COMMUNICATIONS IN
DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Individual soft avatars in digital clothing development using the example of compression stocking-leg interaction

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INFO

CDAPT, ISSN 2701-939X
Peer reviewed article
2025, Vol. 6, No. 2, pp. 273-284
DOI 10.25367/cdatp.2025.6.p273-284
Received: 02 June 2025
Accepted: 22 December 2025
Available online: 23 December 2025

Keywords
Soft avatars,
Compression,
stocking-leg interaction,
FEM modelling,
Clothing development

ABSTRACT

Digital clothing development still takes place largely on rigid (non-deformable) avatars. This established method is usable for clothing that is far from the body, such as dresses or jackets, but is limited for clothing that is close to the body. Close to the body clothing interacts with the individual body, where both body and clothing deform. This paper presents steps in development of soft (deformable) avatar on example of modeling of a deformable leg in interaction with a compression stocking. These steps include scanning and meshing of the human body part, and the implementation of the clothing product in interaction, modelled by FEM software. This modelling allows the fit and function of the compression stocking to be individually examined and improved.

1. Introduction

The possibilities of digitization are increasingly being used in the industry for product development in order to be able to meet the trend of continuous collection renewal while at the same time reducing sample sewing and the associated personnel and material costs. Virtual fit simulation plays an essential role in this. Market leaders in the production of fashionable clothing have set themselves the goal of physically producing only a third of all prototypes after 2022. In order to achieve this goal and go beyond it, a realistic three-dimensional virtual representation of clothing is an essential prerequisite. Very good results have already been achieved in the field of simulation of clothing that is far removed from the body (dresses, coats). However, there is still a considerable need for research in the field of tight-fitting clothing (lingerie, sportswear, orthopaedic aids). This clothing is often produced "under measure", i.e. when worn, the textile material is stretched and causes a deformation of the soft tissues (including the chest, abdomen, hips) due to the pressure on the body. This deformation influences the fit and cannot yet be depicted or assessed in its effect on the pattern design with the help of current rigid human models (avatars).

A similar problem can be found with technical foams (car seats, upholstered furniture). The textile cover compresses the foams inside. This leads to deviations from the model shape specified by the designer. At present, several iteration loops are required in order to generate a high-quality end product with the required seating comfort, taking into account the textile-physical properties (stress-strain behavior of the textile surface, compression-stress deformation behavior of the foam).

Using 3D/4D scanning technology, it is possible to record the deformation of the body surface due to clothing and movement. An interaction between textile material and the deformation of the body surface can thus be determined, but requires new images for each test subject, each new material and each cut variant (model form). In the process, large amounts of data are generated that have to be evaluated. The technology required for this is very expensive and only sporadically available in the research environment.

The aim is to develop methods for the generation of deformable avatars (soft avatars) and to use them for the fit simulation of tight-fitting clothing. A general method for generating deformable avatars for digital clothing development of tight-fitting clothing was published in [32]. This paper shows the application and transferability of these methods to the development of compression stockings.

2. State of the art

2.1. Digital Deformable Human Models

Both physical and digital figurines or avatars are currently used for fit verification. There are suppliers of physical figurines worldwide, some of which specialize in certain countries and the associated size systems[1, 2]. In addition to an integrated size adjustment, physical figurines with soft inserts are also offered in individual cases to replicate the different soft tissues on the body in the areas of the abdomen, buttocks, chest and arms. The deformation of these inserts is not defined by corresponding material characteristics (compression-stress deformation behavior), but is based on empirical values and varies between suppliers. Existing digital avatars (as of 2024) for fit simulation are currently not yet able to realistically depict the deformation of the soft tissues. Until around 2023, all known CAD tools for fit simulation (including Assyst-Vydia, Lectra-Modaris, Clo3D–CLO, Tukatech-Tukatech) were based on the contact calculation between a flexible textile, represented as a spring-mass system, and a rigid body. For the last 2 years, the well-known CAD tools for fit simulation such as Browswear or CLO3D have been introducing the first soft avatars. These soft avatars can be deformed by tight-fitting clothing. However, these soft avatars have not yet become established. So far, they cannot be individualized in terms of soft tissue properties, deformations are still largely unrealistic and pressures between body and clothing cannot be displayed. Some systems offer rudimentary possibilities to represent the simulated fit and draping effects on moving bodies.

A presented software for predicting the fit of tight-fitting clothing using deformable avatars is VitalFit [3]. The avatars are created by registering a "VitalBody template" on rigid avatars (scan data). The individual avatar consists of a tetrahedral mesh and soft tissue properties that are numerically simulated using the FE method. The avatars can be moved by coupling them to a simplified rig (skeleton). The simulated contact between clothing and soft tissues can predict the displacements of the body surface. In the future, designers and pattern makers will be able to use VitalFit DX, a plugin for Adobe Illustrator®, to create clothing virtually and evaluate the fit. Based on the publication, it is not possible to assess the quality of the simulation result, as no comparison with experimental data (static scanning/motion, MRI images) has been published.

