Maja Mahnic Naglic, Slavenka Petrak
University of Zagreb, Faculty of Textile Technology, Department of Clothing Technology, Zagreb, Croatia, Prilaz baruna Filipovica 28a, +38513712500

Application of the Aramis Optical 3D Deformations Measuring System in Dynamic Anthropometry

Uporaba optičnega 3-D merilnega sistema Aramis v dinamični antropometriji

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 3–2025 • Accepted/*Sprejeto* 5–2025

Corresponding author/*Korespondenčni avtor:*
Dr. sc. Maja Mahnić Naglić
E-mail: maja.mahnic@ttf.unizg.hr
ORCID iD: 0000-0001-9216-5483

Abstract

This paper presents a study on the possible application of the Aramis optical 3D measuring system for analysing dynamic deformations of the human body in motion. A methodology for the use of Aramis in the field of dynamic anthropometry is presented for the first time in this study. Five body movements were analysed on three female test subjects. Based on the surface deformation results, a set of ten characteristic body measurements, relevant for garment design and construction, were identified, analysed and compared to reference values obtained using laser 3D body scanning technology. Changes in measurement dimensions during particular movements were determined in relation to initial measurements in a static standing position, where the greatest body measure deformation recorded was a 37% increase in back width during arm-forward movement and a 23% elongation of the posterior lower body length during forward bending. A comparative analysis of the results indicated a high level of precision of measurements obtained using the Aramis system, which achieved mean absolute errors of less than 3 mm and relative errors of less than 3%, thus emphasising the ability to monitor and analyse surface deformations of the body throughout entire movements and not just in final body positions, as is the case with the use of 3D body scanning technology. The proposed measurement methodology from this study offers valuable data for the development of garment model design, material selection and clothing pattern construction according to the requirements of dynamic anthropometry.
Keywords: dynamic deformations, Aramis optical 3D measurement system, body in motion, dynamic anthropometry, 3D body scanning

Izvleček

Članek predstavlja raziskavo o možnostih uporabe optičnega 3-D merilnega sistema Aramis za analizo dinamičnih deformacij človeškega telesa v gibanju. V tej raziskavi je prvič predstavljena metodologija za uporabo sistema Aramis na področju dinamične antropometrije. Analiziranih je bilo pet telesnih gibov pri treh preiskovankah. Na podlagi rezultatov površinskih deformacij je bil določen niz desetih značilnih telesnih mer, pomembnih za

načrtovanje in izdelavo oblačil, analiziran in primerjan z referenčnimi vrednostmi, pridobljenimi z lasersko 3-D tehnologijo skeniranja telesa. Spremembe merjenih dimenzij pri posameznem gibanju so bile določene glede na začetno meritev v statičnem vzravnanem položaju, kjer sta 37-odstotno povečanje širine hrbta med premikanjem rok naprej in 23-odstotno podaljšanje zadnje dolžine spodnjega dela telesa med upogibanjem naprej bili največji opaženi deformaciji telesne mere. Primerjalna analiza rezultatov je pokazala visoko natančnost meritev, pridobljenih z uporabo sistema Aramis, pri čemer so bile dosežene povprečne absolutne napake pod 3 mm in relativne napake pod 3 %, kar poudarja sposobnost spremljanja in analize površinskih deformacij telesa skozi celotno gibanje in ne le v končnih položajih telesa, kot je to pri uporabi tehnologije 3-D skeniranja telesa. V tej raziskavi predlagana metodologija merjenja ponuja dragocene podatke za razvoj oblikovanja modelov oblačil, izbiro materialov in konstrukcijo krojev oblačil v skladu z zahtevami dinamične antropometrije.
Ključne besede: dinamične deformacije, optični 3-D merilni sistem Aramis, telo v gibanju, dinamična antropometrija, 3-D skeniranje telesa

1 Introduction

Dynamic anthropometry research is most often applied in the development of functional garment models for special purposes, in the context of defining parameters for garment patterns adjustments in the construction process [1]. This most often involves the development of protective and sports garment models. In that regard, case studies are usually conducted on the target subject or smaller samples of specific groups, depending on the purpose of the garment, in which body movements and deformations are analysed in positions specific to performing the targeted activity. The method for determining measurements, the number of analysed positions and the characteristic measures per individual position vary in different studies [2–6]. Choi and Ashdown analysed changes in lower body circumference dimensions in three standard positions on a sample of female subjects and applied the results to the design of women's trousers [7, 8]. Xiao and Ashdown also analysed changes in the lower body, but over a larger range of motion and with a much larger set of characteristic measures to analyse changes in the surface areas of the lower extremities [9]. As part of the investigation and development of a diving suit, Petrak et al. analysed dimensional changes in the upper body, with an emphasis on the shoulder girdle and upper back in diving-specific positions, such as open-arm, over-arm and under-arm positions [10].

The methodology for determining body measurements in dynamic anthropometry is still not clearly defined, neither in terms of body positions specific to a particular activity, nor in terms of defining characteristic measures and methods of body measurement. Determining body measurements in different positions is an extremely time-consuming process, in which the results largely depend on the expertise and training of the person performing the measurement. There are also certain issues in connection with maintaining the body in the target position during the measurement process, given that measurement using the conventional method lasts a certain period of time, during which the subject must stand still and remain in the given position without additional movements and shifts, which is challenging especially with more demanding body positions. For this reason, very few studies can be found in literature that use the conventional measurement method to determine body measurements in different positions. One of the most significant and extensive studies using the conventional measurement method was conducted by Avandanei et al. The study included a sample of 400 subjects who were measured in four specific working positions for body measurement characteristics in clothing construction. Comfort values for the construction of work overalls were defined based on the results, i.e. the differences and relationships between the values of measurements in the standard standing and specific body positions, which the authors defined as a dynamic effect [11].

In the field of dynamic anthropometry, 3D body scanners are used to measure the body in various positions, specific to a particular activity, with the aim of determining the differences in body measurements between the standard upright position and various specific body positions [1]. In terms of locomotion biomechanics, body positions used for 3D body scanning in the field of dynamic anthropometry represent characteristic body positions that are part of the kinematic chain of a particular movement described by the phases of changing the position of a particular body segment. Currently, the measurement of the body in different positions is exclusively interactive, by positioning measurement points on the scanned model and measuring distances or determining the circumference obtained by cross-sectioning the body with planes through given points. Markers positioned on the test subject's body at characteristic anthropometric points are most often used in the scanning process in order to enable the precise determination of measurements [2–6]. It is evident from our literary review that differences in the approach to investigating dimensional changes of the body in various positions depend on the application of the results. Although specific body positions, such as the sitting position, are covered by the standard [12] and some are frequently repeated in different studies, such as lunges, squats and maximum upper limb reaches, the sets of characteristic measures for analysis in a particular position and the methods for determining the value of a particular measure differ primarily with regard to the targeted application.

Significant progress in the application of dynamic anthropometry study results was made by researchers from the Hochenstein Institute in Germany. As part of their research, Morlock and Klepster introduced the terminology of functional measurements, referring precisely to body measurements in specific positions identified using a 3D scanner. They conducted a fairly extensive study of changes in body measurements in different positions, specific to a particular physical activity, on a sample of 93 subjects, and analysed the results and differences in characteristic measurements from the aspect of clothing sizes and body shapes defined by the German standard SizeGERMAN. Significant changes in body dimensions were found in all analysed positions. In particular, changes in back body area dimensions, in the forward bending position can be highlighted. Considering the relatively small initial value of the hip depth in the upright position, a significant increase of up to 21.5% in the posterior back length and up to 39.7% in the hip depth was determined. By linking the dimensional changes of the body in motion with the existing standard, they developed a sizing system that also takes into account the functional measurements of the body in specific positions, thus ensuring the applicability of the research results in practice [13, 14].

