Analysis of Geometry Changes of the Body Wearing Compression Products Using 4D Scanning

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Abstract

Compression products are specially engineered textiles applied for different diseases and situations. Compression therapy is an important stage of rehabilitation after limb amputation for subsequent prosthetics. Analysis and the prediction of the realized compression level at different areas are important for the health process. The main feature of compression cover for amputee is to create gradient pressure with a decrease to the top of the limb to prevent swelling and to form a stump for prosthetics. The required pressure level is set for ankle level with a recommended decrease to 80-50 % at the calf and to 50-20% at the thigh. The wide range of acceptable pressure values and its changes along the limb is a huge problem both for achieving a therapeutic effect and for creating appropriate high-quality compression products. The existing standard establishes 5 basic measurement levels that determine the size of the product. However, the features and diversity of limb shapes, as well as their changes throughout the day or during movement, are not taken into account. The high speed (4D) body scanning is an excellent tool for limb shape assessment and the developed software for measurement provides additional effects, for instance during motion. This work discusses preliminary results from experiments with compression materials.

Keywords: 4D-Body Scanning, Compression Products, Geometry Change Analysis, Point Cloud Processing

1. Introduction

The basic design principle for compression stockings is to provide a certain pressure with its gradual distribution from the bottom to the top of the body (Fig.1). The complex interaction of the garment and the body [1] determines the degree of pressure. From a body perspective, the main factors are: the size and shape of the body part, and the nature of the performed activity. Garment-related factors include the structure and the physical properties of the used materials, as well as the fit and conformity to the body part. These questions remain important for both conventional compression stockings and amputee covers.

The task of creating a functional compression product with a given pressure level and a precise distribution of the applied pressure has remained relevant over the past decade. The existing development of compression clothes focuses on two aspects: the correct prediction of the delivered pressure [2] and the virtual compression product design [3].

This work aims to evaluate the leg changes occurring over time and during different activities, as well as the effect of compression stockings on such changes. The obtained results will be used for an advanced compression product development.

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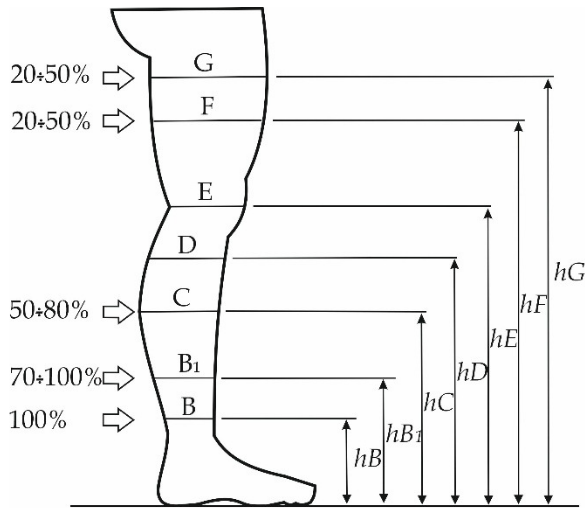


Fig. 1. The standard measured levels and pressure distribution for leg.

2. State of Art

2.1. Compression product development

Compression stockings differ from ordinary socks due to their features that create pressure. Despite years of clinical experience with compression therapy, choosing the optimal grade and pressure distribution remains a challenge [4]. The pressure is produced by the differences in stocking and leg sizes, as well as the elasticity of the textile due to the incorporated elastomer. Therefore, it is of great importance that not only the size but also the shape of the stocking matches the real leg of a particular person [5].

There are generally two types of pressure created by compression stockings: static and dynamic (working) [6]. Static pressure is the constant pressure that the compression material exerts on the tissues and vessels while the muscles are relaxed. Dynamic pressure refers to the pressure exerted by a compression garment during deformation in multiple directions. Working pressure occurs when the muscle resists the compression effect when its volume increases, for example, during movement, and is temporary [7]. Despite the large number of studies in the field of compression clothing, this area remains important in terms of predicting the level of pressure exerted and the effective therapeutic effect. It should be noted that the majority of studies are focused on static pressure [8] at standard points (ankle, ankle, thigh) [9]. It is well known that the human body is a constantly changing object. The body changes over time and during various movements, which affects the pressure exerted by clothing [10] and a particular person`s susceptibility to it. Thus, the dynamic pressure becomes more relevant for the advanced development of compression stockings.