2.2. Material characteristics soft tissue

2.2.1. Experimental Soft Tissue Measurement

The current state of the art does not specify general methods for measuring or modeling soft tissue properties. Two methods for measuring soft tissue could be identified: the first method is ex-vivo: a measurement on the non-living body or tissue, and the second method is in vivo: a measurement on the living body/tissue.

Methods of ex-vivo measurement are indentation tests or dynamic movement examinations of the soft tissue. In the push-in tests, punches are pressed into the soft tissue and the travel distance and force are measured. This method is used in the field of application of stump/prosthesis fitting. [4, 5] Specially developed test devices press into the soft tissue around the stump. A transfer of this technology to other parts of the body could not be found. Only [6] described using an impression test for the determination of breast parameters. A precise description of the experimental setup or device was not described. In the determination of breast tissue, the method of dynamic measurement was also used. The breast is equipped with sensors and examined either by a body movement such as walking or by "lifting and falling" the breast with regard to cushioning behavior or movement. Data from these experiments were also implemented in simulation models. [7–9]

In vivo measurements take living tissue from the human body or test body areas of a dead person. [10] The advantage of in vivo measurement is that classical material characterizing measurements such as density, tensile or compression tests are possible. In addition, measurements of individual tissue layers or muscles are possible. The disadvantage is that the taking of the samples changes the material behaviour to an indeterminable level. Soft tissue and muscles consist largely of water or are permeated with blood. The removal changes this fluid content. Medical examinations of breast tissue properties, for example, to identify or model tissue changes use this method.

2.2.2. Soft tissue modeling

For the modelling of human soft tissue, a wide variety of approaches and no general modelling methods could be identified. Models for medical applications tend to use heterogeneous model setups with non-linear material properties. Different layers of skin, bones, muscles are modeled. [11–14] Clothing-specific models tend to use homologous model setups. Bone structures or the additional modelling of a skin layer have also been identified in isolated cases. [6, 8, 9, 15–17] Material parameters for the models are mainly set on the basis of literature data. [17] Alternatively, results of experimental movement analyses are entered for breast material calibration, for example. The material models are linear-elastic [17], Neo-Hook [18–20] or Mooney Rivlin [9, 15, 21–24]. Tanner et al. investigated that up to a certain degree of compression, the material models have a small influence on soft tissue modelling compared to the model boundary conditions. [14]

2.3. Technical foams

Technical, soft-elastic foams are used for mattresses, upholstered furniture and vehicle seats, among other things. Especially in the automotive and seating furniture industry, PUR flexible foams with different compression hardnesses are used. These have established themselves due to a large number of positive properties (dimensional resistance, ageing resistance, low weight). The upholstery, i.e. the cover with a textile upper material, still poses a challenge. In order to achieve a wrinkle-free draping of the upholstery fabrics, they are processed in a stretched state. In the case of strongly curved foam contours, this leads to a deformation of the geometry and thus to a deviation from the design draft, depending on the compression hardness. To circumvent this, seat foams (side walls) are thickened iteratively using the experience of the foam developers.

In order to take into account the interactions between the foam, the stretched textile and different loading scenarios (sitting position), it is important to have precise knowledge of the respective material characteristics (tensile elasticity of the cover material, compressive stress deformation properties of the foams, contact-pressure distribution), which are determined by means of standard test methods or industry-specific test procedures [25, 26]. These are incorporated into simulation tools within the product preparation process. The main focus is on ensuring safety/comfort.

[27] describes a method for optimising seating comfort for car seats. In particular, the interaction between the pressure-elastic seat and the human is investigated, whereby the form of pressure distribution plays an essential role. Based on the knowledge of the interpretation of pressure distributions, statements can already be made about seat comfort depending on time in the virtual phase of seat development. However, the development does not take into account the geometry change of the compression-elastic foam due to an existing reference stress caused by the cushioning material or its change under compressive stress by humans. [28] also examines the time-dependent changes in the viscoelastic deformation of seat foams under stress. For this purpose, a commercially available FE model for seat components (PAM-COMFORT,® ESI) is used, which is extended by a non-linear model. This takes into account the mechanical properties (compressive stress deformation, tensile elastic and relaxation behaviour) of all seat components. In the pressure analysis, the influence of the cover tension on the geometry of the seat foam could be visualized. The results were used to construct the reference geometry (seat foam without compressive load), but not to quantify the geometry changes under direction-dependent reference stress. In [29, 30] a material model is presented to predict the nonlinear static and dynamic behavior of a seat foam under different pre-loads (body mass, vibration frequencies). It has been implemented in LS-DYNA and also includes a pressure distribution analysis (human/foam), but does not take into account the influence of the upholstery fabric on the seat foam geometry. The improvement of the accuracy of an FE human model (PAM-comfort model) is the content of the results presented in [31]. In order to represent the mass distribution properties of the model more precisely, the abdomen was realized as a homogeneous volume mesh. A refinement of the mesh quality of the buttocks and the back part serves to predict the seat pressure distribution more accurately. In summary, it can be stated that the simulation solutions presented in the literature, which model the interaction between people and seat foam, are more likely to be used to model seating comfort.

