Functional Body Measurements – Motion-Oriented 3D Analysis of Body Measurements

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Abstract

The balancing act between freedom of movement, functionality and fashion orientated fit for different target groups poses new complex challenges on the manufacturers of work and sportswear during development and sales.

Anthropometric data is used for clothing design, PPE, workspaces and human-machine interfaces. Two different sizing systems are used for this: size charts and ergonomic standards. Size charts are the base for the clothing industry, although these cannot cover the functional requirements for workwear and protective clothing. The variability of body measurements during movement is partially noted in the Ergonomic-standard, but these are nonrelated to the clothing sizes. A standard that correlates the sizes with the functional movement of the body while working was not available until now.

The variability of body measurements was investigated in the research project “functional measurements” [1]. In this process the focus was laid on the 3D-analysis of body measurements of women and men in different postures through the 3D-BodyScanner. The precise results of this are: 93 3D-Scans of men and women in different postures, description of bodily variance while in motion, size charts “functional measurements” for men and women, as well as recommendations for optimized allocation of individual customer measurements for standard sizes. The project results can be used for pattern development and fit optimization for clothing with a high ergonomic comfort.

Keywords: 3D body scanning, anthropometric data, functionality, body measurements, size charts, fit, ergonomic wearing comfort, Range of Motion

1. Introduction

Body measurements, which are the basis for the development of clothing, change through movement. Thus, fit and ergonomic wearing comfort of clothing is affected. But to date it was unknown to what extent fit and comfort is affected. In the project “functional measurements” the variability of body measurements was investigated to convert motion-related body measurements into a new size system. The results – based on difference measurements – were implemented into size charts which support the fit and ergonomic design of functional sports and work wear with high wearing comfort.

1.1. Starting Point

Anthropometric data is used to design clothing, PPE, workspaces and human-machine interfaces. Two different sizing systems are used for this: size charts [2,3,4,5] and ergonomic standards. [6,7,8] Size charts are the base for the clothing industry. The variance of body measurements is considered through the definition of body specific size ranges, which are the base for clothing of individual wearers. However, size charts cannot cover the functional requirements of work wear and personal protective equipment. The body measurements deviate significantly during movement (standing, sitting, kneeling, bending, etc.) compared to the measurements taken in a standard standing position.

1.2. Preliminary investigation

Preliminary investigation has shown: the movement of the body in its extremities considerably changes the length and circumference measurements. This is shown in figure 1: a male test person with the German size 50 (bust circumference 100cm). The complete length of the back shows a difference of 12.3cm between the standing and bent over position. This means an extra length of 21.5% due to changing the posture. The small measurement “hip depth” is extended by 7.1cm which even means an increase of 39.7%.

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Fig. 1. Change of body measurements in different body positions

Multiple questions have arisen from the preliminary investigation: Which measurements are needed to design optimal ergonomic comfort clothing? Are there dimensional differences between small and large sizes as well as other figure types, e.g. belly types? Do gender differences exist and what impact do they have?

To meet the complex requirements of functional work and protective wear new concepts are necessary. The intended solution of this project is based on the development of an ergonomic and motion-oriented size system for body measurements. The motion related changes of body measurements were fundamentally investigated and correlated with the traditional size charts.

2. Methods

The first step for the investigation of functional measurements was capturing men and women in different sizes with the 3D-BodyScanner. For this a concept for the investigation range and process was developed and also a scanning process to reproduce recordings of different postures. The description of these steps will be explained in the next paragraphs.