Circular knitting technology is used for the production of most compression stockings. As a knitting cylinder has a constant number of needles, the stocking can be conformed to the leg shape by altering the loop size and the elastomer tension. In this case, it is crucial to define the levels where knitting parameters must be changed. Studying the real geometry of the leg is a step forward in the development of customized compression products.

2.2. Pressure value and its changes

The pressure applied by compression garments varies depending on the area of the body, the treatment, and the individual patient. To manage this, there are currently four levels of compression [11], the first of which is used for disease prevention and does not require a doctor's prescription. Applied pressure should be graduated, being highest at the ankle and decreasing gradually up the extremity. Today, a few classification systems are used, in which the pressure value at the ankle for different compression classes has been fixed. They differ by country and related standards [12]. It should be noted that the limits of possible pressure for a particular compression class are quite wide (Table 1), which does not provide clear recommendations for both medical professionals and manufacturers.

Table 1. Pressure limits for II compression class.

Standard	Pressure [kPa]			Difference [%]
	min	max	Δ	
RAL-GS 387/1: 2008, Germany	3.1	4.3	1.2	38.7
BS 6612: 1985, UK	2.4	3.2	0.8	33.3
ASQUAL: 1999, France	2.0	2.7	0.7	35.0
ENV 12718:2001, Europe	3.1	4.3	1.2	38.7

Laplace's law is the most used equation to predict the static contact pressure created by a compression product. This equation is the subject of continuous revision and improvement [13], but the tension of the material and the radius of curvature remain the most influential factors. The mechanic can be described by the following [14]:

$$P = \frac{T}{R \times w} \quad (1)$$

where P – pressure, Pa;
T – tension of material, N;
R – radius of surface, m;
w – width of applied bandage, m.

It is clear, that an increase in the body`s girth (circumference) leads to an increase in equivalent radius and results in a decrease in the applied pressure. Simultaneously, the compression product is stretched more, resulting in an increase in material tension and, consequently, exerted pressure. The investigation of such interaction is crucial in the design of any compression product.

2.3. Challenges with standard size

The standard [11] specifies recommendations for measurement levels (Fig.1) and leg circumferences for different sizes (Table 2). It should be noted that the recommended range of values is almost constant: 2 cm in the lower part of the leg and 3 cm in the upper part. However, this leads to a difference of 6-9% and 5-6% respectively. As described before, this leads to an increase in the equivalent radius and also requires more stretching of the stocking.

Table 2. Leg circumference [cm].

Site	Size III			Size IV			Size V		
	min	max	%	min	max	%	min	max	%
G	57	60	5.3	60	63	5.0	63	66	4.8
F	49	52	6.1	52	55	5.8	55	58	5.5
E	39	41	5.1	41	43	4.9	43	45	4.7
D	34	36	5.9	36	38	5.6	38	40	5.3
C	35	37	5.7	37	39	5.4	39	41	5.1
B1	28	30	7.1	30	32	6.7	32	34	6.3
B	22	24	9.1	24	26	8.3	26	28	7.7

On the other hand, a compression stocking from a particular manufacturer has clearly defined dimensions. Naturally, the pressure exerted on the legs of two different patients or even on the left and right legs of the same person will be different [15]. In some cases, the exerted pressure can overcome the threshold of painful perception and even the recommended value [16].
Another challenge with standard size is the positioning of measuring sites (Fig.2) and their correlation to the real legs. The compression stocking is typically a circular knit structure that is able to conform to the body contours and volume. An increase in the product`s width is due to the density changes, and it should be done at the correct level [17].
Thus, studying the actual dimensions of the limbs is an important theoretical and practical task for designing a compression product that has a therapeutic effect and is comfortable for a particular patient. This paper evaluates the possibility of using 4D scanning to assess changes in leg sizes without and while wearing compression stockings.

3 Methods

3.1. Scanning protocol

The fit of the compression product [18] is crucial, and anthropometric data [19] is of great importance for delivering accurate pressure and therefore a high therapeutic effect. 3D/4D body-scanning technology [20] provides highly accurate measurement methods and is now widely used not only in medicine [21] but also in clothes manufacturing [22]. 3D scanning enhances product personalization and development according to the needs of a particular person.

