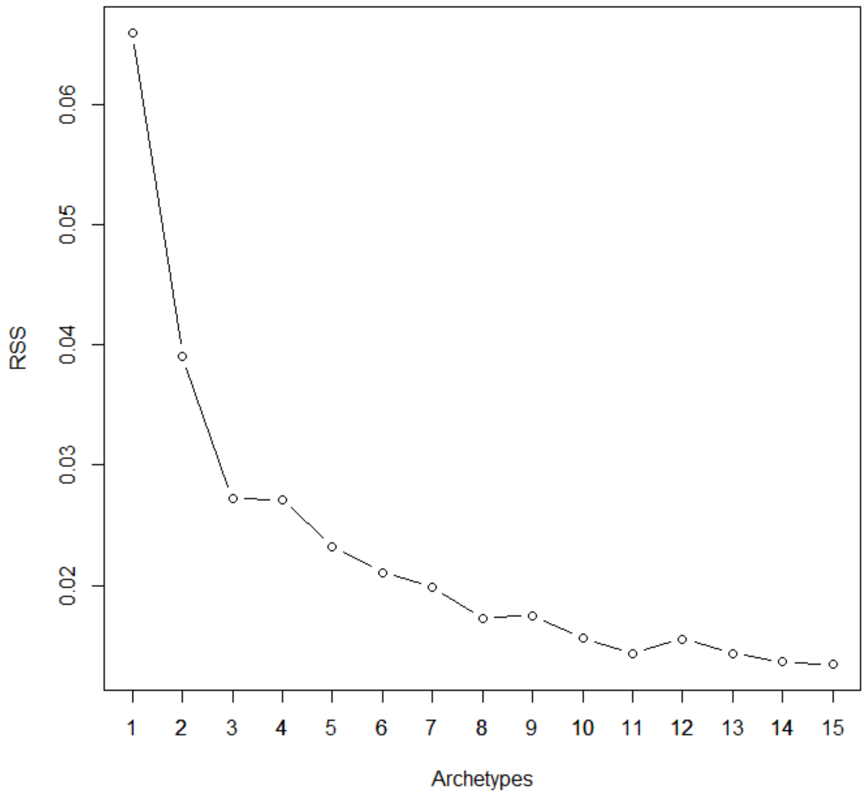
| *Measure* | *Exo* | *Description* |
|---|---|---|
| Shoulder height1 | B | Vertical distance of the footprint to acromion. |
| Shoulder breadth1 | B/S | Horizontal distance across the most prominent soft tissues of the deltoid muscle of the right and left upper arm. |
| Shoulder-elbow length[a] | S | Vertical distance from the acromion to the lowest point of bone of the elbow bent by 90°. |
| Upper arm circumference[a] | S | The largest circumference of the upper arm. |
| Chest breadth[a] | S | Horizontal breadth of the trunk at the height of the mesosternal. |
| Chest depth[a] | S | Horizontal depth of the trunk in the median sagittal plane, at the level of the mesosternal. |
| Upper body length[b] | S | Vertical distance from the seat surface of the thigh to the acromion minus the vertical distance from the seat surface to the highest point of the thigh. |
| High waist circumference[a] | B | The horizontal circumference of the trunk at the centre of the area between the lower ribs and the upper iliac crest. |
| Hip breadth[a] | B/S | Maximum horizontal distance between the outer sides of the hips standing. |
| Thigh circumference[a] | B | Largest circumference of the thigh. |
| Thigh length[c] | B | Vertical distance from the standing surface to the crotch (highest palpable point of the perineum) minus the vertical distance from the standing surface of the feet to the underside of the thigh held at right angles to the lower leg immediately behind the knee. |

Notes: [a]See also DIN EN ISO 7250.
[b]Calculated with ‘sitting thigh clearance’ and ‘sitting shoulder height’.
[c]Calculated with ‘standing crotch height’ and ‘sitting popliteal height’.

## 3 Data analysis

We started by choosing the number of archetypes $k$ by the elbow criterion for the remaining root sum squares (RSS) of the included data as indicating extern criteria, because the selected number of archetypes $k$ determined the generated minimum and maximum limits of the archetypes. For example, if we first calculated five archetypes and then eight archetypes, then these eight archetypes did not automatically include the first five calculated, as the existing values may change to better capture the shape of the dataset. We calculated the possible numbers of archetypes $k$ where we indicated a flattening of the curve. The RSS of $k$ = 2–15 for the variable combination shoulder exoskeleton for women is shown in Figure 2.