3D body scanning in characteristic positions does not actually provide a fully realistic representation of the body in dynamic conditions. Since the body must remain still during the scanning process, the activity of the locomotor system is focused on maintaining the body's balance and position, rather than on performing movements, which due to different muscle activity, also leads to different body deformations [15]. In this regard, the intensive development of the field of dynamic anthropometry over the last ten years has been contributed to by the development of fast stereophotographic 3D body scanning systems that enable the recording of a series of images of a body in motion over a certain period of time, for which the term 4D scanning has been introduced in literature. 4D scanning technology enables comprehensive research in the field of dynamic anthropometry and the analysis of movement dynamics and changes of the body in full motion [15–19]. 4D scanning systems are primarily based on imaging using structured light technology and depth sensors, where upon completion of the imaging, most often using the triangulation method and/or the light cross-section technique, a continuous 3D surface mesh of the scanned body in motion is generated, on which it is possible to conduct analysis and the measurement of body dimensions in any phase of movement. Measurements determined using 4D scanning, according to Klepster et al., are called dynamic body measurements. They used photogrammetric technology and the "Little Alice" 3D scanner from 3Dcopysystems to analyse dynamic body measurements. The scanning system uses 38 cameras to capture images at a speed of three frames per second. The results showed adequate scanning accuracy for analysing changes in body measurements and the surface geometry of body parts in motion, suitable for application in clothing design and the construction process. The method showed limitations in terms of movement recording time length and the number of recorded frames, since an excessive number of recorded frames leads to an overload of the system when reconstructing the model [15].

The methodology of recording with a 4D body scanner, as well as sets of characteristic measures and methods of measurement on a scanned body model in motion, are still not clearly defined. The application of 4D scanning technology in the field of computer garment design is in the initial phase, and has been reduced to testing the possibilities and precision of individual systems and identifying different methods for monitoring changes in body dimensions during motion.

Uriel et al. conducted a study of changes in body dimensions during movement using the MOVE4D 4D scanner [19]. On a sample of 10 subjects, eight body measurements were analysed in four different movements. In order to determine body measurements during movement, a method was developed based on parametric curves, which determine the position of each measurement in the initial body position and facilitate the tracking of the dimension throughout the entire sequence of movement execution [20].

As an alternative to 4D scanning, this study proposes the use of an optical 3D measurement system for dynamic deformation analysis, which has a verified application and is widely used in the fields of mechanical engineering, construction and other manufacturing industries, but has not yet been applied or tested in the field of dynamic anthropometry.

2 Experimental

This paper presents a study on the possibilities of using the Aramis optical 3D measurement system for dynamic analysis of deformations on the human body in motion. The Aramis system, made by the German company GOM GmbH, is an optical system for 3D deformation analysis based on the stereophotogrammetry method, in which the three-dimensional deformations of the recorded object are reconstructed based on two or more images from different positions [21]. The recording and measurement methodology involves the preparation of a test object in terms of creating a contrasting stochastic dot pattern, based on which the coordinates of the surface points are determined and displacements and deformations on the recorded object surface are monitored during motion. Data processing was conducted using GOM Inspect Suite 2020 and ZEISS Inspect Correlate (v. 2023) software, which offer a wide range of tools that enable the precise determination of various parameters of linear and surface deformations, comparable to the parameters used in the development and analysis of 3D simulations and computer garment prototypes. In this regard, a methodology for recording the human body according to the requirements of the measurement system was defined. The research was conducted on five movements in which body deformations in the kinematic chain and changes in body measurements in the final position of the body, relevant for the construction and design of clothing, were analysed. For comparative analysis and verification of the results provided by the Aramis system, the results of body measurements in characteristic positions using a laser 3D body scanner were used. In order to facilitate the comparison of measurement results between the two applied measurement systems, all measurements were performed on the same day, on a sample of three female test subjects, with precisely positioned markers on the body anthropometric points that define each observed measure.

2.1 Defining body movements and positions for dynamic anthropometric analysis

Five body positions were selected for the research (Figure 1), where the movements, i.e. kinematic chains of bringing the body to a certain characteristic position, were precisely defined (Figure 2). The first kinematic chain (KL1) defined the movements of spread-arm (P1) and forward-arm (P2) for recording in the posterior plane. Initially, the subject stood in an upright standing position with a hip-width gap and arms extended alongside the body with palms facing back. With a slow movement from the shoulders and rotation in the posterior plane, the outstretched arms were brought into the spread-arm position with palms facing down (position P1). In this position, the subject paused for two seconds, after which, with a slow movement from the shoulders and rotation in the transverse plane, the outstretched arms were brought into the forward-arm position (position P2) with a two-second hold.

The second kinematic chain (KL2) defined the movements of spread-arm (P1) and arm extension (P3) for recording in the posterior plane. The subject stood in an upright standing position with a hip-width gap and arms extended alongside the body with palms facing back. With a slow movement from the shoulder and rotation in the posterior plane, the extended arms were brought into the spread-arm position with palms facing down (position P1). In this position, the subject paused for two seconds, after which the rotation in the posterior plane continued with a slow movement from the shoulder to the extension position (position P3), with a two-second hold.

The third kinematic chain (KL3) defined the arm extension (P3) movements for recording in the sagittal plane. The subject stood in the forward-arm position (P2) with the hip-width distance between the feet. With a slow movement from the shoulders and rotation in the sagittal plane, the arms were brought from the forward into the extension position (position P3), with a two-second hold.

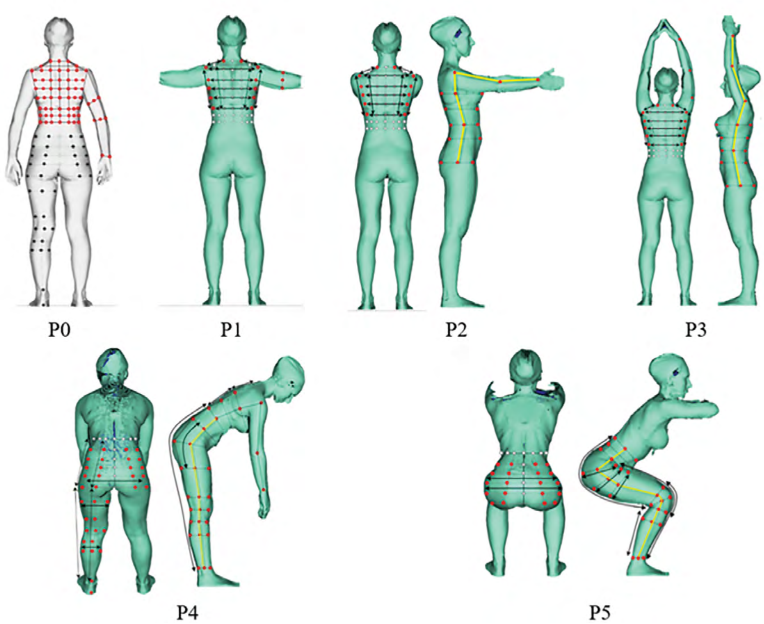


Figure 1: Characteristic positions selected for the analysis of changes in body dimensions

The fourth kinematic chain (KL4) defined the forward bending movement (P4) for recording in the posterior and sagittal planes. The subject stood in the forward-arm position (P2) with the hip-width distance between the feet. By slowly bending the spine and torso forward, the body was first brought into a forward bending position with the arms reaching the knee height, where it was held for two seconds, after which the torso was brought into maximum flexion (position P4) in which the subject was held for two seconds.