2.1. Definition of body postures in the 3D-scanner

First of all work-typical postures and movements were analyzed to establish a concept for the investigation range and process. All together 10 scans / postures (see figure 2) were defined. The derivation of the functional measurements is based on the difference that results when comparing different body postures with the standard standing position, which are measured according to the clothing standard [2] [9,10]. The standard standing position is also called “relaxed” since the implementation of the SizeGERMANY size survey. In the standard DIN EN ISO 20685 this is considered the standard body position B. [10]

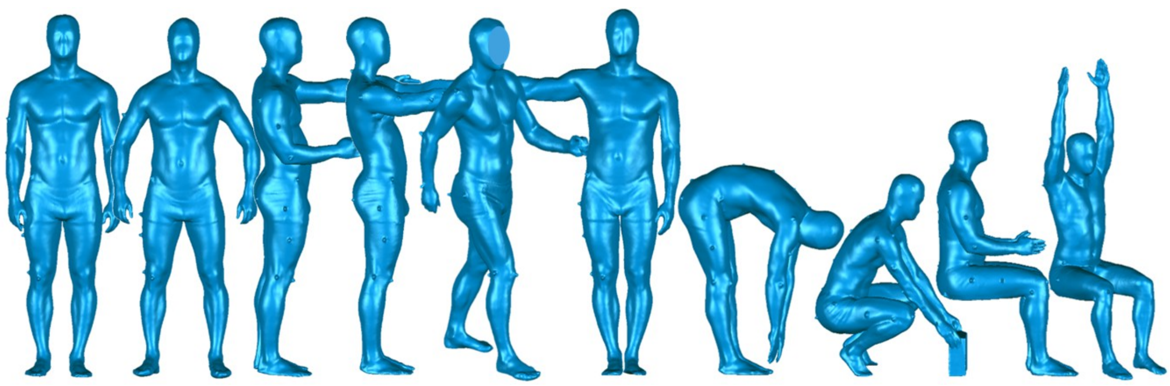


Fig. 2. Defined scan positions for the analysis of the range of movement (ROM)

Same as during the SizeGERMANY size survey the already tested postures “standard“, „reach“ und „seated 1“ were recorded. Additionally, six more postures were defined. These are “reach 2”, “right arm extended”, “lunge”, “bend”, “squat” and “seated 2”.

2.1.1. Framework for the definition of body postures

The challenge was to define body postures that were measurable in the 3D-BodyScanner "Vitus Smart XXL" [11] at Hohenstein, as well as postures the test people were able to implement in an appropriate timeframe. The limitations of the framework for the definition of scan postures are explained below.

- *Reasonability for the test people*

Due to the limitation of the research funds for this public funded study, the participating test people were not payed. Therefore, the time investment was restricted to half an hour.

- *Feasibility for the test people*

Full body scans can be taken in a few seconds. However, it is academically proven that people's posture shows a huge variety. [12] [13] [14] The posture needed for the scan process is shown by the staff, either verbally or through visual pictures. To implement this the test person must have the ability of proprioception, which is the perception of body movement and body posture in a specific area. This is not the same for every person. The replicability of body postures demonstrates a significantly big challenge. Even for the execution of simple postures flexibility and holding force are necessary (see figure 3). Therefore, simple scan postures had to be defined, to ensure that most test people could easily execute them.

- *Comparability of measurements*

Only if it is ensured that the postures of the test people are reproduced correctly, then the body measurements can safely be taken in the different postures. Therefor the postures had to be defined fairly simple. Typical execution differences that were relevant for the measurement results particularly happened in the "bend" and "squat" postures (also see figure 3).

- *Technical boundaries of the BodyScanner*

The 3D recording of the postures was carried out with the 3D-BodyScanner Vitus Smart XXL. [11] The scanner works with the measuring principle of optical triangulation. The downside is the limited scanning area of the scanner, which leads to not being able to scan all postures. For example, the standing position with arms extended upwards cannot be realized for tall people, because they exceed the scanning area while standing. For this reason, the posture with extended arms was scanned while seated. Furthermore, the rigid setting of the scanner hinders the recording of horizontal areas such as armpits and the crotch area, which is shown as shadows on the scans. With postures such as "bend" or "squat" even more parts of the body are hidden. This also results in not recorded areas and shadows on the scan. So far, there is no scanning system that can record all body parts without shadowing.
One alternative are hand-operated 3DScanners. In comparison to the 3D-BodyScanner they can also scan areas that are covered by other parts of the body. However, the test person would need to hold each posture a lot longer. Due to the bodily construction this is not possible for many test people. Based on the long recording time hand-operated scanners can only be used to complete the database. For larger test groups this is not an option.