**Figure 2** Screeplot of the remaining RSS shoulder exoskeleton for woman




We generated archetypes with the software R (R Core Team, 2020) and the package *archetypes* (Eugster and Leisch, 2009). We did this separately for shoulder and back exoskeleton body parameters. Once we had generated the possible number of archetypes *k*, we scored all archetypes in terms of the minimum and maximum values of each body parameter and calculated the perceptual coverage of the dataset by the limits that we took by the value of the archetypes. The database objects of the dataset were then compared with the determined minimum and maximum limit values. A database object was considered to be within the archetypal limits only if all relevant body parameters from table 1 for the corresponding exoskeleton (shoulder or back), were within the selected limits. The cases were only accommodated if they fit in the maximum and minimum boundaries for all values. Cases where one of the body parameters was outside the limit values were not considered. For both, the back and shoulder exoskeleton, archetypes were generated until their values allowed an accommodation level >90% of the database objects for the dataset. In addition, we subsequently checked the generated values for their accommodation level of the weighted dataset as a representation for all of Germany. We analysed the body parameters for back and shoulder exoskeletons separately.

### 3.1 Percentile analysis

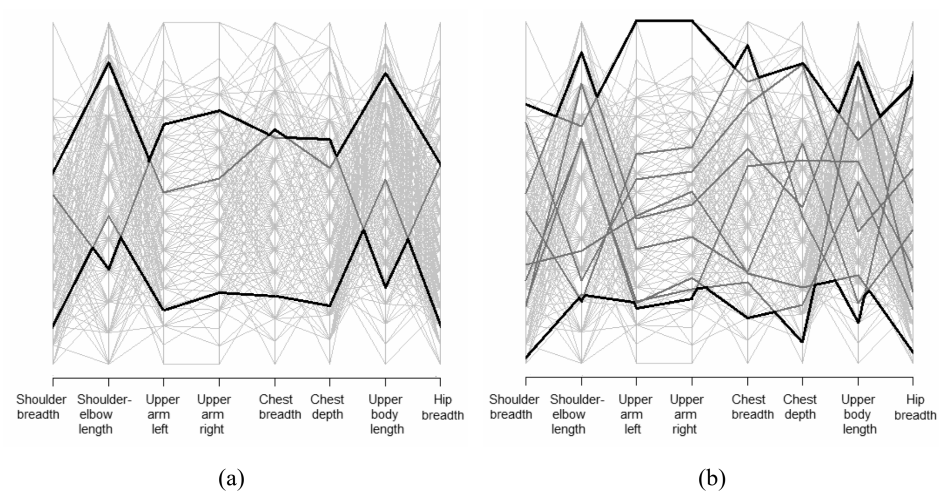
After performing the archetypal analysis and collecting the accommodation level of the determined minimum and maximum values, we performed a check of the accommodation level with gender-specific percentiles of our dataset. To do this, we again selected the appropriate body parameters for shoulder and back exoskeletons and calculated the corresponding value for the 5th and 95th percentiles for men and woman separately. Afterwards we used the values as minimum and maximum limits, as done before with the archetype values. We used all body parameters given in Table 1.

## 4 Results

### 4.1 Body parameters for shoulder exoskeletons

The analysis of the RSS of $k$ = 2–15 for the body parameters of the shoulder exoskeleton of the women resulted in one elbow criterion at $k$ = 3 and two others, at $k$ = 9 and $k$ =11. We applied the cut-off values obtained from the results of the calculations of three archetypes to the unweighted women dataset but could only cover 55% of the cases. The calculation of nine archetypes resulted in 91% data coverage (see also Figure 3). Therefore, no calculation was performed with $k$ = 11 for the women dataset.