The fifth kinematic chain (KL5) defined the squatting movement (P5) for recording in the posterior and sagittal planes. The subject stood in the forward-arm position (P2) with the hip-width distance between the feet. By slowly lowering the torso and bending the knees, the body was brought into a squatting position (position P5) with a two-second hold.

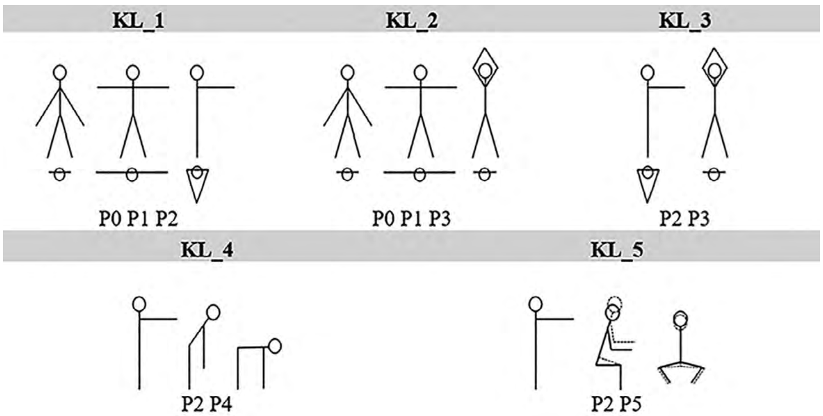


Figure 2: Schematic representations of the five defined kinematic chains

2.2. Recording of the body in motion using the Aramis 3D measurement system for dynamic deformation analysis

Using the optical 3D measurement system for dynamic deformation analysis Aramis, five predefined movements (Figure 2) were recorded on three subjects (I1, I2 and I3). The final positions of each movement correspond to the previously defined characteristic body positions P1 to P5, Figure 1.

2.2.1 Preparation of test subjects

According to the previously described methodology of the measurement system, a stochastic dot pattern was manually applied to the bodies of the test subjects wearing sports underwear using a black body paint. Black and white circular markers were placed at the positions of the anthropometric points to ensure the precise positioning and monitoring of the anthropometric points during the surface measurement and deformation analysis (Figure 3).

2.2.2 Creation of 3D surfaces and definition of surface geometry parameters for body deformation analysis

The processing of recorded results and the 3D analysis of body surface geometry deformations during motion were carried out using the GOM Inspect Suite 2020 and ZEISS Inspect Correlate (v. 2023) software. The processing of the recorded results included the creation of the body 3D surface and segmentation of the surface parts, depending on the movement and the targeted body zones for further analysis (Figure 4), and the adjustment of the coordinate system for each segment of the surface (Figures 5 and 6). Given that the continuity of the stochastic pattern was interrupted on parts where the body surface was covered with clothing, and as due to markers that differed in size from the rest of the pattern, additional facets were created in order to obtain a better quality of testing geometry (Figure 4) when creating the measuring 3D surfaces for testing.

Figure 3: Preparation of test subjects for the body motion recording using the Aramis system

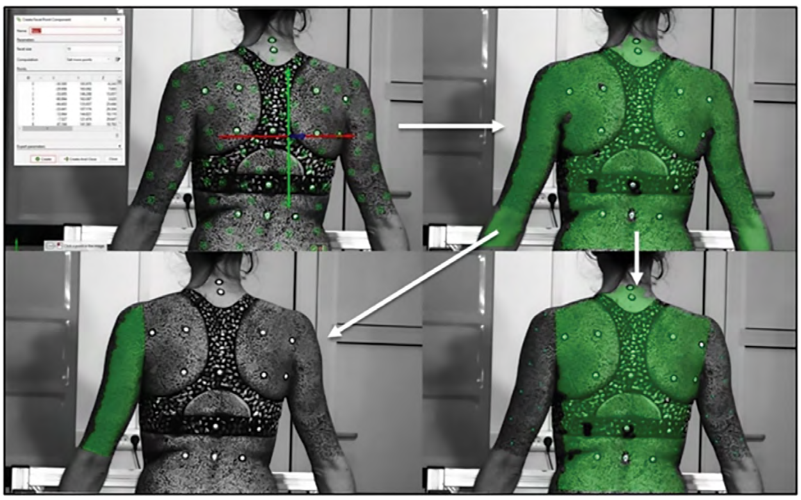


Figure 4: Recorded data processing – creating surface components for the analysis

The created surface geometries of the recorded bodies were defined by a local coordinate system at each point of the geometry. Deformations in the x direction were always calculated as local coordinates that move with the material. Therefore, the program calculated the stress in the moving coordinate system, not the global coordinate system. The z direction was used as the thickness direction. The local x direction was the result of the product of the intersection of the normal plane vector and the global y axis, while the local y direction was the result of the product of the local z and x axes (Figure 5) [21].

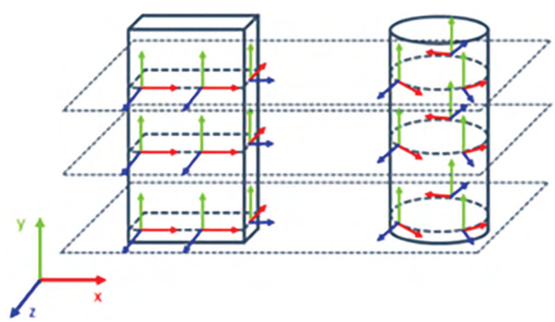


Figure 5: Positioning the local coordinate system on the surface of a recorded object in the Aramis system [21]

Due to the complexity of the human body, especially regarding the position of the upper and lower extremities, it was not possible to position the coordinate system in a way that the tensors were oriented in the desired direction across the entire single measurement geometry. Therefore, for each movement, parts of the measurement geometry were segmented depending on the initial position of the body, while the direction of the coordinate system was adjusted depending on the segment being analysed (Figure 6).

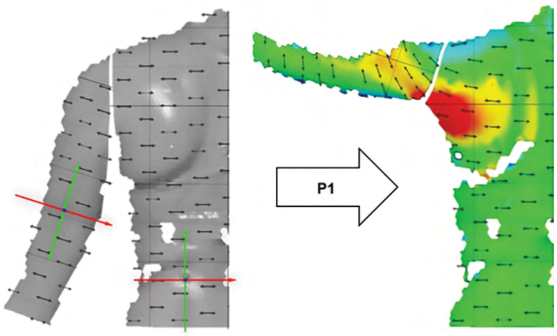


Figure 6: Adjustment of the coordinate system on segmented surface geometry in the initial position – KL1

When analysing longitudinal deformations in the arm-extension movement (KL3, P3), due to the initial arms position, the measurement surface was divided into a body and arm segment, while the coordinate system on the arm surface segment was adjusted so that the x direction still followed the transverse dimension and the y direction followed the longitudinal dimension (Figure 7).

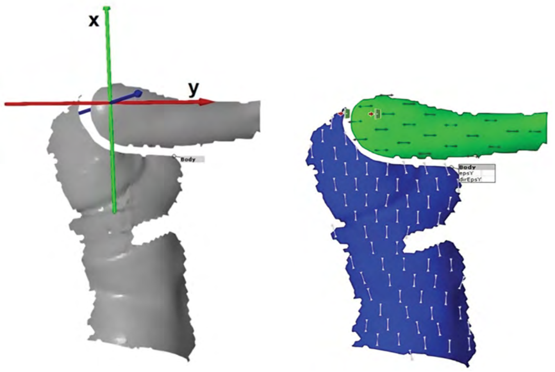


Figure 7: Adjustment of the coordinate system on segmented surface geometry in the initial position – KL3

When recording movements KL4 and KL5, greater deficiencies in the measurement surfaces were observed on the lower parts of the body due to the coverage of the hips and buttocks area by underwear (Figure 8).