The MOVE 4D scanning system [23] from IBV UPV at ITM TUD was used to perform a scan. Figure 2 provides a schematic overview over the scanning system. A total of 12 camera modules is positioned around a scanning area. The scanning area is quadratic and has a side length of approx. 1.5 meters. During scanning, the cameras take synchronized captures using a common trigger signal. From these 12 different captures, a single point cloud is generated in a first step of post processing. In a second step, a mesh is computed from an A-Pose capture and fit to every point cloud captured during the scanning process. This high-speed body scanning instrument can capture the whole body in movement at a frequency of up to 178 frames per second [24]]. Spatial precision of less than 1 mm yields high-quality scan data.

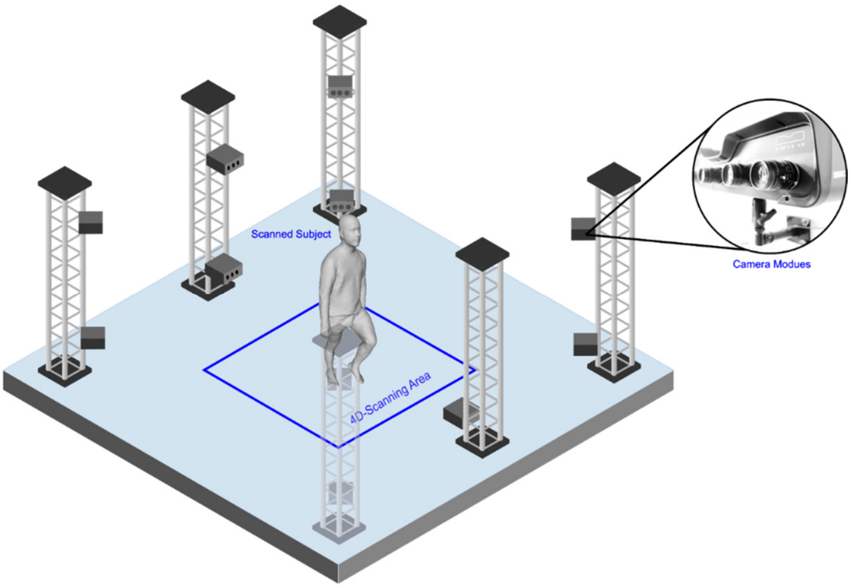


Fig. 2. The MOVE 4D scanning system in ITM TUD

For our research the scanning setup was 60 frames per second with 3 seconds for movement. The scanning was done before (Leg) and just after putting on stockings (+2CCl), in the morning (Leg) and after 4 hours (Leg4). The persons were scanned at static positions (A and T poses) and during four movements (tiptoe, bending over, sitting down, and stepping). Within 4 hours between scans, the person did his usual activity without any restriction.

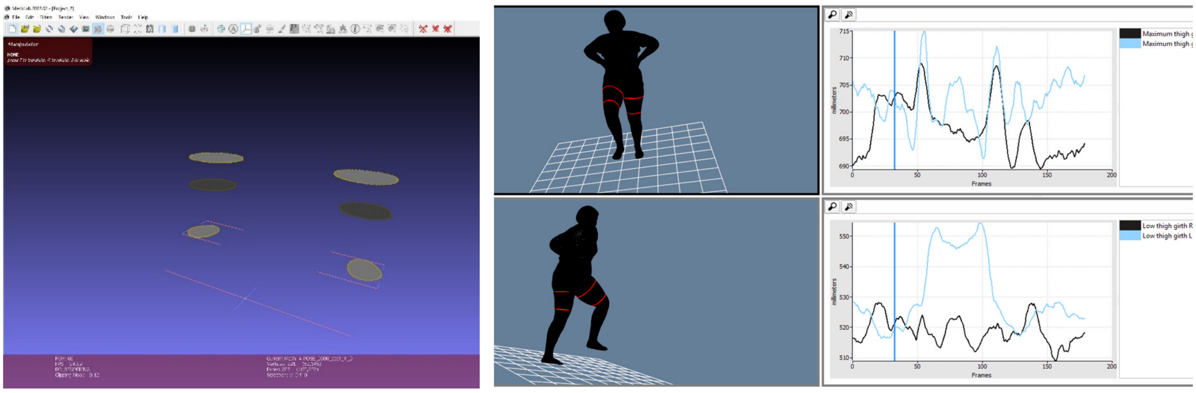
Table 3. The characteristics of volunteers.

