COMMUNICATIONS IN
DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Analysis of lower-body dimensions and their implementation in compression garment development

Kasey Hatch[1*], Carol McDonald[2], Anke Klepser[3], Kristina Brubacher[1], Simeon Gill[1]

[1]*University of Manchester, Manchester, UK*
[2]*IEEE Standards Association, USA*
[3]*Hohenstein, Bönnigheim, Germany*
*kasey.hatch@postgrad.manchester.ac.uk

INFO

CDATP, ISSN 2701-939X
Peer reviewed article
2024, Vol. 5, No. 2, pp. 187-194
DOI 10.25367/cdatp.2024.5.p187-194
Received: 01 April 2024
Accepted: 23 September 2024
Available online: 20 December 2024

ABSTRACT

This experimental study aims to develop an approach to quantify dimensional changes in the lower body of female football players, with the intention of demonstrating how the results can be used to inform the development of lower body sports compression garments. A framework was established in order to analyze 3D body scans in functional postures using Rhinoceros 3D® and Grasshopper as a response to the limitations of current scanner software. The outcome provides an alternative methodology to locate landmarks on the body and extract dimensions in various sporting postures. Suggestions have been made as to how this information can aid pattern making, sizing, and grading of sports compression leggings that can provide the wearer with optimal clothing fit, pressure delivery and comfort.

Keywords
3D body scanning,
pressure,
clothing fit,
compression,
dimensional change

1 Introduction

1.1 Sports compression garments

Sports compression garments (SCGs) are worn by amateur and professional athletes as ergogenic aids, attempting to enhance performance, prevent injuries and accelerate recovery [1]. The fit of these garments is tight enough to put pressure on the body, encouraging venous return [2] and therefore allowing more oxygen to be supplied to the muscles during physical activity. This oxygenation fuels the muscles and prevents the accumulation of lactic acid [3]. In order for the wearer to feel the benefits, the garment must fit accurately, too loose and insufficient pressure will be applied to the body [4] and if too tight, the garment can cause discomfort and restricted circulation [3].

Accurate fit is essential for pressure delivery; however, previous research neither evaluates the fit of the garments before quantifying their efficacy nor assesses sizing methodologies for commercially available SCGs. Sports compression leggings are usually developed based on standard trouser and hosiery production systems, because of the lack of research and understanding of industry professionals. Specific considerations are necessary to create sizing systems for these garments: mechanical properties of their constituent fabrics, applied pressure levels and the size and shape of the target demographic.

1.2 Body scanning for SCG development

3D body scanning can aid the product development of SCGs, by quickly and accurately obtaining body measurements from consumers [5]. Scan software can automatically identify landmarks and extract body measurements from scanned populations, which can be utilized in the development of garment patterns and sizing systems, from which consumer-facing size charts are created. Subjects are scanned in the standard A-pose, standing up-right with arms and legs abducted away from the body. This posture is not often assumed in reality and does not give any consideration for how the body changes whilst moving. SCGs are typically worn during physical activity, so dimensional changes to the body whilst in motion must be measured as this will affect the amount of pressure being applied to the body. As the body moves, muscles contract and joints rotate, causing increased fabric strain in the garment worn and increasing interface pressures. To quantify this dimensional change, subjects can be scanned in functional postures, which are static poses that replicate movement. Previous studies have scanned participants in various postures including seated [6], squat [7], rowing [8] and T-pose, in order to determine ease allowances for garments [9,10]. Despite this, there is no research that identifies dimensional changes in the body and uses the information to predict pressure fluctuations on the wearer.

There are limitations with assessing 3D functional postures as when the body is static, muscle groups may be engaged to hold the body in position that may not be used during dynamic movement. 4D scanning has been suggested as a way to combat this and enable participants to be scanned in motion [9,11]; however, this technology is still in its infancy and has its own limitations. Anthropometric data is unable to be auto-extracted from 3D functional postures and 4D dynamic postures using scanner software, and manual extraction tools available in the software are not accurate or reliable as data collection methods as repeatability is an issue. Another weakness to scan software is the lack of cohesion between different scanners' landmark definitions, which will cause discrepancies in research outputs.