3. Methodology

The structure of an individual Softavater is described in detail in [32]. In the following, the developed methodologies are applied to the example of an individual, deformable leg. A compression stocking is put on this leg, which allows a realistic, digital fit simulation to be performed. The fit simulation is carried out using the finite element method (FEM). This is an established method to accurately determine pressures and deformations. The finite element model (FE model) is generated and calculated in LS-PrePost.

3.1. Creation of an individual, deformable leg

To capture the geometry of the leg, a static 4D scan is performed with IBV's Move4D scanner. The area of interest is then selected to shorten later calculation times (Figure 1a). The leg is then cross-linked to solid elements in LS-PrePost according to the method from [32]. The element formulation is set to ELFORM = 10. The leg is then divided into individual areas (Figure 1b, colored areas) to assign individual material properties to them.

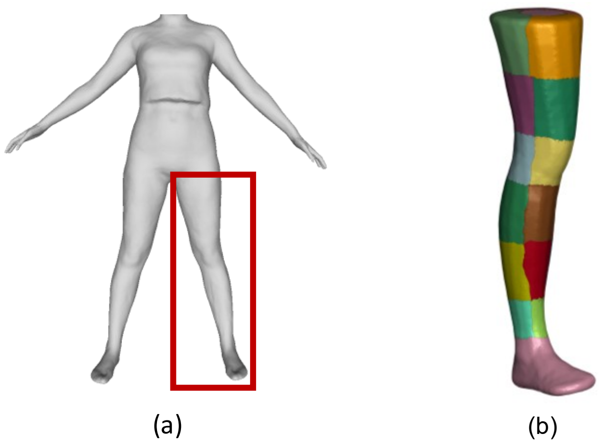
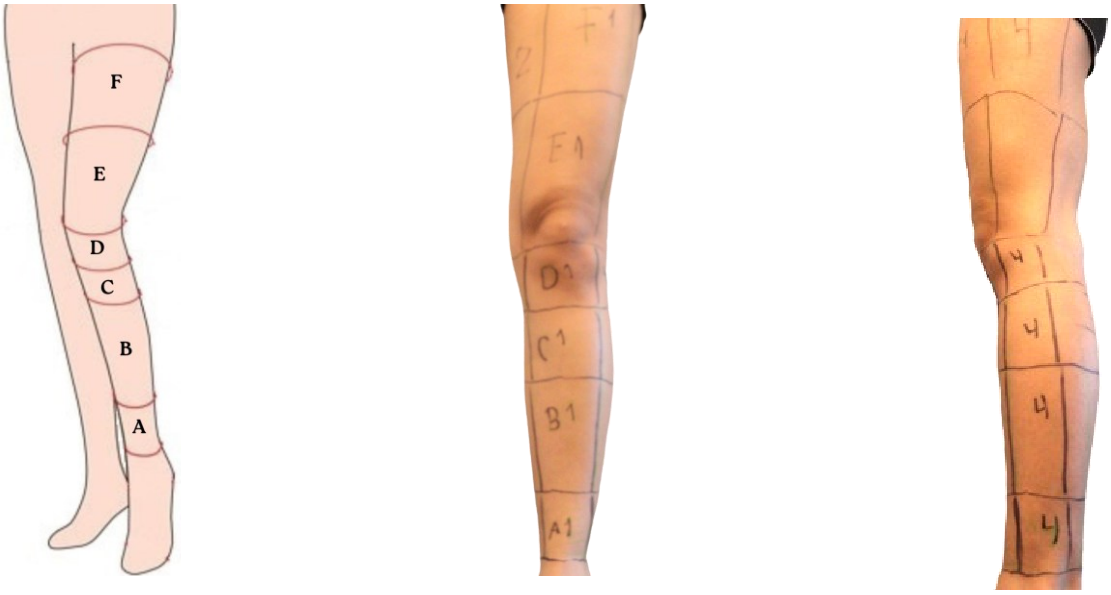


Figure 1: Development of a human model with bone structures (a) 4D scan in an A-pose, (b) meshed leg structure

3.2. Measurement of soft tissue parameters on the leg and calibration of the simulation model

With the method developed in [32] to determine soft tissue parameters, the IndentoPro is used and the calibration is carried out by simulating the experiment in the finite element simulation. The leg is adapted to the zones of the compression stockings in the areas of measurement of the material properties (Figure 2a). In Figure 2b is the division of the leg into the approximated zone areas. Figure 2b visualizes the zone areas of the leg from A to F on the test subject. Each zone is additionally divided into 4 areas (Figure 2c). During the use of the IndentoPro, the indentation force and the indentation path are measured to characterize the material behavior of the leg zone. The output of the device is a force-displacement curve, which represents the non-linear material behavior of the soft tissue. The advantage of the IndentoPro over other measurement methods and devices is that it is portable and can be used on different parts of the body [32].



