Approach for Digitising the Softness of Human Tissue for Implementation in 3D Soft Avatar Clothing Simulations

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Abstract

Patterns are virtually simulated in 3D CAD programs before production to check the fit. However, achieving lifelike representations of human avatars, especially regarding soft tissue dynamics, remains challenging. This is mainly since conventional avatars in garment CAD programs are simulated with a continuous hard surface and not corresponding to the human physical and mechanical body properties of soft tissue. In the real world, the human body's natural shape is affected by the contact pressure of tight-fitting textiles. To verify the fit of a simulated garment, the interactions between the individual body shape and the garment must be considered. This paper introduces an innovative approach to digitising the softness of human tissue using 4D scanning technology. The primary objective of this research is to explore the interactions between tissue softness and different compression levels of apparel, exerting pressure on the tissue to capture the changes in the natural shape. Therefore, to generate data and model an avatar with soft body physics, it is essential to capture the deform ability and elasticity of the soft tissue and map it into the modification options for a simulation. To aim this, various methods from different fields were researched and compared to evaluate 4D scanning as the most suitable method for capturing tissue deformability in vivo. In particular, it should be considered that the human body has different deformation capabilities depending on age, the amount of muscle and body fat. In addition, different tissue zones have different mechanical properties, so it is essential to identify and classify them to back up these properties for the simulation. It has been shown that by digitising the obtained data of the different defined applied pressure levels, a prediction of the deformation of the tissue of the exact person becomes possible. As technology advances and data sets grow, this approach has the potential to reshape how we verify fit digitally with soft avatars and leverage their realistic soft tissue properties for various practical purposes.

Keywords: 4D body scanning, soft body physics, soft avatar, biomechanics, 3D simulation

1. Introduction

The material properties are decisive in clothing technology to fulfil the intended use of the textile. The physical characteristics of the material not only impact its functionality and appearance but also greatly influence the fit and comfort of the final textile product. In garments designed to fit tightly or have a compression effect, the contact pressure between the individual and the fabric becomes a decisive factor in evaluating the fit, functionality, and overall quality of the product. [1] While conventional computer-aided design (CAD) programs for clothing offer the ability to assess fit through 3D simulations, it is important to note that these programs typically simulate avatars with rigid surfaces. However, for an accurate evaluation of the fit of tight-fitting garments, it is also essential to consider the mechanical properties of the individual for whom the product is being developed. [2] Therefore, this study aims to search for methods that capture the softness of human tissue and, most importantly, to digitise the ability of human tissue to be deformed to evaluate the influence of the garment on the shape of the wearer's body. First, the soft tissue characteristics of the human body is stated since it should be noted the body is composed of different muscle, fat, and other tissue zones, as well as bone and skin. Following different methods for recording the deformation possibilities, the soft tissue in vivo is researched. Subsequently, the selected method is then applied to finally translate the softness values into Blender for a soft avatar simulation.

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1.1. Related Work

There has been a growing interest in developing soft avatars for clothing fit simulations in recent years. This emerging field has attracted researchers from various disciplines, including computer graphics, computer vision, and biomechanics. Several studies have been conducted to explore different aspects of soft avatars and their applications in clothing fit simulations.

One notable paper in this area is “Learning nonlinear soft-tissue dynamics for interactive avatars” by Casas and Otaduy [3]. The authors comprehensively review the existing techniques and methodologies for creating human body models. Here an innovative method for improving vertex-based human body models by integrating soft tissue dynamics is presented. The newly proposed model is trained to forecast 3D shifts per vertex, termed dynamic blend shapes, which mimic non-linear mesh deformation effects reliant on pose information. This technique facilitates the creation of lifelike 3D mesh animations, encompassing soft tissue influences, by solely utilising skeletal motion data.

The paper “Fitting Close-to-Body Garments with 3D Soft Body Avatars” from Harrison et al. [4] introduces VitalFit, an end-to-end system for predicting the fit of close-to-body garments using soft body avatars. VitalFit combines tetrahedral mesh-based soft avatars with finite element simulations by using a generalized Rivlin-type polynomial model, enabling designers to evaluate garment fit and deformation in various activities through a plugin for Adobe Illustrator®.

The paper “Applications of Using 4D Scanning Technologies in Biomechanics” from Helios De Rosario et al. [5] investigates human movement analysis using 4D data, creating reference distributions from the CAESAR database for body segment volumes and mesh vertices connected to anatomical landmarks. The study explores lower limb asymmetry in a 10-year-old child and compares it with reference data. The research demonstrates the potential of 4D scanning for assessing volumetric asymmetries and offers new opportunities in biomechanics.

In the study “A 3D Biomechanical Model for Numerical Simulation of Dynamic Mechanical Interactions of Bra and Breast during Wear” Y. Li et al. [6] introduce a 3D biomechanical model of the female body with elastic breasts and a rigid body, considering bra-material linearity and geometric non-linearity. The contact between the body and bra is represented as a dynamic sliding interface using contact mechanics theory. Finite Element Method (FEM) is employed to solve the dynamic contact problem, and the model’s simulation results demonstrate accurate predictions of bra pressure and stress distributions during body movement, exhibiting a reasonable match with experimental measurements.