- *Recording of measurement extrema*

The goal was to figure out the measurement extrema, so the minimum and maximum parameters of length and circumferential dimensions while in motion which a garment needs to cover and compensate for. For example, the length of the leg is shortest in the standard position, but longest while squatting. All other movements in between, for example climbing a ladder are covered by the maximal parameter from the squatting position. The largest possible coverage was achieved after testing and considering all of the above-mentioned framework of the 10 scanning postures.

2.1.2. Replicability of defined body positions

The greatest challenge scanning different body postures is the individual posture variation of each test person. The execution of each posture can still vary greatly through individual flexibility and body perception of the test person, even if the instructions were the same. This was particularly evident in the postures "bend" and "squat".

In figure 3 four different test people are shown in the "bend" posture. The back curvature and the leg extension differ significantly. Subsequently the difference between the fingertips and the floor show a big variation. The difference between the test people was up to a 50cm. This has a big influence on the body measurements that are taken in this posture. The body measurements of back length and leg length of the two test people on the left cannot be compared with the measurements of the two test people on the right. The reproducibility of measurement results is not given in this form. This is based on the different bodily conditions and the corresponding flexibility of each test person. The left two test people are very sportive and can bend over easily, whereas the right two test people are clearly not able to bend down even comparably.

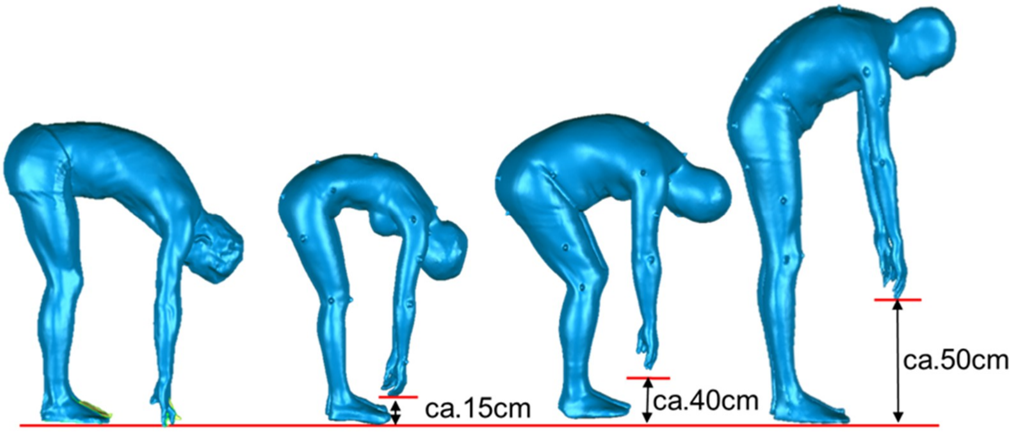


Fig. 3. The challenge of „reproducibility" using the example of the bend

The body measurements can only be taken and compared if the scan postures are similar enough. To help the complexity of this problem, a solution was found for the "bend" position. Each test person had to execute the "bend" in two different ways. Variation 1: the test person bends over as much as bodily restrictions allow. Variation 2: the test person bends over until the fingertips reach the middle knee point. Through variation 1 the maximum ROM is recorded. Variation 2 shows the measurement in regards to individual height, leg length and/or knee height and can be evaluated accordingly.

Figure 4 shows the complexity of the problem to replicate the squat posture. Here the test people also execute the posture differently, although the instructions were the same. Most test people don't put their heel on the ground. Therefor the squatting position was also defined accordingly. Still a few people kept their heel on the ground, like the test person to the left of the image. Most people can either do one or the other foot position and are not able to change this position in a relaxed way. The other aspect is the same as with the bending position, the back curvature varies from very bent to almost straight.