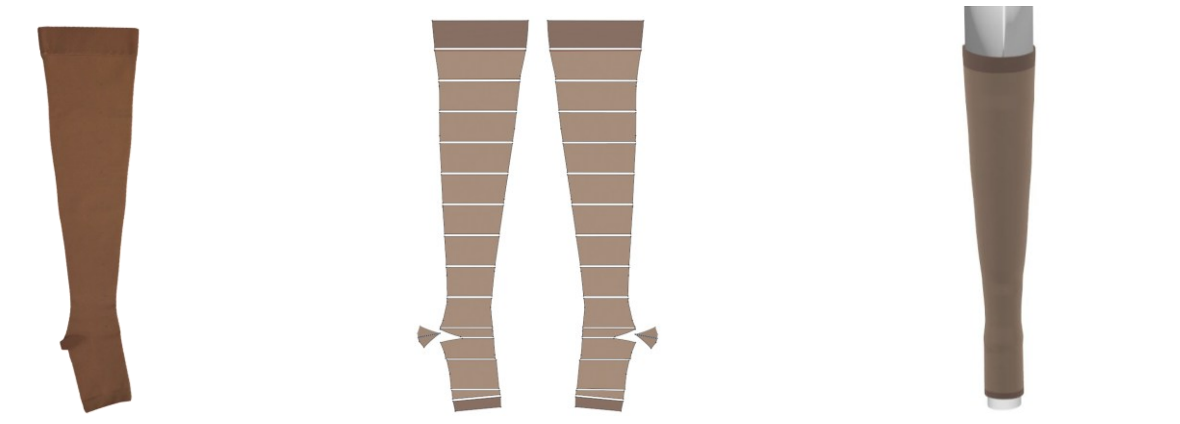
(a) (b) (c)

Figure 2: Measurement zones of soft tissue properties with the IndentoPro on the body (a) Compression areas, (b) and (c) Transferred compression areas to the leg with zone numbering

The material MAT_ELASTIC is used as the material for the simulation model. The density is set to 1.06E-9 t/mm³, and the Poissons number v = 0.495 to model incompressibility. The modulus of elasticity is adjusted until the experimental values agree with the modeled values. For example, the modulus of elasticity for zone B1 was calibrated to 56 kPa.

3.3. Modeling of the digital compression stocking

The digital compression stocking is modeled using the CLO3D clothing software. The advantage is that many clothing companies already use clothing software and changes to the design can be implemented quickly. In order to digitize the compression stocking, it was measured and transferred to CLO3D as a pattern. The stocking was then modeled as 3D geometry (Figure 3) and exported as a .obj file. This file can then be imported into LS-PrePost for the leg model.

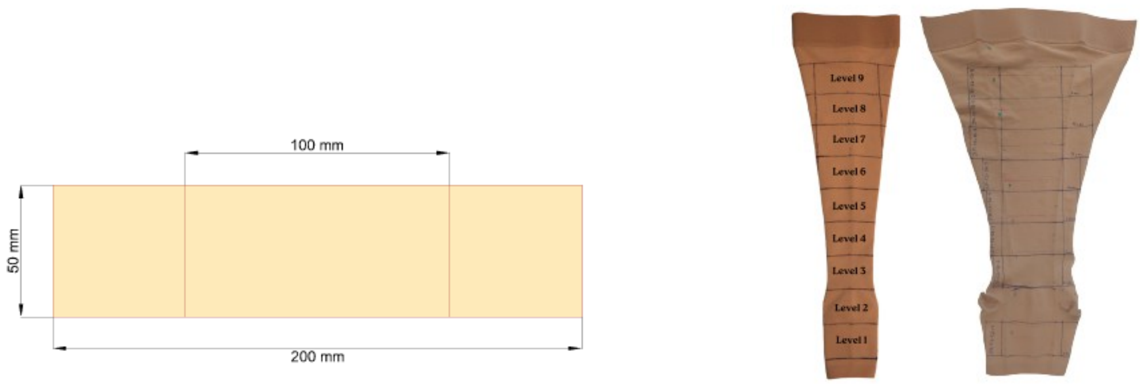


Original stocking Digitalized Pattern Digital (modelled) stocking

Figure 3: Digitization of compression stockings with CLO3D

3.4. Measurement of the material properties of the compression stocking and calibration of the simulation model

Cyclic tensile tests, thickness and density tests were carried out on the stocking. A compression stocking from Lastofa made of cotton in the compression class || and size 2 according to the International Organization for Standardization (ISO) standard 13934-1 for standard-sized textiles (Figure 4a). The 50 mm x 50 mm end areas are intended for placing and fixing the specimen in the terminals of the Universal Testing Machine (UTM), while the middle 100 mm area is the part of the stocking that was later subjected to the tensile test. Prior to carrying out the tensile test, the thickness of the stocking was measured on all sections using the Silvac 229 thickness gauge in accordance with ISO 5084. A 20 cm² disc and a pressure of 1 kPa was used. At least four measurements were taken for each layer of each stocking, and the mean thickness for each layer was calculated. These values were used to determine the total thickness of the entire stocking in the simulation model.