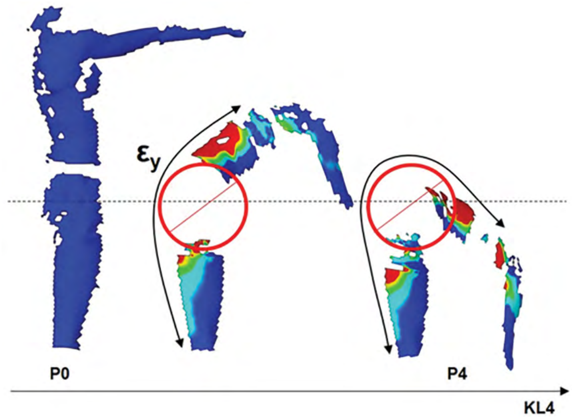


Figure 8: Longitudinal body deformation (ε_y) by phases of the kinematic chain KL4 of body moving into the forward bending position (P4) – test subject I1 in the sagittal view

Since the most significant changes were expected on the lower body area in the movements of bending the body forward (P4) and lowering into a squat (P5), the study included the recording and analysis of test subjects dressed in tight overalls, constructed according to the body measurements and characteristics of the particular test subjects (Figure 9).

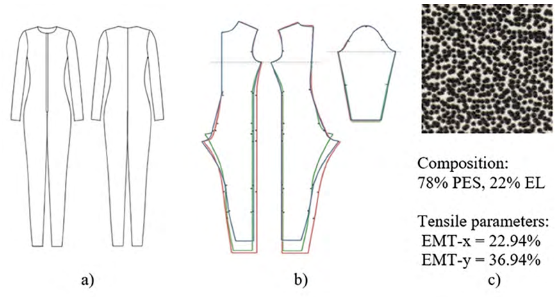


Figure 9: Model of a tight jumpsuit: a) model sketch, b) pattern adjusted to the measurements of three test subjects, c) sample of dot-printed knitted material with presented fibre composition and tensile properties parameters

The overalls were made of knitted material with a high content of elastane fibres. Since the model fit closely to the body, deformations of the body surface were reflected on the surface of the garment, which was used in this part of the research to obtain more complete and high-quality geometry surfaces for analysis. A stochastic dot pattern defined by the Aramis system methodology was applied on the knit using the digital printing technique, Figure 9c.

2.3 Analysis of deformations and changes in body measurements depending on body motion

For the analysis and more precise monitoring of the body surface geometry and segments deformations in each movement, networks of transversal and sagittal sections on the lines of characteristic body circumferences and measurements were created, enabling a link between research results and garment design and development process (Figure 10). The positions of the sections and curves on each test subject body were determined based on the measurements obtained by the 3D scan. A network of curves was defined by transverse sections at the shoulder blade height, the back width at armpit level, the chest circumference, the waist circumference and two auxiliary sections. Sections along the sagittal plane were defined at the mid-back line, the back width line at armpit level and three auxiliary sections dividing the back width into quarters (Figure 10).

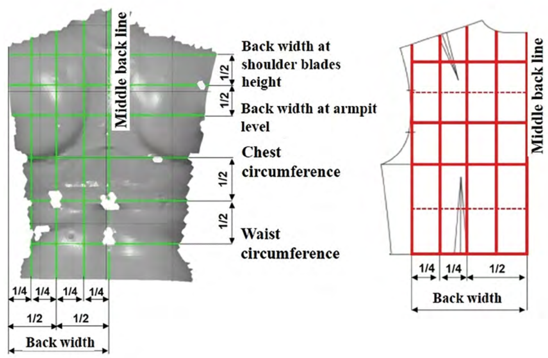


Figure 10: Characteristic cross-sections for upper body analysis in positions P1 to P3 (a) and link with garment construction measurements (b)

In each of the five defined kinematic chains, deformations in the transverse and longitudinal directions of the body surface were analysed, and the zones of the greatest deformations in each position were determined. Further analysis investigated the changes in body measurements affected by the deformation zones, and the dimensions of the targeted body curves and their segments, i.e. changes in body measurements in the defined movements (Figure 11).

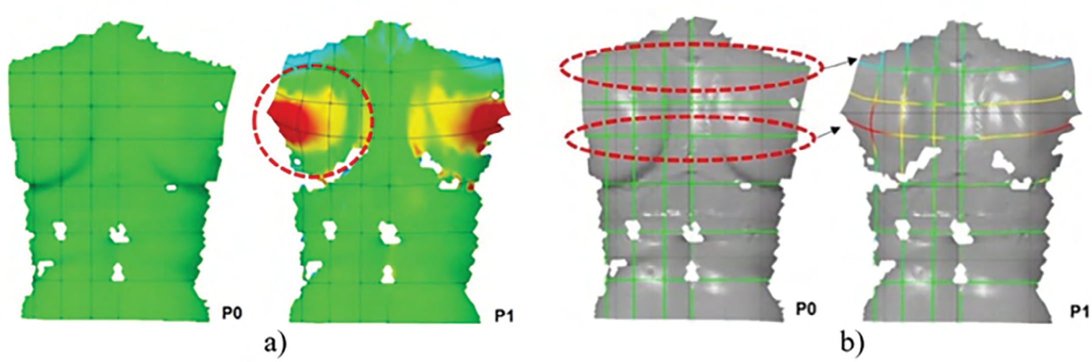


Figure 11: Analysis of body deformations in the transverse (x) direction in position P1: a) analysis of surface segments, b) analysis of curves on characteristic sections

The deformations of the lower body surface were analysed in the frontal and sagittal planes (Figure 12). A network of curves was determined by transverse sections at the lines of the chest, waist, hips, thighs, knees and lower legs circumferences, longitudinal sections at the mid-body corresponding to the lateral suture line, and sagittal sections dividing the hips width into quarters.

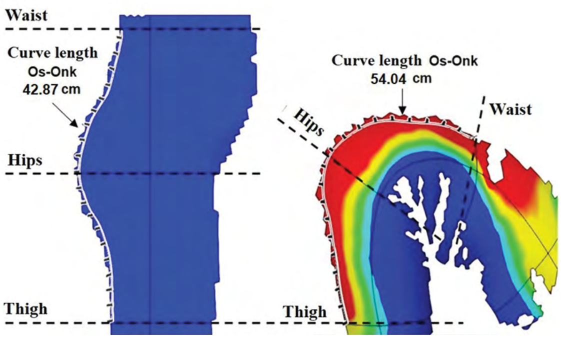


Figure 12: Analysis of the posterior body curve length in the P4 position

2.3.1 Definition of a set of body measurements for the analysis of dimensional changes depending on a characteristic position

Based on the identified zones of greatest body deformation using the Aramis system, a set of 10 body measurements relevant for the design and construction of clothing was defined, which are located in the areas covered by deformations in a particular movement (Table 1). Changes in relation to the standard upright body position were analysed on a defined set of body measurements, and a comparative analysis of the determined results was conducted with the results of measurements of the subjects on scanned 3D body models in characteristic positions, as a verification of the applicability of the optical 3D measurement system for deformation analysis.