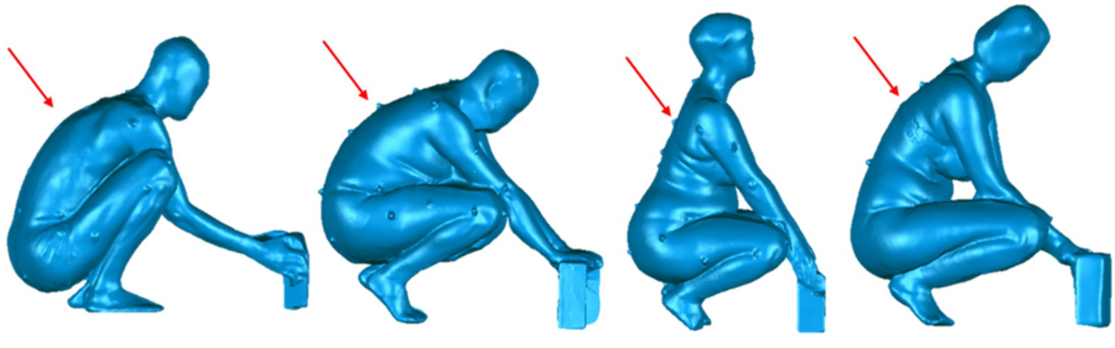


Fig. 4. Challenge „reproducibility" using the example of the squat

The different individual implementations of body postures effect the measurement results significantly. Compared to the standard standing position, the back measurement elongates while bending or squatting. This is due to the vertebra moving so the skin lengthens and the measurement is automatically longer. In figure 4 the third test person from the left kept her thoracic spine very upright, leading to a shortened measurement in the back length instead of a longer one. In this example the back measurement is 2.7cm shorter than in a standing position. This negative example was only observed with a few test people, which are considered outliers and not regarded in the end results.

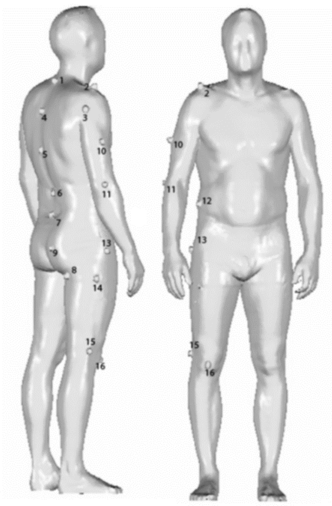
As the examples „bend" and "squat" position demonstrate, it would be wise to create specific groups for future testing. This would allow for a differentiated analysis and evaluation of the measurements. To implement this very large sample groups would be necessary.

2.2. Landmarking

Anthropometric landmarks are required for documenting replicable body measurements. Most anthropometric landmarks are identified through feeling the bone structure underneath the skin, for example the spinous process along the spinal column. 3D-Scanners only capture the surface of structures and bodies. The bone structure can only be seen on slim people with small clothing sizes if at all. To be able to take the length and the circumferential dimensions in different body postures physical markers are placed on the body before scanning. In this way changes due to movement can be traced and compared.

Reflexive markers are used for Motion-Capturing to analyze motion. These would technically also be good to use in the 3D-Scanner. However, they are very expensive due to their reflective surface. A cheaper alternative is the use of commercial styrofoam balls. For this project different sizes were tested. Two things were required: for one that the smallest ball size as possible is used so that it does not influence the measurements negatively, for the other that the scanning system can see and record the data reliably.

Styrofoam balls with a diameter of two centimeters were the optimal choice. These were attached on the skin at specific pre-defined anthropometric landmarks such as the 7th cervical vertebra with double sided tape. The markers were only used if it was necessary to determine certain measurements. In this study 16 markers were used per person and placed on the skin at specific anthropometric landmarks and other helpful points (such as the middle of arm fold at the back) while in the standard position (see figure 4).