(a) (b)

Figure 4: Specimen preparation for the tensile tests of the compression stockings (a) specimen size, (b) specimen division on the compression stocking

The tensile test was carried out in accordance with the ISO 13934-1 standard. A preload of 0.2 N was applied and the test speed was set to 100 mm/min. The measuring length with a distance of 100 mm between the handles was approached for five load cycles up to an elongation limit of 100%.

3.5. Modelling of stocking-leg interaction

The stocking is put on by the method of thermal stocking from [32].

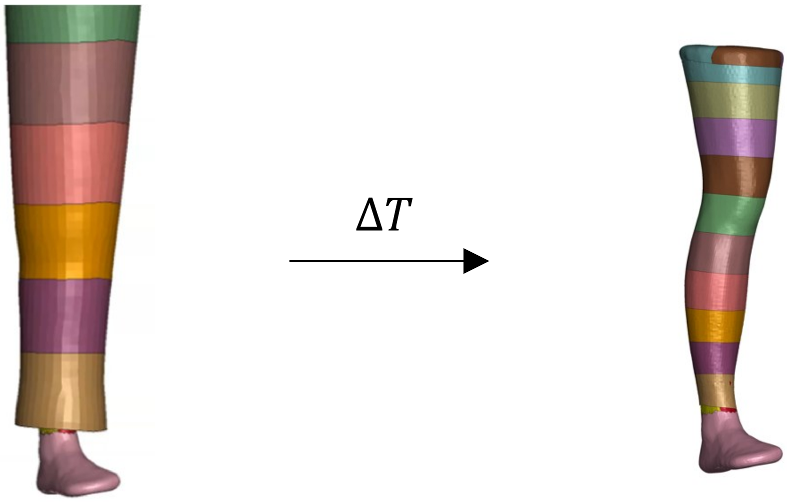


Figure 5: Tightening of the stocking according to the method of thermal shrinkage

4. Results

The following are the results of the modelling of an individual, deformable leg in interaction with a compression stocking.

4.1. Measurement of soft tissue parameters on the leg and calibration of the simulation model

In section 3.2, the measuring ranges for determining the soft tissue parameters of the deformable leg were presented. Figure 6 presents the experimental results of the areas B1-B4 as examples. It can be seen that a non-linear behavior of the soft tissue properties can be represented. In addition, it can be seen that various material properties can be measured. The harder shin area (B1, orange) has a much steeper curve rise than the softer calf areas (B2-B4, yellow, blue, grey). This confirms the usability of the IndentoPro for the determination of soft tissue properties.

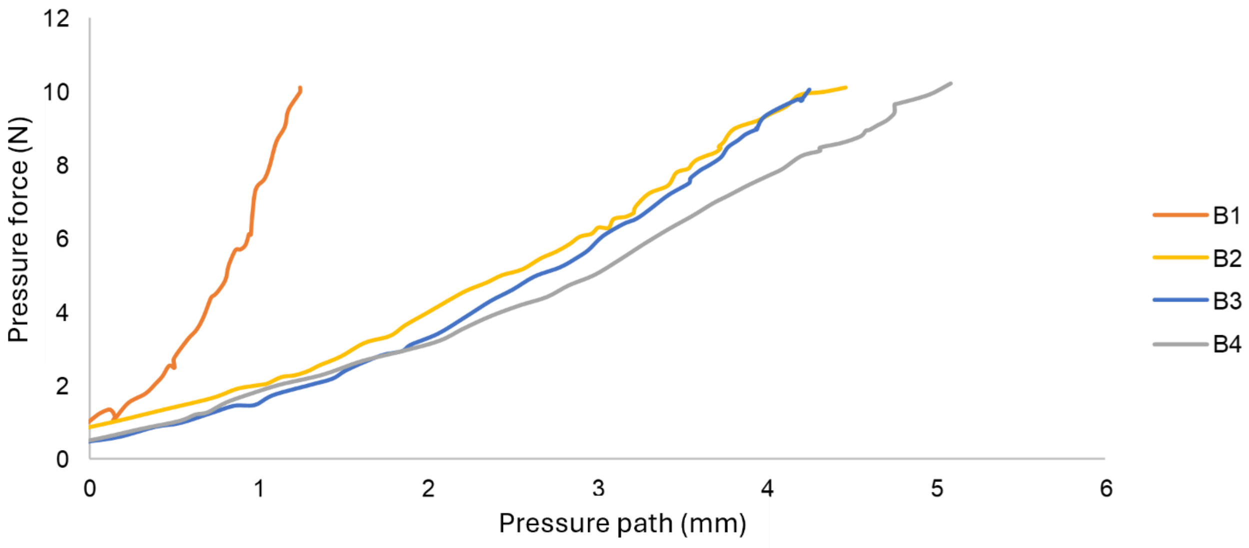


Figure 6: Measurement points and results to determine the material behaviour of the soft tissue of the leg