2 Methodology

2.1 3D body scanning

Six German amateur football players, with an average age of (19 ± 4) years, were recruited by Hohenstein and scanned using the 3D Vitus Smart Laser scanner (Human Solutions GmbH, Germany). Each participant was scanned in two functional postures (Fig. 1) that represent two points on the running gait cycle, the 'take off' point in the swing and stance phase of the cycle and the 'heel-contact' point at the start/end of the cycle.

Fig. 1 Participant 1 in postures 1 & 2.

2.2 Scan analysis

This study utilized the Rhinoceros 3D® version 7 (McNeel, USA) software as well as its plug-in Grasshopper, an algorithm editor, to develop algorithms for the auto-extraction of body measurements. Measurements were selected dependent on their usefulness in compression legging development (Table 1). Circumferential measurements along the limb are most important for lower body compression garments as the limb circumference will determine the amount of pressure applied across the limb [12,13]. This paper focuses on using the dimensions to predict pressure changes in the garment, although for pattern development, length measurements are also necessary as the garment needs to be long enough to reach the ankle but not too long that fabric bunching/folding occurs, distorting pressure application. It is also important to consider areas of high skin stretch, e.g., flexion of the knee can stretch the skin on the anterior leg by up to 50%, which may increase during more strenuous exercise [14]. Pressure will be applied to the body if the fabric stretch does not correspond to the stretch of the skin's surface. However, for the purposes of this paper only crotch point and calf circumference are discussed. The crotch point is the first landmark located for each participant and forms the basis to identify other landmarks and measurements, whereas the calf circumference is used as it is significant for SCG development as it is a notable pressure measurement location [15,16].

Table 1. Extracted measurements and their definitions [17,18].

Measurement	Definition
Crotch Point	Lowest point of the torso on the midsagittal plane with the virtual human body.
Waist Circumference	The circumference of the abdomen at the height of the small of the back, within a range of 2 cm (SOB + 2 cm).
Seat Circumference	The most posterior point or center of the most posterior area of the buttocks.
Thigh Circumference	The largest circumference of the upper leg occurring due to the muscles of the upper leg.
Knee Circumference	The midpoint of the posterior superior border of the patella.
Calf Circumference	The largest circumference of the lower leg (shank) occurring due to the muscles of the lower leg.
Ankle Circumference	The ankle point is the middle point of the malleolus. Medial is at the lower extremity of the tibia.

3 Discussion

For this paper, only two of the measurement extraction processes required for garment development are discussed, to demonstrate how the use of this software can provide a method to obtain functional measurement data and how it can be applied to (modified) Laplace's Law to predict pressure fluctuations at various locations across the limb.

3.1 Crotch point

The coding in Grasshopper (Fig. 2) of the sport posing scanned bodies or humanoids took advantage of the upright poses. The upright poses allowed for the crotch points to be found within 42% and 52% of total height. As noted by landmarks paper by the IEEE 3DBP [17], while in a standing or upright pose, body landmarks can be found within a certain percentage range of body height. The precision of the measurements is at one millimetre for this study, so height measurements were taken at every millimetre of vertical height after measurement height zones were determined. This allowed for a shorter computational time than if the entire scan had height measurements at every millimetre. Even though Rhino/ Grasshopper uses “z” as the vertical dimension, the “y” dimension was kept as vertical dimension for the scans as this was for an apparel application.

By creating horizontal planes at each vertical millimetre of height measurement, cross-sectional curves could be found. Each millimetre height plane had multiple cross-sectional curves, either two legs or arms with humanoid curves. This created a data tree which can then be used for filtering curves by count or location. Cross-sectional curves for the arms were filtered out by using a testing circle on each millimetre height. After applying this filter, due to the fact that there was no bridging between the two legs near the crotch region, the code was set up to count the number of curves for each branch. This filter worked 83% of the time. Other visual reviews were required for the other 17% due to folding of the fabric creating multiple cross-sectional curves in the torso region. The centre point of the body is found at the centre line through the middle of the cross-sectional curves of the torso. As there are two poses per 6 humans, 12 crotch points were obtained.