Table 1: Set of body measurements for analysing changes in characteristic body positions

No.	Measurement	Positions
1.	Šl1 – back width measured across the shoulder blades height line	P1, P2, P3
2.	Šl2 – back width measured at armpit level	
3.	BDps – lateral length of the upper body measured between the armpit height and the waist circumference	P3
4.	SŠb – back hip width	P4, P5
5.	Šnk – thigh width	
6.	SDgk – the length of the back body curve between the chest and the knee circumferences	
7.	SDgs – the length of the back body curve between the chest and the waist circumferences	
8.	SDsb – the length of the back body curve between the waist and the hip circumferences	
9.	SDbnk – the length of the back body curve between the hips and thigh circumferences	
10.	SDnkk – the length of the back body curve between the hips and knees circumferences	

2.4 *Research and analysis of changes in body measurements in characteristic body positions using a 3D body scanner*

Using the Vitus Smart laser 3D body scanner, subjects I1, I2 and I3 were scanned in five characteristic body positions P1 to P5. Interactive measurements on scanned 3D models determined the values of 10 given body measurements, according to anthropometric points highlighted with markers positioned on test subjects' bodies. Dimensional changes were analysed in relation to the standard upright body position.

3 Results and discussion

The results show the identified zones of greatest body deformation in five defined movements and a comparative analysis of the results of the identified differences in body measurements in relation to the results of measurements on scanned 3D body models in each characteristic position.

An analysis of body surface deformations during arm movements revealed significant transverse deformations in the back area. Figures 12 to 14 show transverse (x) and longitudinal (y) deformations by phases of kinematic chains of recorded arm movements, using the example of subject I1. If we look at the sections network of characteristic body lines, the zone of maximum deformation extends around the line of the back width at the armpit level. Looking at the transverse sections, in position P1, the deformation appears and increases from the back line, where there is almost no deformation, towards the lateral lines with maximum deformation in the area of the second quarter of the back width (Figure 13).

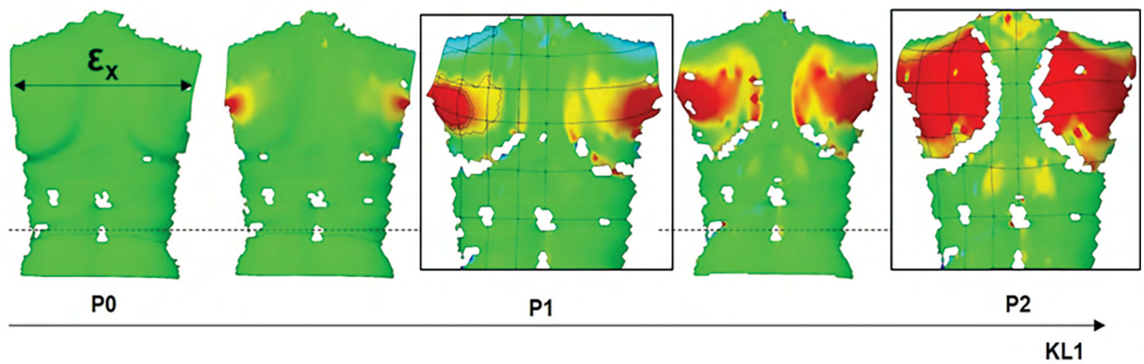


Figure 13: Transverse body deformation (ε_x) by phases of the kinematic chain KL1, which includes the spread-arm position (P1) and forward-arm position (P2) – test subject I1 in posterior view

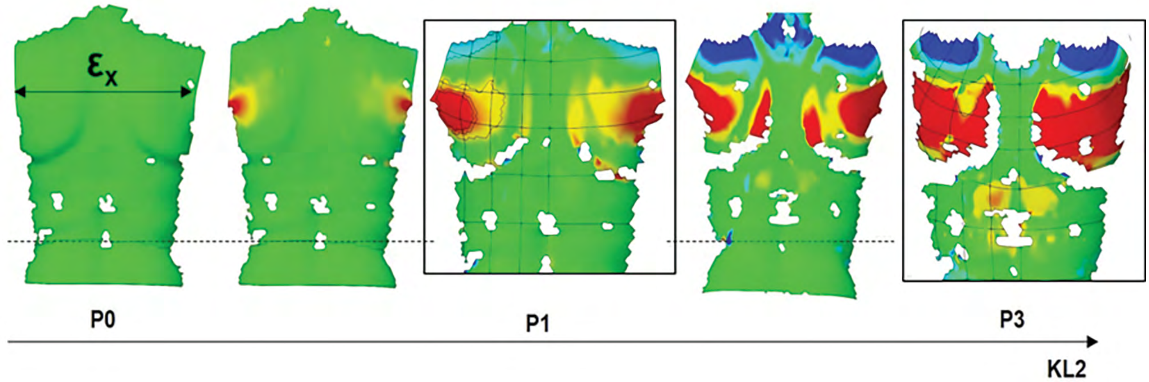


Figure 14: Transverse body deformation (εx) by phases of the kinematic chain KL2, which includes the spread-arm position (P1) and extension-arm position (P3) – test subject I1 in posterior view

In the forward-arm position (P2), transverse deformations extended across the entire surface of the back, from shoulder height to chest circumference (Figure 13). In the extension-arm position (P3), the deformation in the back area was slightly smaller compared to P2 (Figure 14). In addition to transverse deformations, in the extension-arm position P3, viewed in the sagittal plane, significant longitudinal (y) deformations of the lateral body part were observed, and were especially pronounced in the armpit area (Figure 15). In the kinematic chain KL3, surface breaks were visible on parts of the body around the chest circumference line due to the coverage of this body part by clothing. Therefore, when determining the overall dimensions of the curves on the lateral body, missing parts of the curve were measured as the distance between the edge points of the curve on the upper and lower parts of the surface.

Figure 16 shows the longitudinal (y) deformations by phases of the recorded kinematic chains KL4 and KL5, using the example of test subject I1.

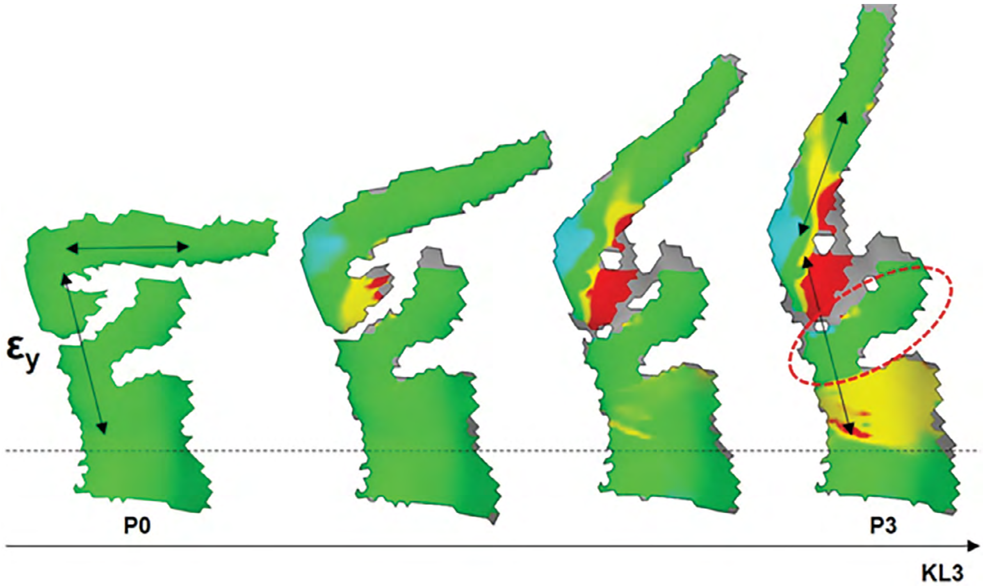


Figure 15: Longitudinal body deformation (ε_y) by phases of the kinematic chain KL3, which includes the forward-arm position (P2) and extension-arm position (P3) – test subject I1 in sagital view

An analysis of surface deformations in the movement of bending the body into the forward bending position (P4) revealed significant deformations in the longitudinal (y) direction on the back of the body, in the length from the chest to the knee circumference and in the back length of the leg from the hip to the thigh circumference. An analysis of surface deformations in the movement of lowering the body into the squat position (P5) revealed significant longitudinal deformations in the length from the waist to the upper thigh circumference and the transverse deformation zone in the hip area.