Leg calibration results are available in Figure 7 see. The stamp of the IndentoPro was remodeled as in [32] (Figure 7 left) and the force-displacement curve was exported (Figure 7 blue curve). It can be seen that there are deviations of the curves from an indentation depth of 2.5 mm. However, these are classified as negligible, as no high indentation due to the ankle is to be expected in the area of the leg. The other leg areas were calibrated equivalently.

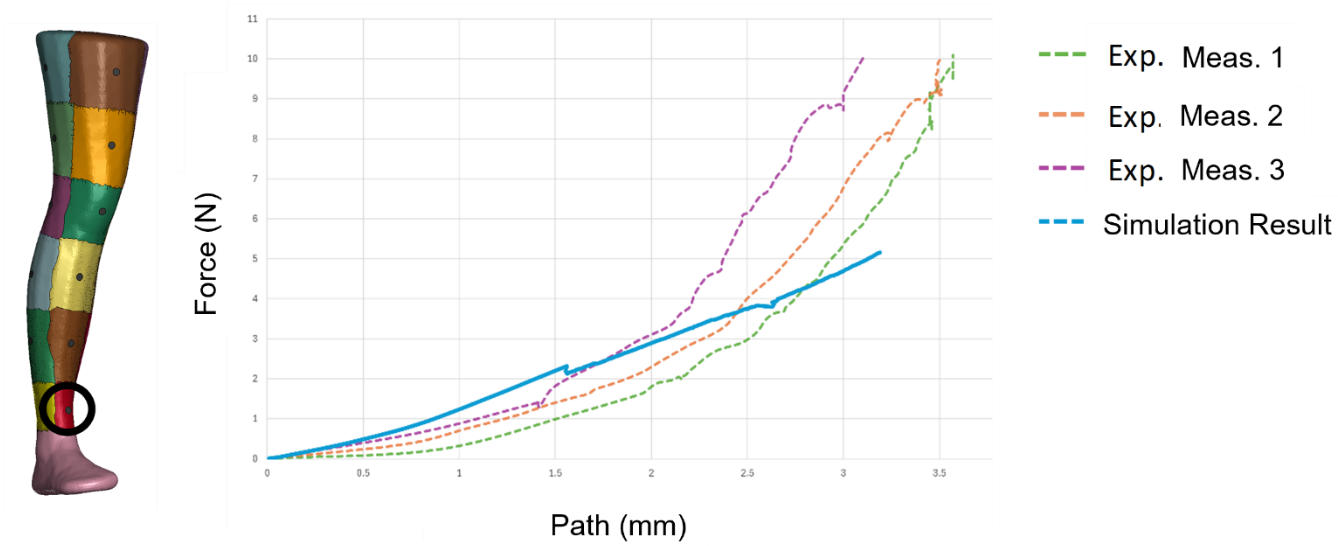


Figure 7: Leg material calibration based on the experimentally recorded IndentoPRO values of the soft tissue of the leg

4.2. Measurement of the material properties of the compression stocking and calibration of the simulation model

Results of the experimental thickness and density test are available in Figure 8 to. Changing thickness and density values can be seen depending on the stocking levels. These values are used to simulate the compression stocking.