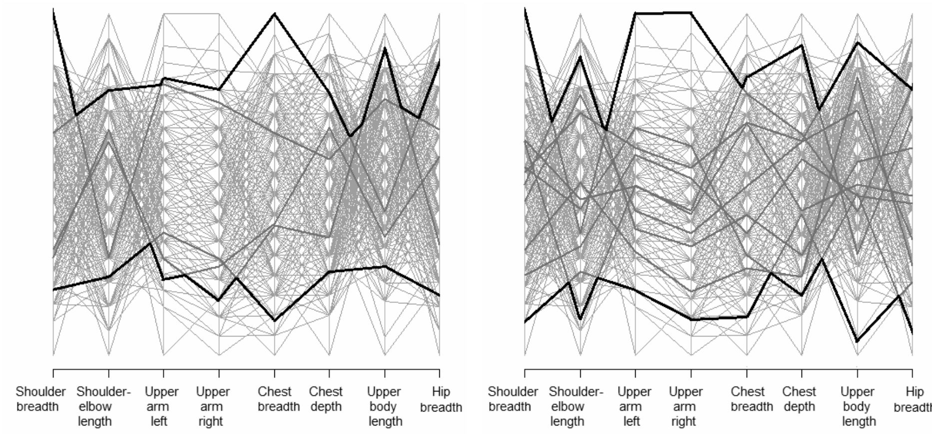
**Figure 3** Archetypes shoulder exoskeleton women with (a) three and (b) nine models




Note: Black lines – boundaries by the minimum and maximum values of all generated archetypes.

For men, we detected elbow criterions at $k$ = 5 and three others, at $k$ = 10, $k$ = 12 and $k$ = 14 for the shoulder exoskeleton body parameters. We transferred the limit values obtained from the results of the calculations of five archetypes to the men dataset but could only cover 81% of the cases. After performing the calculation with ten archetypes, we got a result of 93% accommodation, therefore no more calculations were performed with $k$ = 12 and $k$ = 14 (see Figure 4).

**Figure 4** Archetypes shoulder exoskeleton men with (a) five and (b) ten archetypes



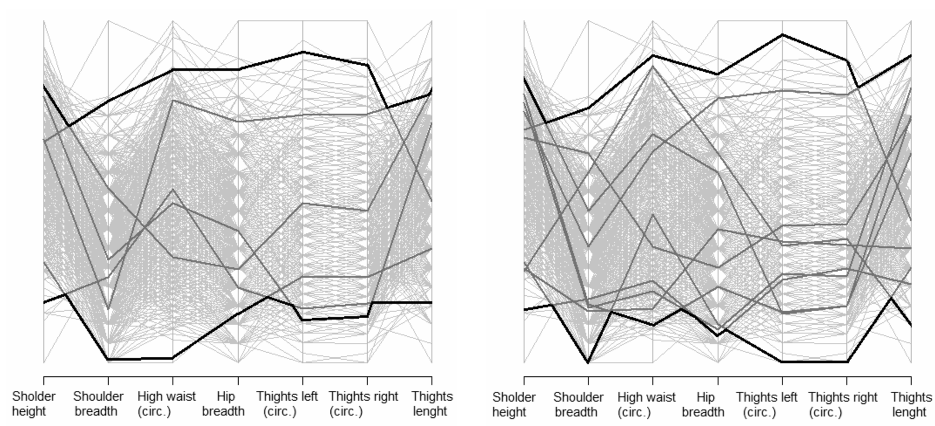

(a) (b)

Note: Black lines – boundaries by the minimum and maximum values of all generated archetypes).

## *4.2 Body parameters for back exoskeletons*

The analysis for the body parameters of the back exoskeleton for the cases of women, resulted in one elbow criterion at $k = 6$ and two others, at $k = 10$ and $k = 13$. We applied the reached limits of six archetypes to the women's dataset, but could only cover 84% of all cases. By checking the accommodation of 10 archetypes, we reached a level of 94% of the women data coverage. Therefore no more calculation with $k = 13$ was performed (see Figure 5).