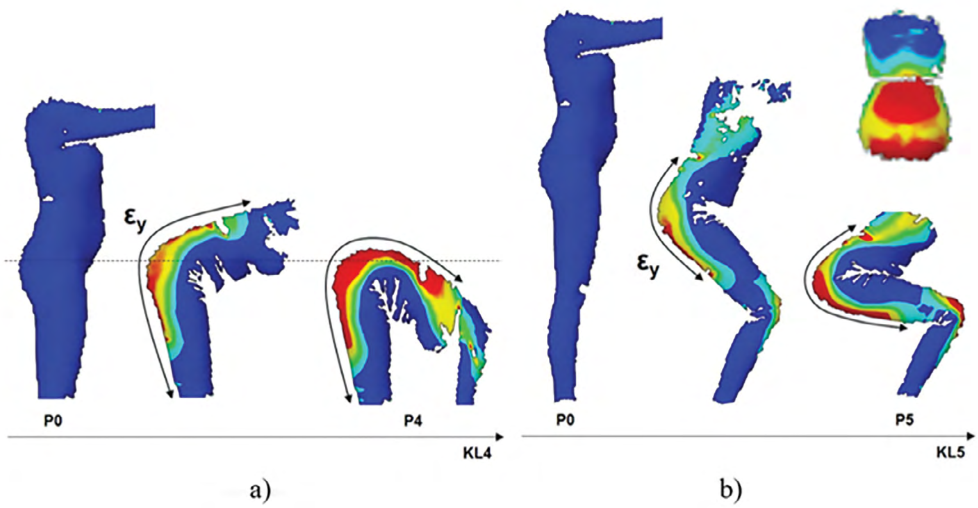


Figure 16: a) Longitudinal body deformation (εy) by phases of the kinematic chain KL4 of body bending in the forward bending position (P4), b) Longitudinal (εy) and transverse (εx) body deformation by phases of the kinematic chain KL5 of body lowering in squat position (P5) – test subject I1 in sagital view wearing tight overall

3.1 Analysis of the body measurement results and dimensional changes determined by the Aramis system in relation to the data obtained by 3D body scanning

The results of the research and analysis of dynamic body anthropometry determined using the Aramis 3D dynamic deformation analysis system and the 3D body scanner are presented below. The determined values and changes in body measurements for the three subjects in the final positions P1, P2 and P3 are shown in Table 2. For both applied measurement systems, the determined changes in dimensions are shown as differences in the length of the curve in relation to the initial position and as elongation expressed in percentages.

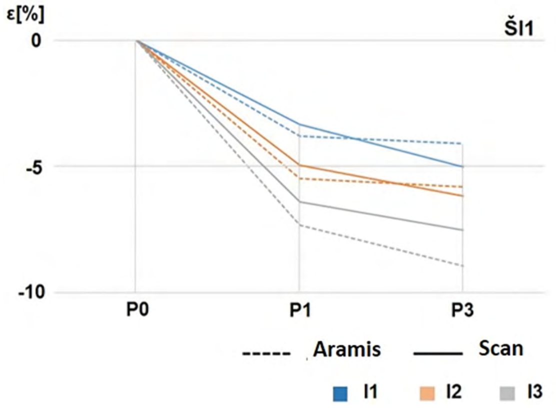
In positions P1 and P3, a negative dimensional change was observed in the body measurement of the back width at the height of the shoulder blades (Šl1), i.e. a decrease in the value of the measurement compared to the initial position. The negative changes measured in the three subjects ranged from -1.2 to -2.7 cm. The most pronounced negative changes, from -6.42% to -7.54% compared to the initial length, were identified on test subject I3. The measure of the back width at the armpits level (Šl2) increased significantly in all subjects when the arm position changed. The most significant changes in the Šl2 measurement were identified in the forward-arm position (P2), with an extension of 31.64% to 36.52% compared to the initial position (Tables 2 and 3). In position P3, a significant increase in the value of the Šl2 measurement was observed in subject I2, where an extension of 36.66% was measured compared to the measurement in the standard position. In subjects I1 and I3, the Šl2 measurement in position P3 was smaller compared to the maximum change in the forward arm position (P2), while in subject I2 the largest deformation was identified precisely in position P3.

Table 2: Body measurements of the upper body in positions P1, P2 and P3, determined on 3D body models in motion obtained by the Aramis system and by interactive measurement on scanned 3D body models

System	Position	Measurement [a]	Subject								
			I1			I2			I3		
			Measure [cm]	Δ [cm]	ε [%]	Measure [cm]	Δ [cm]	ε [%]	Measure [cm]	Δ [cm]	ε [%]
Aramis	P1	Šl1	33.98	-1.34	-3.79	29.80	-1.73	-5.49	32.58	-2.58	-7.34
		Šl2	41.07	5.83	16.54	35.43	4.51	14.59	38.22	4.31	12.71
	P2	Šl1	40.73	5.41	15.32	36.65	5.12	16.23	40.58	5.42	15.41
		Šl2	47.12	11.88	33.71	42.34	11.42	36.93	44.42	10.51	30.99
	P3	Šl1	33.88	-1.44	-4.08	29.69	-1.84	-5.83	32.01	-3.15	-8.96
		Šl2	45.30	10.06	28.55	43.21	12.29	39.75	43.47	9.56	28.19
		BDps	21.80	2.82	14.86	22.35	2.77	14.15	22.87	1.74	8.23
3D body scanning	P1	Šl1	34.6	-1.2	-3.35	30.8	-1.6	-4.94	33.5	-2.3	-6.42
		Šl2	40.3	4.9	13.84	34.8	3.7	11.90	38.4	3.9	11.30
	P2	Šl1	41.6	5.8	16.20	37.3	4.9	15.12	41.9	6.1	17.04
		Šl2	46.6	11.2	31.64	42.1	11.0	35.37	47.1	12.6	36.52
	P3	Šl1	34.0	-1.8	-5.03	30.4	-2.0	-6.17	33.1	-2.7	-7.54
		Šl2	44.3	8.9	25.14	42.5	11.4	36.66	43.6	9.1	26.38
		BDps	20.6	1.1	5.64	22.8	2.7	13.43	23.0	1.6	7.48

[a] See legend in Table 1.

Figures 17 and 18 show a comparison of the identified changes in body measurements in characteristic positions P1, P2 and P3, determined on 3D models of bodies in motion using the Aramis system and scanned 3D body models.