1. 7th cervical vertebra
2. Acromion
3. Middle of arm fold (arm base to acromion)
4. Scapula (middle point)
5. 8th thoracic vertebrae
6. Waist point back
7. 4th lumbar vertebrae (4. LW)
8. Transition thigh to buttock
9. Buttock (highest point)
10. Upper arm (maximum circumference)
11. Elbow point (lateral)
12. Hip bone
13. Hip height
14. Thigh (maximum circumference)
15. Knee joint (lateral)
16. Patella (frontal)

Fig. 5. Picture display of the anthropometric landmarks

2.3. Study procedure

Goal of the study was to scan men and women with different clothing sizes, figure types and age groups in the 10 defined scanning positions to research the change of body measurements in relation to movement.

This study „functional measurements“ was done with the stationary 3D-Bodyscanner Vitus Smart XXL [11] at the research laboratories of Hohenstein in the Stuttgart area, Baden-Württemberg, Germany. The scanner is a reliable and exact system that was already tested in many previous studies.

The test people were randomly approached through many different advertising tactics in close proximity of Hohenstein. Because the project was publicly funded, test people could not be reimbursed, which resulted in only voluntary test people. The randomness of this nevertheless shows a good regional distribution over the whole of Germany. This is due to the mixture of population through changes of residence.

2.4. Gathering, analyzing and evaluating functional measurements

Based on the scanned body postures, body shape changes were analyzed and the measurement extrema identified. For this appropriate body measurements were determined which are fit relevant for product development and which influence the ergonomic wearing comfort. The basis for this is explained below.

2.4.1. Fundamentals of measurement recording

Altogether 22 body measurements were determined which are relevant for the clothing specific product development. These include, besides the primary measurements such as the breast circumference and other length, circumference and distance measurements. The common standard measurements are based on the SizeGERMANY measurements as well as the ISO 8559 [15, 16]. In addition, new measurements were investigated such as the distance between the "7th cervical vertebra and the 4th lumbar vertebra".

Taking each measurement in every single posture is not always wise or feasible, because certain shadows or overlays can occur depending on the position and body circumference. This can lead to certain measurements not being accurate. For example, the hip girth is not measurable while squatting. For this reason, each measurement had to be looked at individually to determine whether it was relevant to be taken or not for each position.

Several measurements had to be adapted to the new objective. For example, the armlength was not measured from acromion to wrist anymore, but from the middle of the back arm fold to the carpal bone wrist. This enables the determination of the maximal arm reach which directly correlates with the back width. A clothing product with high wearing comfort needs to cover this body extension.

2.4.2. Statistical evaluation of functional measurements

Extensive comparative measurements and 3D based analysis through the 3D-Software were taken for the documentation and analysis of functional measurements. The variable length and circumference measurements of the bodies and their extremities were measured and compared based on the 3D scans. The biggest possible spectrum and therefor the biggest share in the market was determined through statically analyzing the measurements from the scans and taking the average value. Additionally, the minimum and maximum value was taken into account.

The measurement difference between gender was extracted based on size to evaluate the differences between the gender groups. The statistical analysis was topped off with 3D based body shape comparisons to visualize the body's proportional changes at significant muscle groups.

The ergonomic oriented functional measurements were evaluated in relation to the traditional sizes for clothing products. A multidimensional evaluation was required according to size and figure type. For men the size ranges extra short, short, normal, long, extra long as well as the figure types extra slim, slim, normal, large, extra large in the size range 42 to 60 were evaluated. For women the size ranges were short, normal, long and the figure types slim, normal, wide hipped in the sizes 32 to 60. In the final evaluation only a difference was identified between the body height, not between to figure types.

2.4.3. Reproducibility of body measurements on different scanning postures

One important point is the comparability and reproducibility of body measurements. This is especially challenging in regards to functional measurements. The reproducibility of the measurements in different postures is only given if the measures are evaluated differentiated according to different posture characteristics of the test persons, as shown in figures 3 and 4. Furthermore measurements cannot be measured after the ISO regulation in certain postures. The circumference of bust, waist and hip are all measured horizontally along the body. This however cannot be adapted in all movement postures such as the bend. Hence, the circumference measurements were taken as vertically to the imagined body axis as possible. Different measurement methods were tested. The method of taking it vertically to the imagined body axis turned out to be the most certain, although measurement uncertainties need to be accepted.