Person		1	2	3
Sex		female	female	female
Age		48	43	47
Weight [kg]		89	61	75
Height [m]		170	168	168
Circumference (right/left leg) at standard sites [cm]	b	24.5 / 24.5	23.0 / 23.0	24.0 / 24.5
	c	44.0 / 42.0	40.0 / 40.0	40.0 / 40.5
	d	42.5 / 40.5	34.5 / 34.5	36.0 / 36.0
	f	62.0 / 61.0	45.5 / 45.5	55.5 / 50.0
	g	68.0 / 67.0	52.0 / 52.0	60.5 / 60.5
Size		5	3	4

Three healthy volunteers were involved in this study. First, informal consent was obtained from all of them to use the scan data for this research. Their leg perimeters were measured to prescribe the correct size of medical compression stockings according to the manufacturer`s recommendation in agreement with RAL-GS 387/1 [11]. The characteristics are summarized in Table 3. For this study, MEDIVEN Plus compression stockings of the second compression class (31% elastane, 69% polyamide) from Medi were used.

3.2. Data processing

After the scanning and data processing by MOVE 4D, a large list of obj files with the body geometry is available for its evaluation [25]. In this study, several possibilities were explored. Firstly, the MeshLab 2022.02 software [26] was used for planar section and for circumference measurements (Fig.3.a). Then the new functionality of the Anthropometry Package tool of the beta version of Move4D software was tested (Fig.3.b). Data sorting, organizing, and calculation were done using Excel 2016.



a) b)