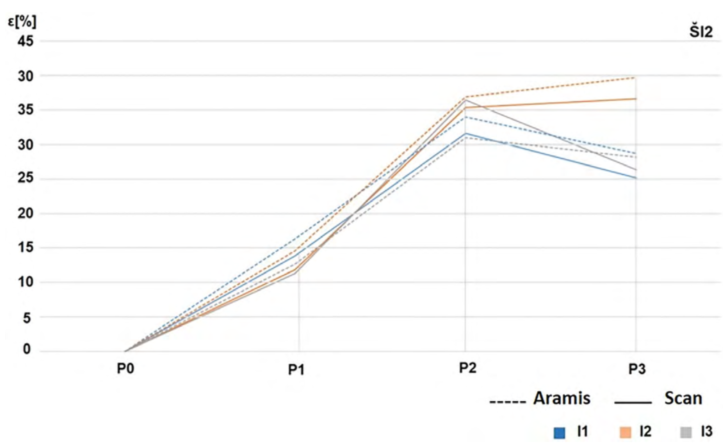
Legend: I1 – first test subject, I2 – second test subject, I3 – third test subject

Figure 17: Analysis of dimensional changes in the body measurement of back width at the height of the shoulder blades (Šl1), in positions P1 and P3, determined using the Aramis system and 3D body scanning

In the forward bending position (P4), all three subjects had a similar value of the back body line extension, measured along the vertical curve at a quarter of the back width, from the height of the chest circumference to the upper thigh circumference (Table 3). Differences of 12.9 to 13.5 cm were identified compared to the measurement in the standard upright position, i.e. an elongation of the measurement of 22.84% to 23.60%.

The results of the curve segments dimensional analysis in P5 position were divided into the upper part from the chest to the waist circumference, the lower part from the waist to the hips circumference and the upper leg part from the hips circumference to the middle of the thighs. In the squatting position (P5), an increase from 13.86% to 15.91%, compared to the initial value, was determined on the measurement of the hips width in the posterior plane. In the measurement of the posterior body line, measured from the waist circumference to the upper thigh circumference, an elongation of 20.91% to 22.16% was determined, which is a slightly lower value compared to the elongation in the P4 position.

Figure 19 shows a comparison of the dimensional changes in body measurements in the characteristic position P4, determined on 3D body models in motion analysed using the Aramis system and scanned 3D body models. For all analysed measurements, minor deviations were identified between the results of the measurements on 3D models using two different systems. Although the measurements of scanned 3D models were performed interactively, where the precision of the person performing the measurement had a major impact on the accuracy of the results, markers positioned at characteristic anthropometric points on the subjects' bodies during the scanning ensured a high level of measurement precision, as is evident from the comparison of the results.



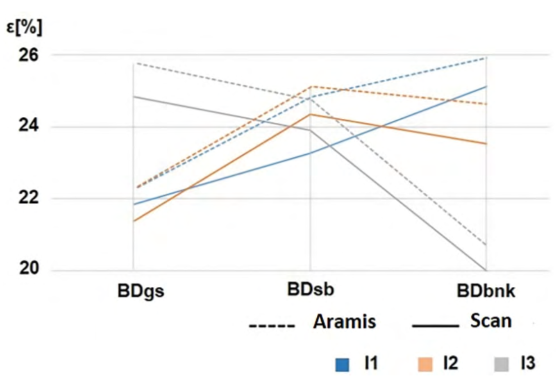
Legend: I1 – first test subject, I2 – second test subject, I3 – third test subject

Figure 18: Analysis of the dimensional changes in the body measurement of back width at the armpit level (Šl2), in positions P1, P2 and P3, determined using the Aramis system and 3D body scanning

Table 3: Body measurements in positions P4 and P5, determined on 3D body models in motion obtained by the Aramis system and by interactive measurement on scanned 3D body models

System	Position	Measu-rement [a]	Subject								
			I1			I2			I3		
			Measure [cm]	Δ [cm]	ε [%]	Measure [cm]	Δ [cm]	ε [%]	Measure [cm]	Δ [cm]	ε [%]
Aramis	P4	SŠb	37.06	3.37	9.91	38.49	4.52	13.31	40.36	4.56	12.74
		SDgnk	72.47	14.29	24.56	70.45	13.70	24.14	69.76	13.38	23.73
		SDgs	18.73	3.42	22.34	19.86	3.63	22.37	19.64	4.02	25.73
		SDsb	26.15	5.20	24.82	24.62	4.94	25.10	28.09	5.57	24.73
		SDbnk	27.59	5.67	25.87	25.97	5.13	24.61	22.03	3.79	20.78
	P5	SŠb	38.13	4.72	14.13	39.48	5.45	16.02	40.81	5.01	13.99
		Šnk	19.09	2.26	13.43	18.60	1.39	8.08	20.17	2.45	13.83
		SDgnk	52.07	9.09	21.15	48.95	8.02	19.59	49.24	8.67	21.37
		SDsb	25.37	4.36	20.75	24.21	4.03	19.97	26.75	4.84	22.09
		SDbnk	26.70	4.73	21.53	24.74	3.99	19.23	22.49	3.83	20.53
3D body scanning	P4	SŠb	37.4	3.5	10.32	39.2	4.7	13.62	40.6	4.5	12.47
		SDgnk	70.7	13.5	23.60	68.5	12.9	23.20	65.4	12.2	22.93
		SDgs	18.4	3.3	21.85	19.3	3.4	21.38	19.1	3.8	24.84
		SDsb	24.9	4.7	23.27	24.0	4.7	24.35	22.8	4.4	23.91
		SDbnk	27.4	5.5	25.11	25.2	4.8	23.53	23.4	3.9	20.00
	P5	SŠb	38.6	4.7	13.86	40.0	5.5	15.91	41.3	5.2	14.40
		Šnk	19.5	2.4	14.04	19.4	1.5	8.38	20.5	2.3	12.64
		SDsnk	51.4	9.3	22.09	48.0	8.3	20.91	46.3	8.4	22.16
		SDsb	24.5	4.3	21.29	23.5	4.2	21.76	22.7	4.3	23.36
		SDbnk	26.9	5.0	22.83	24.5	4.1	20.10	23.6	4.1	21.03

[a] See legend in Table 1.



Legend: I1 – first test subject, I2 – second test subject, I3 – third test subject

Figure 19: Analysis of dimensional changes by segments in the measurement of posterior body length, from chest to thigh circumference, in the P4 position, determined using the Aramis system and 3D body scanning

Although the study involved subjects with comparable anthropometric characteristics, the results revealed notable differences in body surface deformations, particularly in the scapular, waist and knee areas. These variations suggest that body shape characteristics, such as shoulder width, spinal curvature or fat distribution, directly influence the value and distribution of dynamic strain. The results revealed that the test subject with a more pronounced lumbar curve showed a 26% elongation in posterior lower body length during forward bending, compared to 22% and 21% of elongation on the other two test subjects. Similarly, the test subject with narrower shoulders exhibited reduced back width expansion in the arm-forward position (31% vs. 37%), indicating implications for additional garment pattern modelling. These findings support the use of the Aramis system for anthropometric analysis in the process of developing garment designs that accommodate body measurement changes in motion, thus achieving high functionality and fit. Future work should incorporate a wider range of body types to formalize the link between static morphology and dynamic deformation, enabling more precise fit customization.