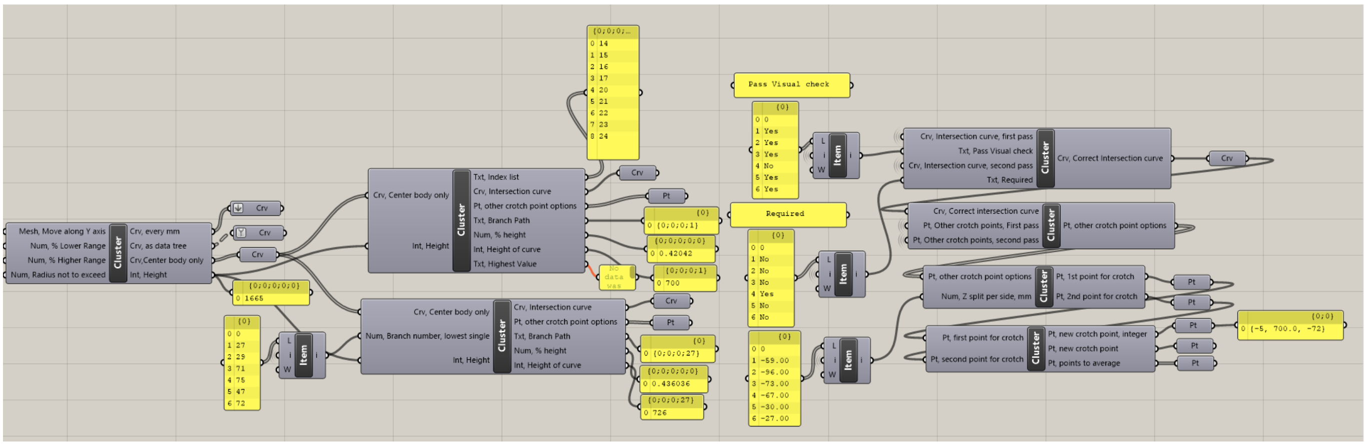

Fig. 2 Partial code to generate crotch point as x, y, z value.

3.2 Calf circumference

The next measurement that was obtained was the maximum calf circumference. Depending on the orientation of the lower leg segment, either horizontal or vertical planes were used to obtain the cross-sectional curves. For the human body, it is noted that the calf will always be located between the ankle and the knee. This assumption allowed for the percentage of the human height or human depth to be visually observed and obtained within the proper mesh region; however, these curves were not perpendicular to the angle of the lower leg body segment. By determining the centre line of the humanoid body segment and using the perpendicular planes to the centre line, the proper perpendicular curves for measurements were obtained. Perpendicular planes were then used to intersect with the scan mesh. By a simple ranking of the curve lengths from largest to smallest, the largest calf dimension was then determined (Fig. 3). The success rate for this filtering method was 87.5%, with the remaining 12.5% requiring other visual reviews to obtain the maximum calf measurement. As there are two different postures for each of the 6 humans and 2 legs per human, 24 calf circumference measurements were acquired.

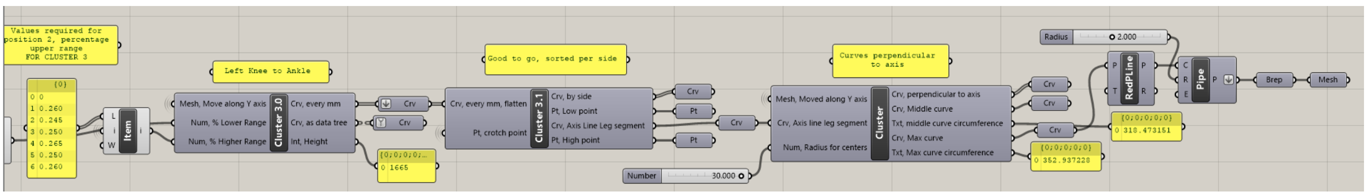

Fig. 3 Partial code to generate maximal calf circumference point in mm.