Fig. 3. Example of data processing: a) by MeshLab; b) by MOVE 4D software

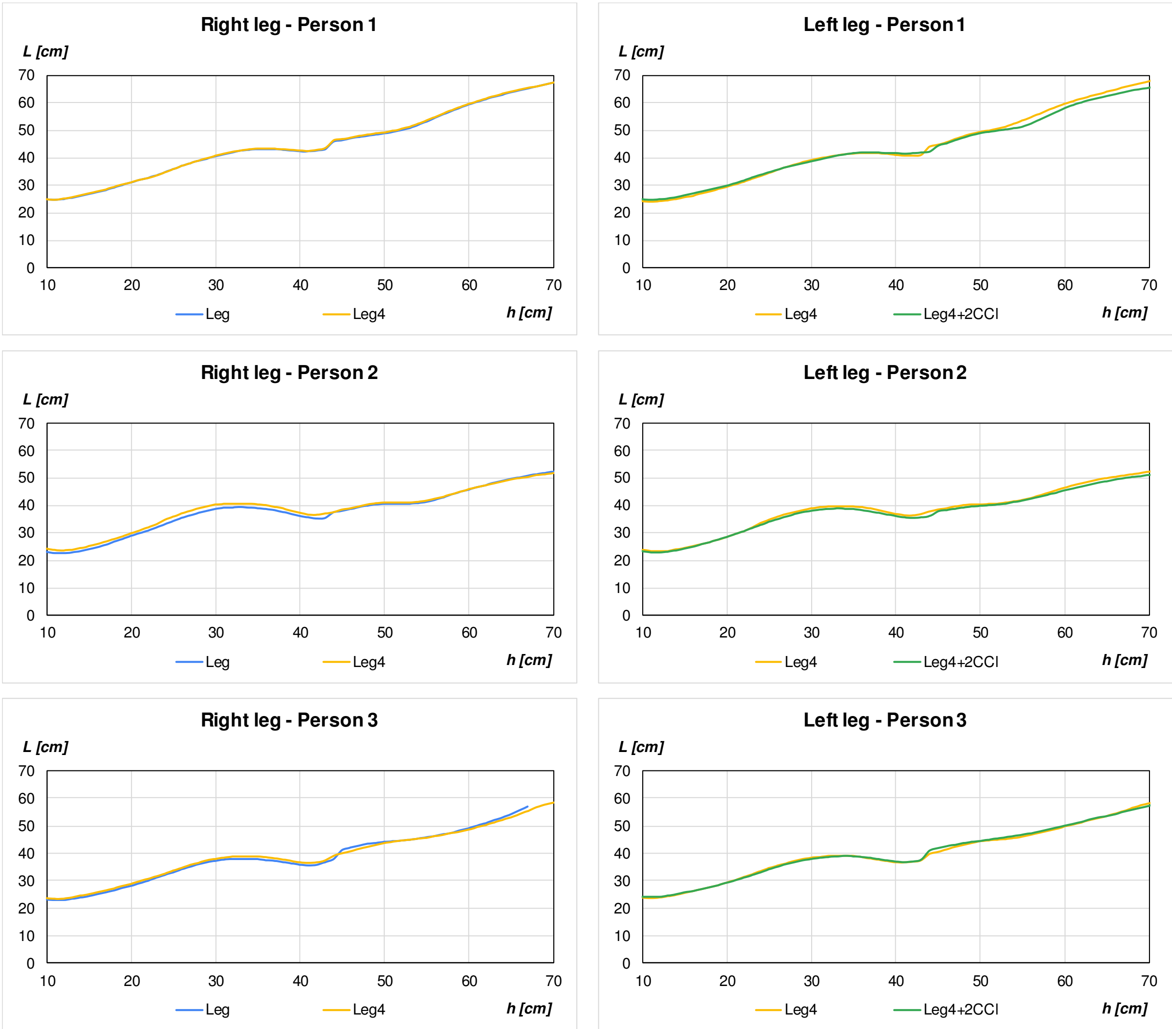
4. Results and analysis

4.1. Leg`s size changes in static position

The obtained data for the static position were systematized for each person, and the results are presented in Table 3 and as plots in Fig. 4. It is obvious that the size of the legs increases during the day for all volunteers. The most significant changes (up to 6.6%) occurred for the second volunteer, despite the smaller size of the legs, and the changes (up to 2.6 %) are not significant for the first person with the largest values of the girths.

Most importantly, the obtained scanning data allows us to estimate the degree of change at all levels and to recognize the most significant area: the low thigh is for the first person, the calf is for the second, and the calf and knee are for the third. It should be noted that the change of 6.6 % at the calf level for the second volunteer is beyond the standard 5.9 %. The obtained data confirm the need for an individual approach in the design and manufacture of compression products.

Putting on compression stockings resulted in changes in leg circumference, with the significant change at the thigh area (Table 4). Naturally, the level of change decreased over time, but remained noticeable. Scanning gives a clear overview of the stocking effect. Thus, an analysis of the left leg after 4 hours from the first scan (Fig.4.b) showed the following. Compression has the greatest effect on the thigh of the first volunteer and on the calf of the second, while the changes in size in the third volunteer are almost unnoticeable.



a) b)

Fig. 4. The dependence of leg circumference (L) on site height (h): a) effect of time; b) effect of compression.

Table 4. Leg circumference differences with time and 2CCl stocking wearing.

Person	1		2		3	
Leg	Left	Right	Left	Right	Left	Right
Maximum difference between leg in the morning and after 4 hours [%]	2.6	1.3	6.6	4.9	3.2	3.4
Leg level of the most significant changes [cm from ground]	44-49	52-55	10-33	10-36	13-32	31-44
Maximum difference between leg and leg with 2CCl stocking in the morning [%]	– 5.2	– 4.4	– 3.1	– 2.1	– 2.6	– 2.9
Leg level of the most significant changes [cm from ground]	63-68	56-60	55-72	44-49	44-48	59-67
Maximum difference between leg and leg with 2CCl stocking after 4 hours [%]	– 5.5	– 5.2	– 4.5	– 2.8	– 1.6	– 0.9
Leg level of the most significant changes [cm from ground]	55-72	56-72	41-48	21-30	22-32	29-40
Maximum difference between leg circumference in cm	3.6	2.7	2.6	2.2	3.1	2.1

During the analysis of the scanning data, some problems were faced. One of them is that in some areas (for example, the calf level for the first volunteer) the leg circumferences after putting on the compression stockings became larger than without them. We can only explain this by the thickness of the stocking itself, which increases the leg volume, albeit slightly. Thus, there is a need to develop an algorithm for calculating obtained girths without compression products, and all measurements must be revised according to it. The future investigation of this issue is necessary.

4.2. Leg`s size changes during motion

The obtained data for the dynamic positions were systematized for each person and for each movement. The examples are presented as plots in Fig. 5.