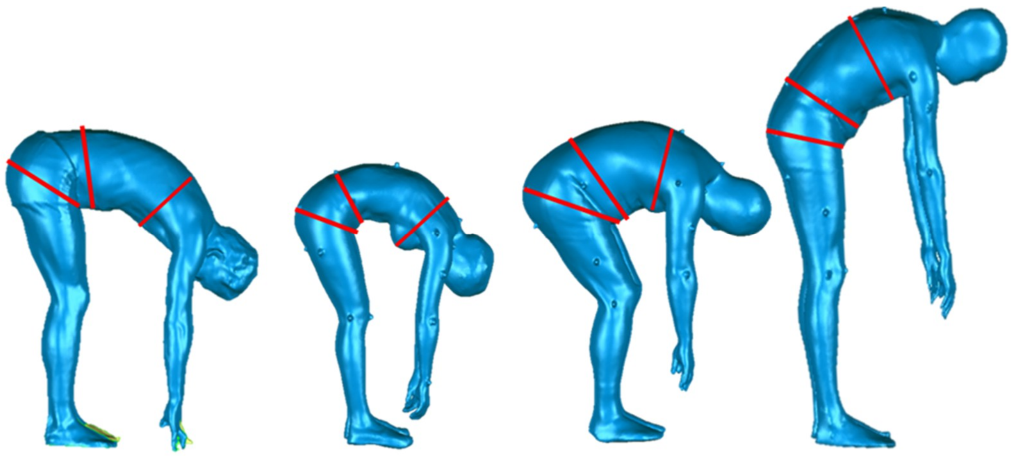


Fig. 6. Challenge „Reproducibility of circumference measurements“

3. Results

3.1. Test people structure

All together 93 test people (men and women) between the ages of 17 and 65 took part in this study. Even though the test people were picked randomly, there was a good coverage of size and age range. This random sampling covers the German men's size range 42 – 64 (chest circumference 84 – 128cm) and the German women's size range 36 – 52 (breast circumference 84 – 122cm). The standard size range of height and figure types could be covered for the most part.

3.2. Measurement results

22 body measurements were interactively measured and statistically evaluated on 93 3D-Bodyscans (men and women) in 10 different postures. All together this equals about 8000 individual measurements per person that were measured on the scans, which clearly demonstrates how high the effort is to research functional measurements. Even though 93 test people do not sound like that much compared to other size surveys, it is multiplied instantly through the different movements where more measurements need to be examined.

The body measurements that were derived from the scans were differentiated after clothing size, body height, figure type and gender for the different movements and then compared with each other. The appropriate differential measurements were calculated and statistically evaluated to then be mapped out in a new size chart "functional measurements" for men and women (see next chapter). A distinction is made between gender, size groups and height. The figure types do not show a significant difference.

The first step was to look at the complete range of each measurement for gender and posture. The clothing size stayed unconsidered for the moment. The measurement differences that are displayed are the comparison between the measurements of the standard "relaxed" position and the measurements of the other scan postures. In the diagram below (see figure 7) the maximum and minimum values, as well as the average for all postures are shown. The diagram also indicates extreme measures which are left unconsidered when creating the size charts.

Figure 7 shows the measurement results of the men's back width. The spectrum between the minimum and maximum back width in the different positions is significant. The positions "seated 2" as well as "right arm extended" show the smallest differences. Significantly big are the differences in the positions "reach 2", "bend" and "squat". Here all measurement differences are in the positive range. The maximum change is on average up to 16cm. The large bandwidth is caused by the different back postures of the test people. Those with a rounded back have a much wider back width than they have in an upright posture, whereas the difference is only small with an upright back. Gender specific differences cannot be identified reliably.