A mesh is imported into the Rhinoceros 3D® software and attached to the code created in Grasshopper to extract numerical measurement data. However, Rhinoceros 3D® can be used as a visual aid to verify positioning of measurements and landmarks (Fig. 4).

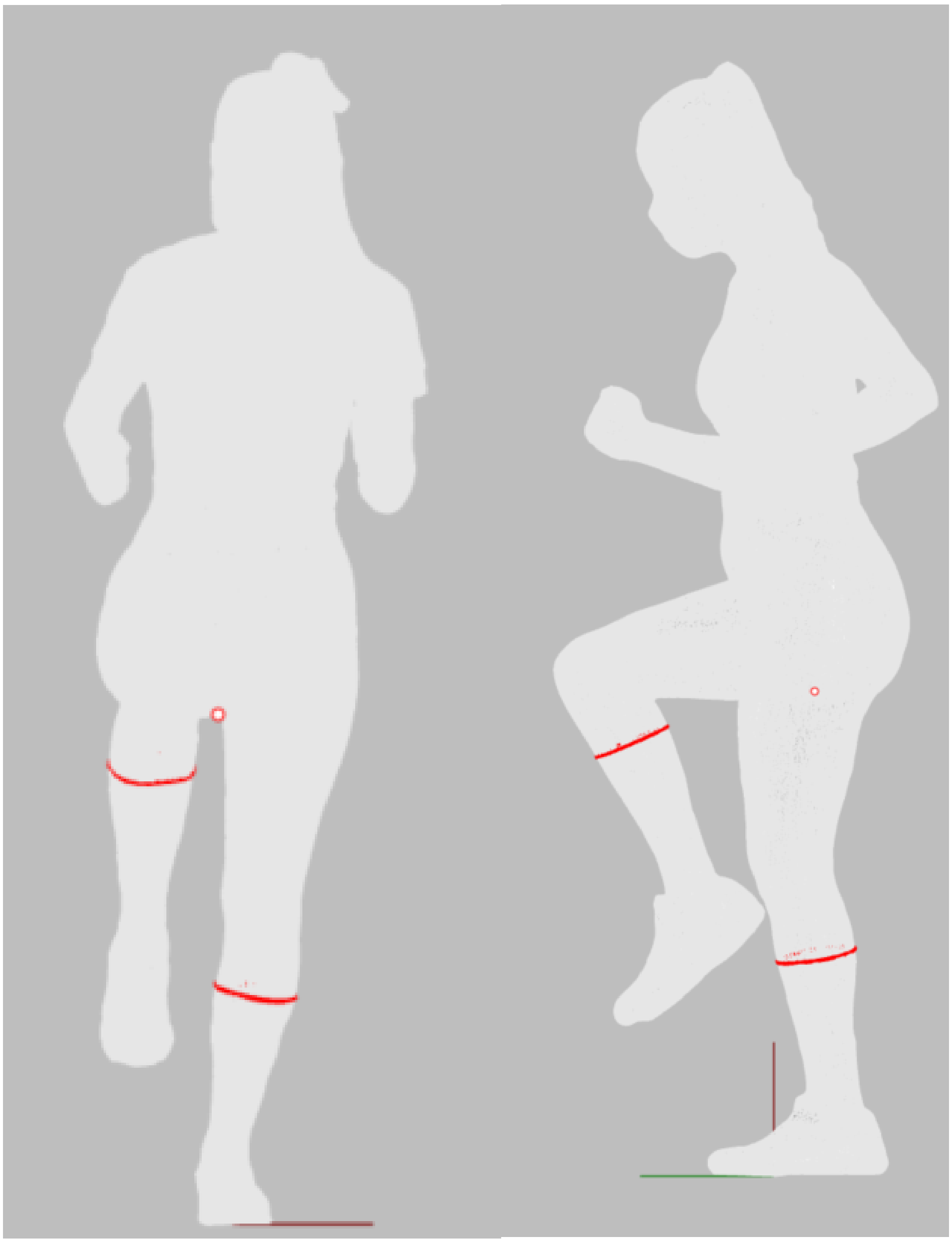

Fig. 4 Participant 1, posture 1 with crotch point and maximal calf circumferences (front and side views).