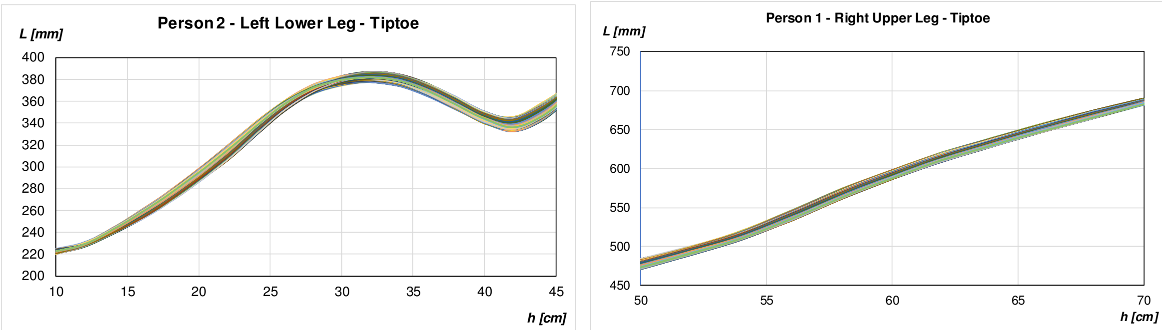


Fig. 5. Example of experimental data for changes in leg circumference during movement

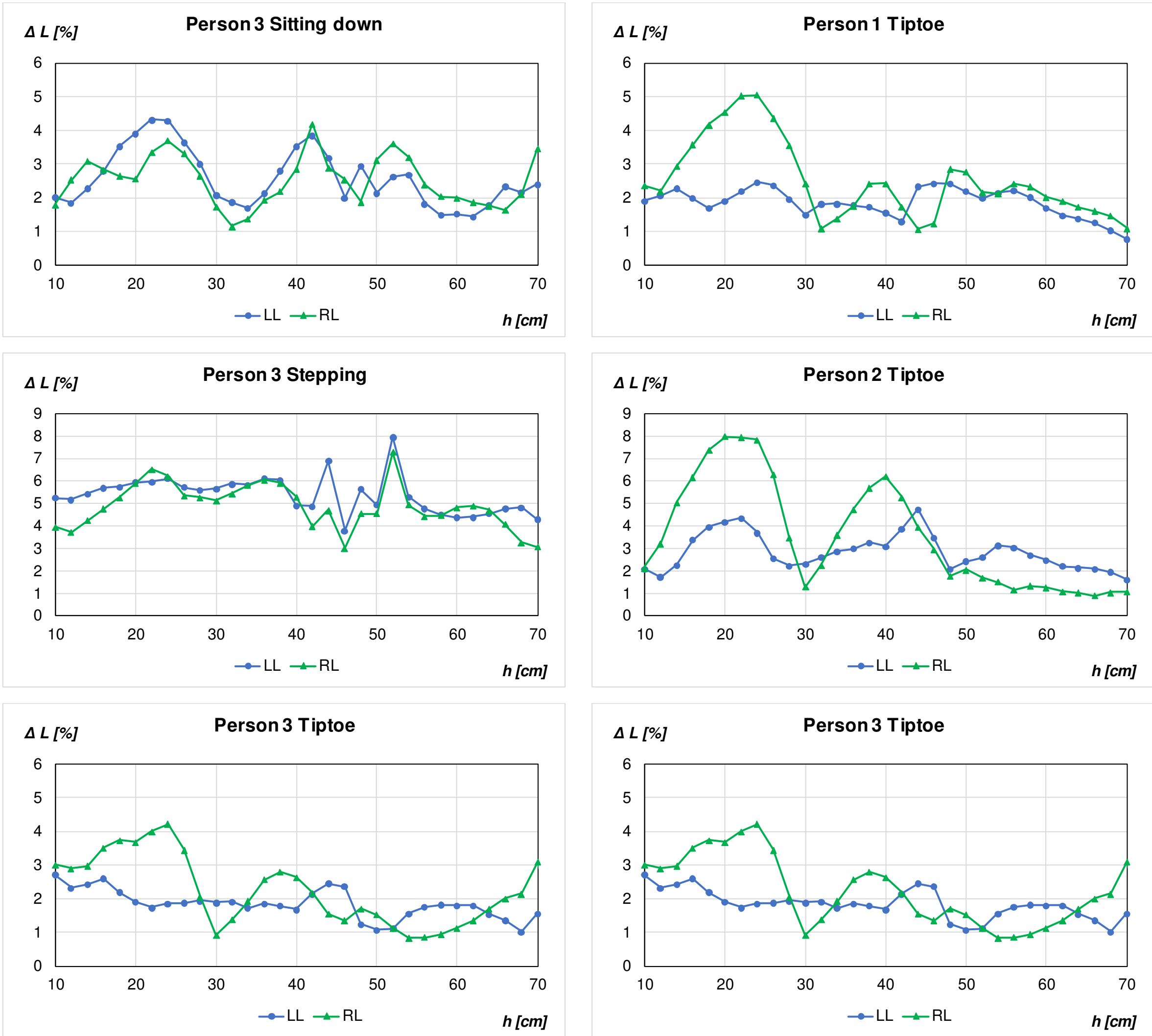
There is no doubt that the leg circumference, especially in the calf area, changes due to muscle activity. The degree of circumference change depends on the type of movement [27]. For example, for the 3rd volunteer (Fig. 6.a), the most significant change was recorded during stepping onto a box (up to 7%). It should be noted that the trend of changes for both legs was the same.