**Figure 5** Archetypes back exoskeleton women with (a) six and (b) ten models

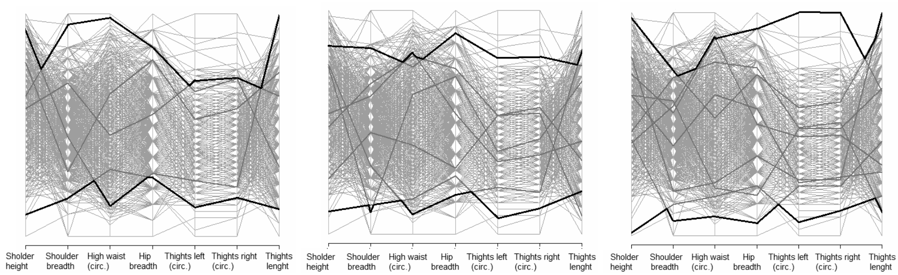



(a) (b)

Note: Black lines – boundaries by the minimum and maximum values of all generated archetypes.

The analysis of the RSS of $k$ = 2–15 for the body parameters of the back exoskeleton of the men, showed elbow criterions at $k$ = 5, $k$ = 7, $k$ = 9 and $k$ = 11. For the limits of five archetypes an accommodation level of 87% could be reached, and for seven archetypes we calculated 87% coverage for the men's data cases. A review of the values of nine archetypes was then able to confirm a coverage of 93%, therefore a calculation of $k$ = 11 was not performed (Figure 6).

**Figure 6** Archetypes back exoskeleton men with (a) five, (b) seven and (c) nine models




(a) (b) (c)

Note: Black lines – boundaries by the minimum and maximum values of all generated archetypes.

## 4.3 Weighted dataset

After we achieved a sufficient level of accommodation >90% for the described parameter combinations for men and women for the original dataset, the generated values were applied to the weighted dataset. The results confirmed good coverage for the weighted dataset for shoulder and back exoskeleton body parameters. Still, with transfer of the determined values and accommodation check with the weighted dataset for the shoulder exoskeleton limits for women was able to achieve >90% coverage and an accommodation of 87%, men of 90%. In contrast, the coverage of the body parameters of the back exoskeleton reached 91% for women and 91% for men (see Tables 2 and 3).

## 4.4 Percentiles

The results of the determination of the accommodation level for the 5th and 95th percentile values of the dataset showed a coverage of 69% for the shoulder exoskeleton body parameters in women for the original dataset and an accommodation of 64% for the weighted data. For the shoulder exoskeleton specific body parameters in men, we were still able to determine an accommodation level of 69% for the original data and a coverage of 63% for the weighted dataset (Table 2). When reviewing the back exoskeleton body parameters for women, the percentile values yielded a coverage of 70% for the original and 63% for the weighted dataset. When transferring the back exoskeleton specific percentile values for men, we were able to calculate a coverage of 71% for the original data. The examination of the weighted data even showed an accommodation level of 64% (Table 3).

**Table 2** Body parameters shoulder exoskeleton (cm)

| | *Men (n = 1,092)* | | | | *Woman (n = 923)* | | | |
|---|---|---|---|---|---|---|---|---|
| | *P5* | *P95* | *archetypes* | | *P5* | *P95* | *archetypes* | |
| Shoulder breadth | 46 | 55 | 43 | 61 | 41 | 50 | 39 | 53 |
| Shoulder-elbow length | 36 | 42 | 33 | 44 | 32 | 39 | 32 | 40 |
| Upper arm (left) circ. | 28 | 36 | 25 | 42 | 25 | 34 | 25 | 40 |
| Upper arm (right) circ. | 28 | 36 | 26 | 42 | 25 | 34 | 25 | 40 |
| Chest breadth | 33 | 42 | 31 | 43 | 29 | 37 | 28 | 40 |
| Chest depth | 22 | 30 | 21 | 33 | 19 | 26 | 18 | 29 |
| Upper body length | 43 | 52 | 38 | 54 | 41 | 49 | 38 | 51 |
| Hip breadth | 34 | 40 | 31 | 41 | 33 | 42 | 32 | 46 |
| Acc. % | 69% | | 93% | | 69% | | 91% | |
| Acc. weighted data% | 63% | | 90% | | 64% | | 87% | |