3.3 Pressure prediction

Using the methodology outlined circumference values are collected from the scans in various positions. Differences in circumference measurements of each participant between the different positions can be analysed, to determine the average dimensional change at each location. Circumference measurements of all participants can be input into Laplace's equation (1), to calculate the pressure.

$$\mathrm{P} = \frac{T}{R} \qquad (1)$$

Laplace's Law states that under constant tension *T*, the radius *R* of curvature of a cylinder is inversely proportional to the interface pressure *P* [13]. This method was never developed to be used to predict pressure exerted by compression garments, so it fails to consider tissue variation (fatty tissue, muscle and bony prominences [19]); therefore only an average pressure value across the cross-section can be calculated. In reality, there is variation in curvature around the calf circumference due to the shin bone located at the anterior aspect and the gastrocnemius muscle at the posterior aspect [20] (Fig. 5).

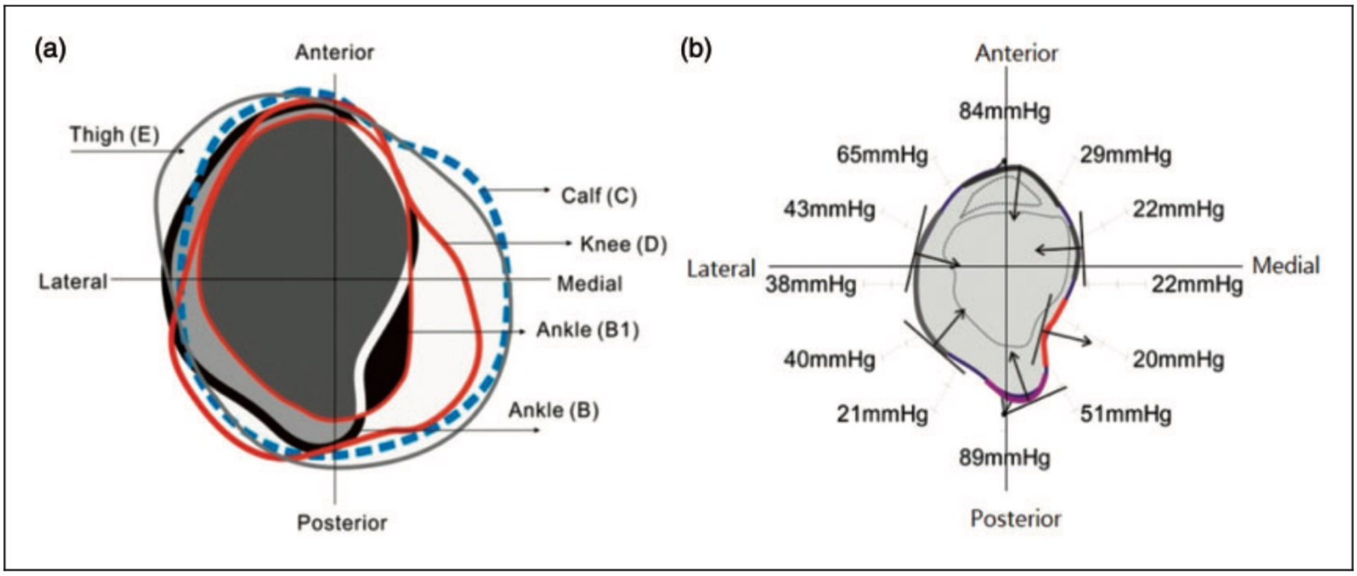

Fig. 5 Effect of variation in radii of curvature on pressure application [20]

Researchers have adapted Laplace's Law for medical compression bandages [21] and compression sleeves [22]; however, the version of Laplace's Law that will be used in this study is Eq. 2 [13].

$$P = \frac{2\pi\varepsilon E e}{C}, \qquad (2)$$

where P is interface pressure (mmHg), ε represents the fabric extension, E is the elastic modulus, e is the garment thickness and C is the leg circumference (m). This pressure prediction method has been modified to make it more appropriate and accurate for the intended use, by using circumference instead of radius of curvature, which is much easier to obtain from scan data and fabric parameters which influence how much pressure is applied to the skin.