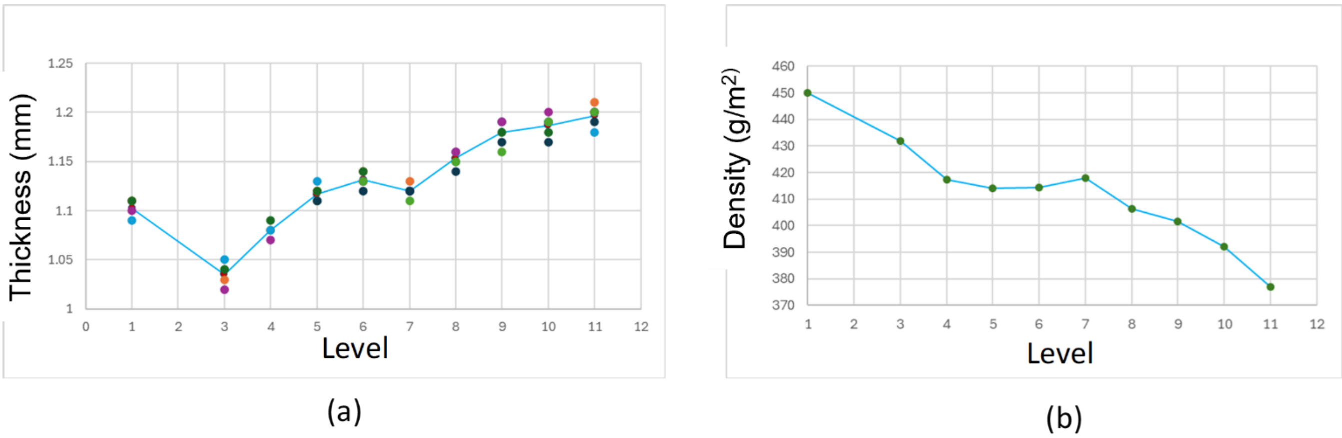


Figure 8: Test results of the thickness and density tests on the compression stocking specimens (a) thickness values, (b) density values

Figure 9 presents the results of the cyclic tensile test of cycle five for Level 1 and Level 9 in the loading phase. These results are used to calibrate the material behavior of the individual compression levels.

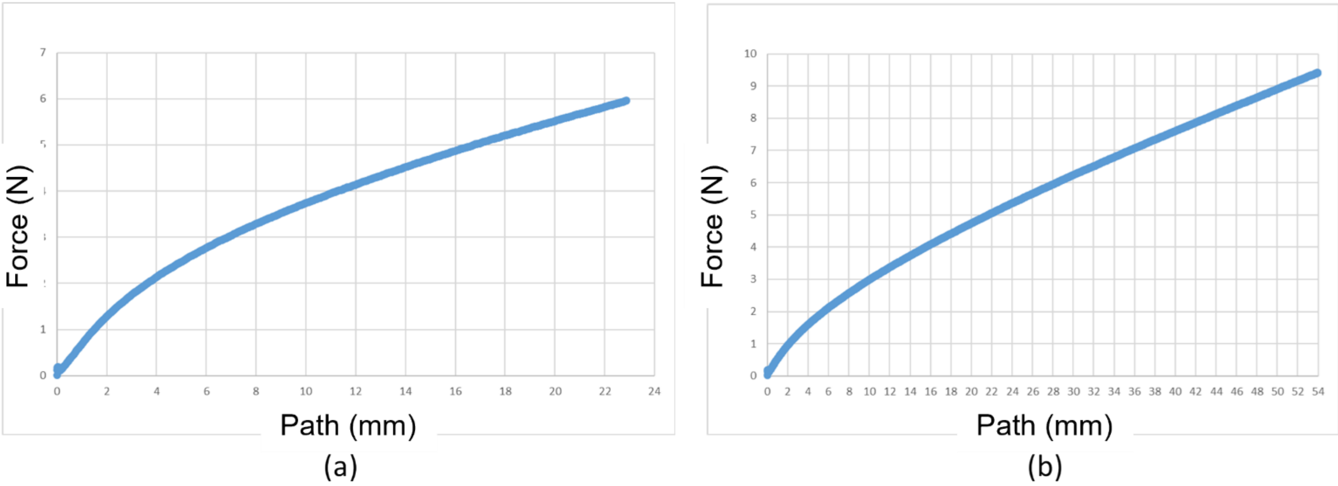


Figure 9: Test results of the tensile test on the compression stocking specimens for Level 1 and Level 9 (a) Level 1, (b) Level 9

After material calibration, the modulus of elasticity was set to 560 kPa for Level 1 and 425 kPa for Level 9.

4.3. Modelling the interaction between stocking and leg

Figure 10 shows the compression stocking on the left as it sits tightly on the deformable leg. This is a sign that the method used and the patterns developed lead to a realistic fit. In the coloured Figures (b) the pressure gradients on the leg can be seen. It can be seen that there is a higher pressure on the ankle (color: red-green) than on the upper thigh (color: green – blue). This is a realistic result, as compression socks are designed in such a way that the pressure to the upper thigh decreases. Furthermore, pressure peaks can be seen, e.g. on the ankle front. At this point, the bone is directly under the skin and has a harder material behavior. The higher pressure on the calf compared to the tibia is due to the radius of curvature. Overall, the results reflect a realistic behavior of the compression stocking in interaction with the leg.