The generalized data for several sites on the thigh are presented in Table 5. As can be seen, the most significant changes in this part of the leg occur during the movement "stepping". In this case, the part above the knee (low thigh) undergoes greater changes.

It should be noted that during the processing of the MOVE 4D scanning data, another problem was detected. The movement "bending" was not recognized, and most of the frames were empty. We attributed this to the fact that the eye fixation of the scanned person was lost during the scanning. Therefore, data for this movement were calculated and analyzed only partly.

Table 5. Changes in circumference [%] at thigh level during movements.

Person		1		2		3	
Leg		Left	Right	Left	Right	Left	Right
Tiptoe	Low thigh	2.2	2.1	3.1	1.5	1.6	0.8
	Mid thigh	1.4	1.7	2.1	1.0	1.5	1.7
	Max thigh	1.2	0.7	1.2	0.8	5.7	1.3
Bend over	Low thigh	3.2	2.7	2.6	2.9	2.1	1.7
	Mid thigh	2.5	1.1	1.8	1.9	3.3	2.2
	Max thigh	1.7	1.8	2.9	5.1	13.2	5.5
Sitting down	Low thigh	5.7	4.5	3.1	3.1	2.7	3.2
	Mid thigh	2.1	1.9	3.6	2.0	1.8	1.8
	Max thigh	3.7	2.5	2.8	3.2	5.6	3.6
Stepping	Low thigh	7.4	3.7	5.8	6.6	5.3	4.9
	Mid thigh	4.7	4.4	5.2	4.7	4.5	4.7
	Max thigh	3.4	2.8	3.7	3.1	7.6	4.5



a) *b)*

Fig. 6. Changes in leg circumferences during movement: a) for person 3 (size 4) during different movements; b) for different persons when going tiptoe.

A comparative analysis of leg changes during the same movement showed that this is also a feature of each person. Thus, during the movement "rising on tiptoes" (Fig.6.b), the greatest changes were for person 2 (up to 8%), and the smallest for person 3 (up to 4%). It should be noted that the general tendency was for greater changes in the area below the knee, while the changes in the right leg were more noticeable.

4.3. The generalized data for compression stocking development

The obtained results allow us to comprehensively evaluate changes in the leg circumferences that occur during the day when people are active. The plots in Fig. 7 show the changes that take into account both factors (time and movement). This data is essential for evaluating the functionality and comfort of the compression stockings.