4 Conclusion

This ongoing study aims to further previous research [9,10,23] into dimensional changes of the human body during movement by using this to improve sizing and fit of sports compression leggings, guaranteeing an adequate pressure application within a range. The study highlights the need to integrate the automaton of functional measurement extraction in scanner software, to minimize the time it takes to process the functional scans in alternative software. Limitations include the size of the study; six participants of the same nationality, sex and sport do not represent the whole population and values may differ between individuals. However, this study provides a framework to enable other populations to be evaluated in the same way. This is also a time-consuming process which requires proficiency in the software to set up the code to work for all meshes. As well, the participants are wearing clothes (tight-fitting leggings, tops, and shoes), which has affected measurement extraction at the ankle and waist particularly, where either movement or length of the leggings has caused fabric to fold. Possible applications for this research quantifying dimensional changes of the lower body will enable a greater understanding of how interface pressures between garment and skin may fluctuate during exercise, using pressure prediction. Understanding this is important when thinking about garment development; ensuring pressures do not rise to the point of discomfort but always apply enough to function is key. Fabric selection will impact pressure delivery, so recognising how the stress/strain behavior of the fabric may alter during movement and what affect this has on pressure application is important.

Author Contributions

K. Hatch: writing – draft preparation, investigation, methodology, data analysis; C. McDonald: software, methodology, writing – draft preparation; A. Klepser: participant recruitment, data collection – 3D body scanning; K Brubacher: supervision, writing – review and editing; Simeon Gill: supervision, writing – review and editing.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Engel, F.; Stockinger, C.; Woll, A.; Sperlich, B. Compression garments in sports: Athletic performance and recovery. In *Compression Garments in Sports: Athletic Performance and Recovery*; Springer International Publishing, 2016. DOI: https://doi.org/10.1007/978-3-319-39480-0.
2. Brophy-Williams, N.; Driller, M. W.; Kitic, C. M.; Fell, J. W.; Halson, S. L. Wearing compression socks during exercise aids subsequent performance. *Journal of Science and Medicine in Sport* **2018**, *22*(1), 123–127. DOI: https://doi.org/10.1016/j.jsams.2018.06.010.
3. Xiong, Y.; Tao, X. Compression garments for medical therapy and sports. *Polymers* **2018**, *10*(6), 663. DOI: https://doi.org/10.3390/polym10060663
4. Brubacher, K.; Apeagyei, P.; Venkatraman, P.; Tyler, D. 8th Asia-Pacific Congress on Sports Technology, 2017. http://apcstcon.com/
5. Gill, S. A review of research and innovation in garment sizing, prototyping, and fitting. *Textile Progress* **2015**, *47*(1), 1–85). DOI: https://doi.org/10.1080/00405167.2015.1023512.
6. 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: https://doi.org/10.1177/0040517510377822.
7. Dabolina, I.; Lapkovska, E.; Vilumsone, A. Dynamic Anthropometry for Investigation of Body Movement Comfort in Protective Jacket. In *Functional Textiles and Clothing*; Springer Singapore, 2019; pp. 241–259. DOI: https://doi.org/10.1007/978-981-13-7721-1_20.
8. Vasile, S.; Cools, J.; de Raeve, A.; Malengier, B.; Deruyck, F. Effect of rowing posture on body measurements and skin–sportswear interface pressure and implications on garment fit. *Journal of Industrial Textiles* **2021**, *51*(2), 206–224. DOI: https://doi.org/10.1177/1528083719877005.