**Table 3** Body parameters back exoskeleton (cm)

| | *Men (n = 1,092)* | | | | *Woman (n = 923)* | | | |
|---|---|---|---|---|---|---|---|---|
| | *P5* | *P95* | *archetypes* | | *P5* | *P95* | *archetypes* | |
| Shoulder height | 140 | 160 | 127 | 166 | 129 | 148 | 122 | 150 |
| Shoulder breadth | 46 | 55 | 42 | 56 | 41 | 50 | 39 | 52 |
| High waist circ. | 83 | 117 | 76 | 123 | 70 | 104 | 67 | 114 |
| Hip breadth | 34 | 41 | 31 | 43 | 33 | 42 | 32 | 46 |
| Thighs (left) circ. | 50 | 63 | 43 | 77 | 50 | 67 | 44 | 78 |
| Thighs (right) circ. | 50 | 63 | 45 | 77 | 50 | 67 | 44 | 76 |
| Thighs length | 28 | 38 | 27 | 42 | 31 | 39 | 28 | 42 |
| Acc. % | 71% | | 93% | | 70% | | 94% | |
| Acc. weighted data% | 64% | | 91% | | 63% | | 91% | |

## 5 Discussion

This study allows for the identification of which body parameters and according anthropometric values are necessary for the design of shoulder and back exoskeletons. It represents a suitable methodological approach to perform a multivariate analysis and to find suitable adjustment range for shoulder and back exoskeletons relevant body parameters, to ensure the correct fit of exoskeletons, which is essential for comfort of such systems. As a recommendation for the design of exoskeletons, the range between the maximum and minimum values of the described body parameters can be used as a guide. Thus, the described body areas of the respective exoskeleton should allow a range of adjustment in the determined rage to cover a particularly large part >90% of the possible user population. As we show, the use of a current and meaningful dataset is significant. The comparison of our calculated values with the percentile values shows the importance of multivariate analysis. The clearly more reliable calculation of out-limit values, calculated by means of archetypes, gives a higher accommodation level for all calculated body parameters, both for men and for women. The results confirm that percentile values are not meaningful for exoskeleton design.

As we show in this paper, archetypal analysis is suited for generating models and values for exoskeleton fitting. However, in our analysis it was often necessary to generate a large number of archetypes to achieve the desired accommodation >90% for the women's and men's data. Still, when the number of human parameters to consider increases, the proposed method allows the designer to make a universal design and take in account seven to eight body parameters, as we did in our example for exoskeletons. Nevertheless, it is difficult to perform an archetypal analysis, especially when not all body parameters correlate with each other to the same degree. For example, 'hip width' and 'waist circumference' are body parameters that have had a large influence in the generation of the archetypes and show a large variance between minimum and maximum limit values. Among other things, this may be because these body parameters are primarily dependent on the body mass of the individual and are not related to the length of limbs. Unfortunately, in the archetypal analysis we cannot do a prioritisation of body parameters, all parameters in the archetypal analysis are on the same priority line.

Additionally, it has to be taken into account, that the accommodation levels of the weighted data are limited, because the SHIP dataset was partially incomplete at the distribution edges. A rounding process ensured the calculation of reliable weighted data, but currently only within the 5th and 95th percentile (Bonin et al., 2021). The desired accommodation could therefore deviate to a small extent. An expansion of the dataset and improvement of the weighting coefficient is planned.

In general, archetypal analysis can lead to variation problems because of no possibility to optimise and of choosing the most efficient design with low dispersion between maximum and minimum values. Archetype analysis assumes that there are several 'pure' cases or individuals located at the 'edges' of a dataset, however, there is no way to influence the 'pure' cases or the archetype generation. This also leads to the lack of a possibility to optimise limit values of the selected body parameters. It is a main issue, and archetypal analysis offers no solution to this (Epifanio et al., 2013). The possibility to balance the result depending on the priority for the industry should be given to the user. Nevertheless, our paper indicates a good solution; still it is not the optimum. In order to achieve even better results, the dataset will be expanded to include further cases in the future.

The results obtained through archetypal analysis can be seen as an input to suitable adjustment range for shoulder and back exoskeletons and should be used as a starting point for the design of exoskeletons to reconsider already outdated dimensions.

## 6 Conclusions

Our work illustrates that up-to-date datasets are essential for the design of appropriate work systems. Further research should take care to use appropriate datasets to provide users and manufacturers with optimal data for designing safe systems. The archetypal analysis offers an exemplary approach to the analysis of appropriate anthropometric limits for the design of shoulder and back exoskeletons and can also be transferred to other work systems. Nevertheless, further analysis approaches should be tested, which allow for an optimised and need-based determination of corresponding design limits.

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