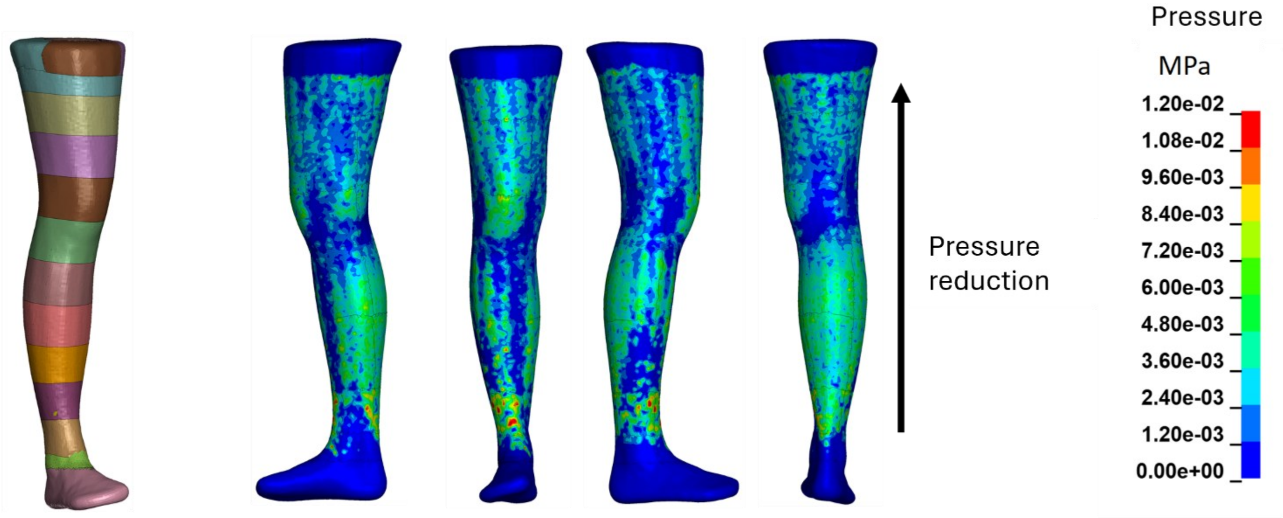


Figure 10: Leg Modeling – Compression Stocking Interaction

5. Transferability of the results to other application examples such as a technical object

The developed methods can also be applied to technical objects such as the interaction between a car cover and the foam. In car seat development, cut development, seam placement, and foam geometry development are still iterative. Simulation is beneficial in the development process to determine the foam hardness and final geometries before production and with fewer iterations. In Figure 11 is an example of checking a cutting pattern of a car cover for a given foam geometry. Figure 11a shows the car pattern. Figure 11b shows the car seat on the seat foam, modelled using the same method as in subchapter 3.5. Figure 11c shows the pressure distribution of the foam geometry, which is generated by the car cover. It can be seen that a higher pressure (red color) is exerted on the foam edges than on the surfaces. This is a realistic result.

(a) (b) (c)

Figure 11: Modelling the interaction of a car cover with a deformable seat foam (a) Cutting pattern of a car seat, (b) Draped car seat, (c) Pressure differences on the foam

6. Summary and discussion

Digitalization supports product development in industry. Market leaders are striving to physically produce only a third of all prototypes. This requires a realistic virtual representation of the clothing. So far, there have been good results in the simulation of off-the-body clothing, but there is still a considerable need for research in tight-fitting clothing. This clothing is often produced "below measure", which leads to deformations of the clothing and the person. This deformation of clothing and people must be realistically reproduced in order to enable digital product development.

In this paper, the method of [32] for the development of individual, deformable bodies in interaction with body-hugging/tensioning textiles is applied to the modeling of compression stockings. An individual, deformable leg is modelled and a compression stocking is put on it. The result is a realistic pressure curve on the leg, which provides information about the function and fit of the stocking. Based on this, material parameters and sections can be adjusted. In the following work, the aim is to reduce calibration times and increase user-friendliness, so that the benefits for micro, small and medium-sized enterprises (SMEs) are further increased.

In the development of technical textiles, too, a modelling of soft moulded bodies with deforming textiles can be seen. In the area of the upholstery, the upholstery fabric interacts with the foam bodies. For a digital development of the foam geometries and cover cuts, it is necessary to represent the deformation of the foam and the cover in its interaction digitally and realistically. Initial tests also show a transfer to a technical object such as the car seat.

Author Contributions

Ann-Malin Schmidt: conceptualization, methodology, investigation, writing – original draft preparation, writing – review and editing, project administration, Ingrid Peraza: validation, investigation, data curation Jana Siegmund: investigation, funding acquisition, Yordan Kyosev: supervision and editing.
All authors have read and agreed to the published version of the manuscript.

Acknowledgements

Gefördert durch:
Bundesministerium für Wirtschaft und Klimaschutz
aufgrund eines Beschlusses des Deutschen Bundestages

Acknowledgements: The IGF project 22435 BR of the Forschungsvereinigung Forschungskuratorium Textil e. V., Reinhardtstr. 12-14, 10117 Berlin, was funded by the AiF as part of the Programme for the Promotion of Industrial Collective Research (IGF) by the Federal Ministry for Economic Affairs and Climate Action on the basis of a decision of the German Bundestag.

Conflicts of Interest

The authors declare no conflict of interest.

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