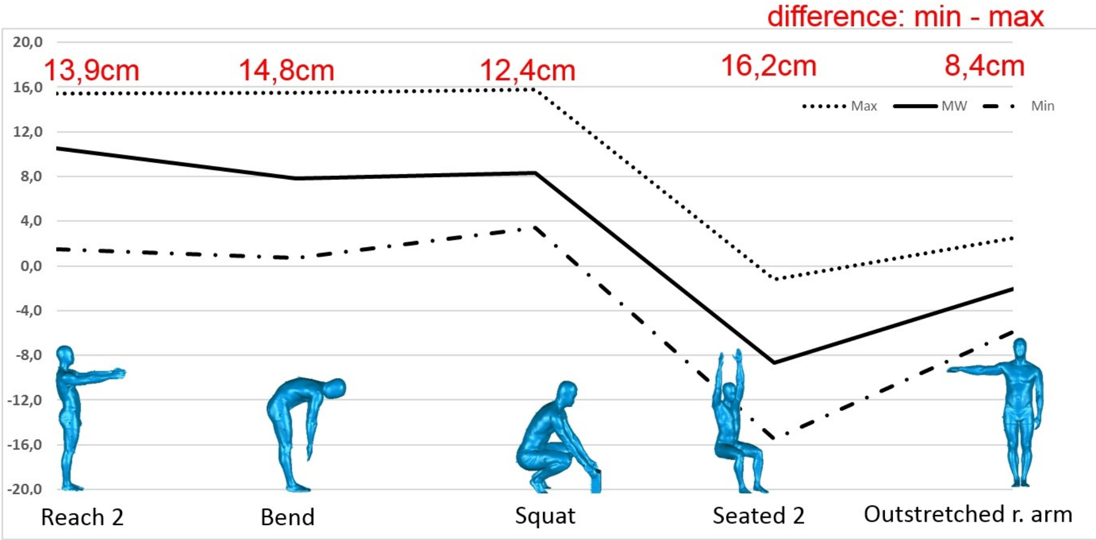


Fig. 7. Measurement difference back width - men

3.3. Size charts „functional measurements“ for men and women

The goal of this project was to research the way the body changes while in movement, to derive the functional measurements for individual postures and to allocate them to the established clothing sizes.

It became clear in the course of this project that it is not wise to indicate each separate measurement, but only the difference measurements that result compared to the standard “relaxed” posture. This approach has the benefit that for one the large spectrum of individual measurements slides into the background, if only the measurement changes are displayed. And for the other that the values can be applied easily to different size systems in different countries.

The functional measurements were analyzed differentiated according to clothing size, size range and figure type for different forms of movement for men and women. There was no significant difference between each clothing size. This may be due to there being no significant difference between the sizes, or due to the pool of 93 test people with a great dispersion of individual measurements not being enough. Therefore, the measurements for men and women were summarized into three different size groups.

Size group men	Size group women
- German sizes 44 to 48 - German sizes 50 to 54 - German sizes 56 to 58	- German sizes 36 to 40 - German sizes 42 to 46 - German sizes 48 to 52

For each of these size groups an average, a minimum and a maximum was determined. Extreme outliers were disregarded during the development of the size charts. For a simple application of the values the average was adapted, and the size groups were homogeneously increased. In addition, minimal differences were identified between the body height types short, normal and long. In regards to figure type no differences were found. This again might be due to the small random sampling data pool, but could also be due to there not being a significant effect of the figure type on the functional measurements. This needs to be verified in additional research projects with a larger pool of test people.