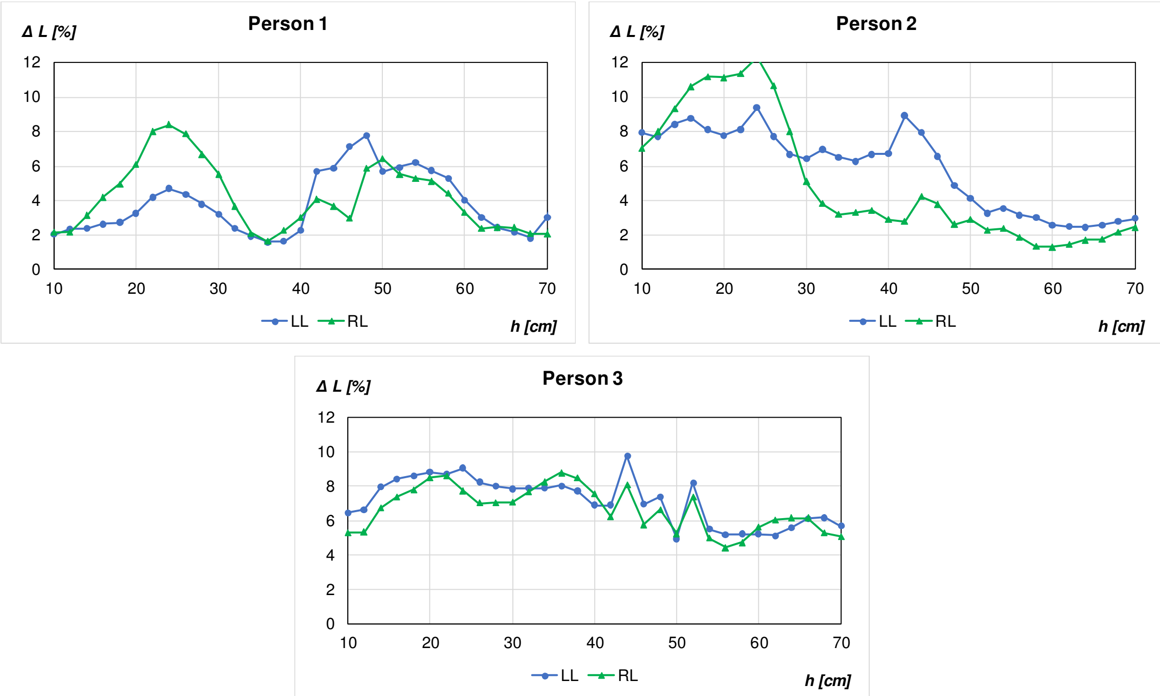


Fig. 7. The comprehensive changes in leg circumference

As an example, the tensile property for materials of 2nd class compression stocking is presented in Fig. 8. The maximum changes in circumference for the first person (up to 8%) are at the calf (Fig.5). An elongation by 8 % (from 30 to 38%) leads to an increase in force by 2 N (almost 30%) that is within the standard limits (Table 1). But such changes can affect the perception of compression.

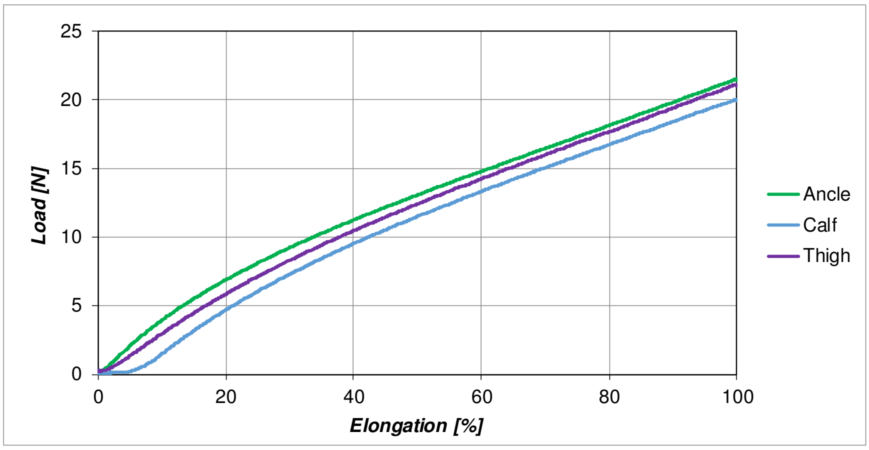


Fig. 8. The load-elongation dependence for 2nd class compression stocking (31% elastane, 69% polyamide).

A completely different dependence is observed for the second person. The maximum changes in circumference are at the calf as well, but it is over 12% in a few points. An elongation by 12 % (from 30 to 42%) leads to an increase in force by 3 N (almost 42%) that is out of standard limits. In some cases, this may lead to exceeding the pain threshold.
Thus, scanning technology makes it possible to determine the magnitude of changes in the shape and size of the limbs and to estimate the expected changes in the pressure of compression products. On the other hand, data on possible changes can serve as a starting point for designing custom compression garments. It is essential to consider the changes not only over time, but also those that occur during various movements.

Conclusion

Investigating the changes in limb sizes that occur during various movements and over time is a crucial stage in designing compression products. Preliminary results presented in the work showed that the change level is a feature of a particular person. It was established that in some cases, the changes exceed the standard limits. Using Move 4D data and MeshLab software, the effect of the II class compression stockings was also studied. The following challenges were recognized: the thickness of compression stockings affects the results; almost half of the frames for movement "bend over" were lost during the processing of 4D scan data.

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