4 Conclusion

The results demonstrate that the Aramis system ensures the reliable and detailed measurement of body deformation during movement, offering multiple avenues for practical application. Monitoring deformation throughout the entire movement performance and the possibility of visualizing and analysing segments of the body surface affected by deformation, as a measurement method, represent a great advantage potential compared to 3D scanning of the body in characteristic positions and determining linear changes in body measurements. By analysing the deformations of the body in motion, where the deformations of the surface geometry are analysed in a specific direction (x/y), depending on the body segment being observed, the obtained data are applicable in the process of garment design and construction, given the possibility of linking the direction of deformation with the structure and direction of the thread system on the textile material. This is particularly important when designing functional garments, particularly sportswear, protective and workwear clothing, where the Aramis data support the development of patterns that reflect actual body deformation under motion. Data regarding deformations and dimensional changes of the body surface by zones can be used to adjust the garment construction pattern with the aim of achieving greater functionality of the model in dynamic conditions of movement, and can also be used for the selection of materials in production process, considering the parameters of material tensile properties. For example, based on the established high-stress zones identified in the armpit, lower back and knee areas, garment construction can be further modified to incorporate textile material of targeted stretch on strategic garment zones. Moreover, the method facilitates virtual fit assessments within CAD systems for garment 3D simulations, thereby reducing the need for physical prototypes and shortening development cycles. Looking forward, this approach holds promise for mass-customization workflows, where user-specific motion data can enhance garment personalization. In the fashion and e-commerce sectors, improved fit prediction based on dynamic morphology may reduce return rates and enhance customer satisfaction. Future work will aim to validate the method on a broader range of body types and incorporate more complex motion sequences, such as jumping and running, and to integrate deformation data into methods and algorithms for garment pattern modifications and digital human modelling systems.

Data availability statement*: All research results related to the measurements of the subjects are listed in the Manuscript. Other data, namely scanned models on which measurements were performed, cannot be provided in the repository due to the protection of personal data and the consent given by each individual subject to the use of measurement data, but not the distribution of complete 3D models, which is in accordance with the code of ethics and Personal Data Protection.*

References

1. CHI, L., KENNON, W.R. Body scanning of dynamic posture. *International Journal of Clothing Science and Technology*, 2006, **18**(3), 166–178, doi: 10.1108/09556220610657934.
2. PETRAK, S., RASTOVAC, I., MAHNIĆ NAGLIĆ, M. Dynamic anthropometry – research on body dimensional changes. *Tekstilec*, 2023, **66**(3), 240–248, doi: 10.14502/tekstilec.66.2023031**.**
3. MORLOCK, S., LOERCHER, C., SCHENK, A., KLEPSER, A. Functional body measurements – motion-oriented 3D analysis of body

measurements. In *Proceedings of 3DBODY. TECH 2019. 10th International Conference and Exibition on 3D Body Scanning and Processing Technologies*, *Lugano, Switzerland, 22-23 Oct. 2019*, pp. 244‑253, doi: 10.15221/19.244.

4. TAMA, D., ONDOGAN, Z. Calculating the percentage of body measurement changes in dynamic postures in order to provide fit in skiwear. *Journal of Textiles and Engineer/ Tekstil ve Muhendis*, 2020, **27**(120), 271‑282, doi: 10.7216/1300759920202712007.
5. DABOLINA, I., LAPKOVSKA, E., VILUMSONE, A. Dynamic anthropometry for investigation of body movement comfort in protective jacket. In *Functional Textiles and Clothing*. Edited by Majumdar, A., Gupta, D., Gupta, S. Singapore : Springer, 2019, pp. 241‑259, doi: 10.1007/978-981-13-7721-1_20.
6. DABOLINA, I., LAPOVSKA, E. Sizing and fit for protective clothing. In *Anthropometry, Apparel Sizing and Design*. Edited by Norsaadah Zakaria and Deepti Gupta. Cambridge : Woodhead Publishing, 2020, pp. 289‑316, doi: 10.1016/B978-0-08-102604-5.00011-1.
7. CHOI, S., ASHDOWN, S.P. 3D body scan analysis of dimensional change in lower body measurements for active body positions. *Textile Research Journal*, 2011, **81**(1), 81‑93, doi: 10.1177/0040517510377822.
8. CHOI, S.Y., ASHDOWN, S.P. Application of lower body girth change analysis using 3D body scanning to pants patterns. *Journal of the Korean Society of Clothing and Textiles*, 2010, **34**(6), 955‑968.
9. XIAO, P., ASHDOWN, S.P. Analysis of lower body change in active body positions of varying degrees. In *Proceedings of the 4th International Conference on 3D Body Scanning Technologies*, *Long Beach CA, USA, 19-20 November 2013*, pp. 19‑20, doi: 10.15221/13.301.
10. NAGLIĆ, M.M., PETRAK, S., GERŠAK, J., ROLICH, T. Analysis of dynamics and fit of diving suits. *IOP Conference Series: Materials Science and Engineering*, 2017, **254**(15), 1‑7, doi: 10.1088/1757-899X/254/15/152007.
11. AVADANEI, M. Dynamic anthropometry – a solution for improving the shape of individual protective garments. *International Journal of Engineering Research & Technology,* 2020, **9**(7), 162‑165, doi: 10.17577/IJERTV9IS070131.
12. ISO 20685:2010. 3D scanning methodologies for internationally compatible anthropometric databases. Geneva : International Organization for Standardization, 2010, 1–20.
13. KLEPSER, A., MORLOCK, S., LOERCHER, C., SCHENK, A. Functional measurements and mobility restriction (from 3D to 4D scanning). In *Anthropometry, Apparel Sizing and Design*. Edited by Norsaadah Zakaria and Deepti Gupta. Elsevier, 2020, pp. 169‑199, doi: 10.1016/B978-0-08-102604-5.00007-X.
14. LOERCHER, C., MORLOCK, S., SCHENK, A. Design of a motion-oriented size system for optimizing professional clothing and personal protective equipment. *Journal of Fashion Technology & Textile Engineering,* 2018, S4, 1‑4, doi: 10.4172/2329-9568.S4-014.
15. KLEPSTER, A., MORLOCK, S. 4D scanning – dynamic view on body measurements. *Communications in Development and Assembling of Textile Products*, 2020, **1**(1), 30‑38, doi: 10.25367/cdatp.2020.1.p30-38.
16. Products [online]. 3dMD [accessed 28 February 2024]. Available on World Wide Web: <https://3dmd.com/products/#https://3dmd.com/products/#!/body>.
17. PARRILLA, E., BALLESTER, A., PARRA, F., RUESCAS, A., URIEL, J., GARRIDO, D., ALEMANY, S. MOVE 4D: accurate high-speed 3D body models in motion. In *Proceedings of 3DBODY. TECH 2019. 10th International Conference and Exhibition on 3D Body Scanning and Processing Technologies, Lugano, Switzerland, 22-23 Oct. 2019*, pp. 30‑32, doi: 10.15221/19.030.

18. BALLESTER, A., PARRILLA, E., RUESCAS, A.V., URIEL, J., ALEMANY. S. To MOVE4D, or not to move, that is the question. In *Proceedings of 3DBODY.TECH 2021. 12th International Conference and Exhibition on 3D Body Scanning and Processing Technologies*, *19-20 October 2021, Lugano, Switzerland*, p. 48.
19. Move4D [online]. Instituto de Biomechanica de Valencia (IBV) [accessed 28 February 2024]. Available on World Wide Web: <https://www.ibv.org/tecnologias/analisis-de-movimientos-4d/move-4d-3>.
20. URIEL, J., RUESCAS, A., IRANZO, S., BALLESTER, A., PARRILLA, E., REMÓN, A., ALEMANY, S. A methodology to obtain anthropometric measurements from 4D scans. In *Proceedings of the 7th International Digital Human Modeling Symposium, 2022,* 7(1), 1-13, doi: 10.17077/dhm.31758.
21. 3D measurement system. ARAMIS 3D Camera. 3D sensor for industrial research [online]. ZEISS [accessed 3 March 2024]. Available on World Wide Web: <www.gom.com/en/products/3d-testing/aramis-3d-camera>.