In the size charts (see figure 8) the average as well as maximum size is indicated for the different scan postures. The description of the scanning posture can be found in figure 9. The average demonstrates an important development parameter. Which measurement change does a clothing piece need to reproduce and compensate for? But also the maximum values are of great importance and the differences to the average values are sometimes considerable. For example, the back width of men while in the bend position has an average of about 8 cm in the middle size range, the maximum lies at about 14cm. This is a difference of 6cm that a clothing piece needs to cover in an extreme case. Therefor the maximum values are of high importance during product development.

		men sizes 44-48						men sizes 50-54						men sizes 56-60					
		scan posture						scan posture						scan posture					
		4	5	6	7	8	10	4	5	6	7	8	10	4	5	6	7	8	10
Back width	MW	10,0	-2,0		7,0	7,5	-7,0	10,5	-2,0		7,5	8,0	-8,0	11,0	-2,0		8,0	8,5	-9,0
	MAX	12,7	0,0		12,3	15,8	-3,8	14,5	-0,5		14,1	13,7	-3,5	14,5	-0,2		11,8	12,1	-1,2
Leg lenght	MW					9,0	7,0					9,0	7,0					9,0	7,0
	MAX					9,6	7,3					10,5	8,0					13,6	10,0

Fig. 8. Extract from the size chart "functional measurements for men"

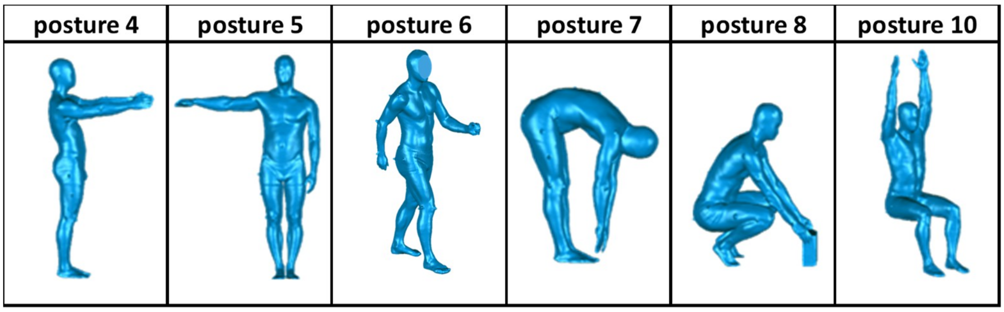


Fig. 9. Description of scanning postures

4. Conclusion

The functional measurements describe the average changes in body measurements during movement in regards to clothing size and represent a valuable addition of the standard size charts. The project research unfolded a lot more challenges though, like for example the reproducibility of the different postures, the replicability of the landmarks and measurements on the body, and the limitations of the 3D-BodyScanner as well as the clearly high processing effort in comparison to the standard size survey. These aspects should be laid out more clearly in future projects.

Recording statistic postures of the human body with 3D-BodyScanners also has its limitations. Dynamic movements can only be recreated. This means that for recreating a "dynamic" posture the test people have to use and tense some of their muscles which normally would not be needed. A requirement that only a few, if at all the test people were able to meet. In addition, it is assumed that the muscle expansion while holding the position is different to the dynamic movement. The technical development from 3D to 4D-Scanningsystems could intermediately be a solution for this problem, since realistic or close to realistic conditions exist for analyzing. Hereby completely new possibilities of research questions arise. This is a question that will be explored further in the public funded project "Restriction of Mobility" (IGF 20163 N, duration from 01.05.2018 to 31.10.2020) [17].

Another challenge arises when implementing this into optimal fit of clothing. The changes in body surface as well as the change in length in its extremities needs to be covered by the textile, for example in the buttock area. This area needs more length while in motion, so that the wearer of this product can bend, kneel or squat comfortably. All layers of the product need to be constructed flexibly enough so that movement can be balanced out through more length, a certain stretch percentage in the fabric, or special clothing elements. For this reason, material recommendations based on characteristic values are to be regarded as mandatory for the development of pattern. For this, the materials must be tested for their stretch ability and elasticity to see if they correlate with the functional measurements. The implementation of the functional measurements into optimal fit of clothing patterns and the correlation with the textile parameters will further be researched in the public funded project "Pattern Construction for Menswear" (IGF 19912 N, duration from: 01.01.2018 to 30.06.2020) [18].

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