9. Klepser, A.; Morlock, S.; Loercher, C.; Schenk, A. Functional measurements and mobility restriction (from 3D to 4D scanning). In *Anthropometry, Apparel Sizing and Design*; Elsevier; 2019; pp. 169–199. DOI: https://doi.org/10.1016/B978-0-08-102604-5.00007-X.
10. Morlock, S.; Loercher, C.; Schenk, A.; Klepser, A. Functional Body Measurements – Motion-Oriented 3D Analysis of Body Measurements. In *Proc. of 3DBODY.TECH 2019 – 10th Int. Conf. and Exh. on 3D Body Scanning and Processing Technologies*, Lugano, Switzerland, 22-23 Oct. 2019, pp. 244–253. DOI: https://doi.org/10.15221/19.244.
11. Pei, J.; Griffin, L.; Ashdown, S. P.; Fan, J.; Juhnke, B.; Curry, C. An exploratory study of bust measurements during running using 4D scanning technology. *International Journal of Fashion Design, Technology and Education* **2021**, *14*(3), 302–313. DOI: https://doi.org/10.1080/17543266.2021.1938699.
12. Liu, R.; Kwok, Y. L.; Li, Y.; Lao, T. T. H.; Zhang, X.; Dai, X. Q. Objective evaluation of skin pressure distribution of graduated elastic compression stockings. *Dermatologic Surgery* **2005**, *31*(6), 615–624. DOI: https://doi.org/10.1097/00042728-200506000-00001.
13. Barhoumi, H.; Marzougui, S.; Abdessalem, S. B. Clothing Pressure Modeling Using the Modified Laplace's Law. *Clothing and Textiles Research Journal* **2020**, *38*(2), 134–147. DOI: https://doi.org/10.1177/0887302X19880270.
14. Voyce, J.; Dafniotis, P.; Towlson, S. Elastic textiles. In *Textiles in Sport*; Woodhead Publishing Series in Textiles, 2005; pp. 204–230. DOI: https://doi.org/10.1533/9781845690885.3.204
15. Hill, J. A.; Howatson, G.; van Someren, K. A.; Davidson, S.; Pedlar, C. R. The variation in pressures exerted by commercially available compression garments. *Sports Engineering* **2015**, *18*(2), 115–121. DOI: https://doi.org/10.1007/s12283-015-0170-x.
16. Brophy-Williams, N.; Driller, M. W.; Halson, S. L.; Fell, J. W.; & Shing, C. M. Evaluating the Kikuhime pressure monitor for use with sports compression clothing. *Sports Engineering* **2014**, *17*(1), 55–60. DOI: https://doi.org/10.1007/s12283-013-0125-z.
17. Gill, S.; Scott, E.; McDonald, C.; Klepser, A.; Dāboliņa, I. *Landmarking for Product Development*. IEEE Standards Association, 2021. https://standards.ieee.org/wp-content/uploads/2022/07/Landmarking-for-Product-Development.pdf.
18. Gill, S.; Parker, C. J.; Hayes, S.; Brownbridge, K.; Wren, P.; Panchenko, A. The True Height of the Waist: Explorations of Automated Body Scanner Waist Definitions of the TC2 scanner. In *Proc. of 5th Int. Conf. on 3D Body Scanning Technologies*, Lugano, Switzerland, 2014; pp. 55–65. DOI: https://doi.org/10.15221/14.055.

19. Brubacher, K. Towards the design of sports compression garments with controlled pressure. 2018. https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.765186.
20. Liu, R., Guo, X., Lao, T. T., & Little, T. A critical review on compression textiles for compression therapy: Textile-based compression interventions for chronic venous insufficiency. *Textile Research Journal* **2017**, *87*(9), 1121–1141. DOI: https://doi.org/10.1177/0040517516646041.
21. Thomas, S. The use of the Laplace equation in the calculation of sub-bandage pressure. *EWMA Journal* **2003**, *3*, 21–23.
22. Macintyre, L. Designing pressure garments capable of exerting specific pressures on limbs. *Burns* **2007**, *33*(5), 579–586. DOI: https://doi.org/10.1016/j.burns.2006.10.004.
23. Gill, S.; Hayes, S. Lower body functional ease requirements in the garment pattern. *International Journal of Fashion Design, Technology and Education* **2012**, *5*(1), 13–23. DOI: https://doi.org/10.1080/17543266.2011.593560.