1.2. Soft Avatars in Clothing CAD

The time factor is decisive in the field of CAD technology for the simulation of clothing for testing the fit. A garment simulation should take as little time as possible, as it is used to visualise and optimise the development. It is always important to find an efficient compromise between the accuracy of the simulation and the time required when it comes to simulating a textiles fit in the development phase. The decision on how accurate the calculations behind the simulation must be varies greatly depending on the industry and the product. Clothing can be produced, sold and worn with minor deviations between simulation and reality, which would already create an unacceptable risk in the case of simulations for the automotive or medical industry. This also explains the use of FEM in areas where the accuracy of the simulation is crucial. However, an FEM simulation, as is always used in the investigations listed under related work, would be very time-consuming and cost-intensive for clothing. The programmes CLO3D and VStitcher each have soft avatars in their programmes, but it is to be noted that the mechanics behind these are not known. First, investigations have shown that the distortions show angular and unnatural deformations under strong pressure. [7]

2. Soft Tissue

2.1. Histology

Histology is an elementary discipline in the field of biology that deals with studying the complex microscopic structure of tissues and cells. Tissues, which consist of organised collections of cells, work together to perform various specific functions in the human body. A deep understanding of the different types of tissues in the human body and their mechanical properties is paramount to developing a realistic soft-body physics model. There are four main types of tissues in the human body:

- Epithelial tissue envelops the external and internal surfaces of the body as well as lines the organs and cavities within and plays a crucial role in safeguarding the body against both external and internal stressors. Additionally, it actively regulates the exchange of substances between the body and its surrounding environment.

- Connective tissue known as the fascia system provides support and structure to the body. It is found in the bones, cartilage, tendons, ligaments, and other organs. This refers to a three-dimensional network of soft, collagen-containing, loose and dense fibres of the connective tissue.
- Muscle tissue is responsible for movement in the body. It comprises cells called muscle fibers that contract and relax to move. A distinction is made between straight and smooth muscles.
- Nervous tissue is in control of transmitting signals throughout the body. It is found in the brain, spinal cord, and nerves. [8, 9]

Each tissue category possesses distinct mechanical characteristics crucial for its physiological role within the organism. For instance, epithelial tissue exhibits a slender and pliable nature, allowing it to bend and stretch in tandem with bodily movements. Conversely, connective tissue manifests robustness and rigidity, furnishing the body with support and structural integrity. On the other hand, muscle tissue demonstrates elasticity and the ability to contract and relax, facilitating efficient movement swiftly. Lastly, nervous tissue showcases delicacy and sensitivity, enabling the precise transmission of signals. [10, 11]

Comprehending the diverse categories of tissues within the human body and their anatomical composition is imperative in developing a precise virtual representation. For instance, adipose tissue possesses a malleable and flexible structure that contrasts with muscle tissue’s firmer and more resilient nature. The mechanical attributes of tissues determine their reaction to external forces, including compression or tension. Proficiency in tissue mechanics, encompassing elasticity, viscosity, and stressstrain relationships, is indispensable in creating a virtual representation that accurately replicates the deformation of authentic human tissue when subjected to pressure from clothing. [12, 13] From a technical perspective, allocating garment sizes to human bodies is based on assessing body length and girth measurements. However, it is essential to note that histological variations among individuals play a crucial role in determining the deformability of bodily tissues. The relative proportion of body fat to muscle mass is a critical determinant in the elasticity of the soft tissues, which are subjected to pressure from the textile material. [14]

2.2. Mechanical Properties

Simulating a soft avatar for clothing fit check simulations requires incorporating various mechanical properties characteristic of human soft tissues whose hyperelasticity can be described by the Ogden material model. [15] The following are some of the key mechanical properties that need to be considered:

- Elasticity: The ability of a material to deform under stress and then return to its original shape when the stress is removed is called elasticity. Human soft tissues, such as muscle and adipose tissue, have high elasticity, allowing them to stretch and recoil during movement.[16]
- Viscoelasticity: Human soft tissues also exhibit viscoelastic properties, meaning they have both viscous and elastic behaviour. They can deform and then return to their original shape but exhibit time-dependent deformation and stress relaxation.[17]
- Plasticity: When subjected to excessive stress or strain, human soft tissues can also undergo permanent or plastic deformation. For example, excessive force on adipose tissue can cause it to rupture or deform permanently.[18]
- Nonlinear behaviour: Human soft tissues exhibit nonlinear behaviour, meaning their mechanical response to stress or strain is not always linear. For example, the stiffness of muscle tissue increases as it is stretched beyond a certain point.
- Anisotropy: Human soft tissues have different mechanical properties depending on their loaded direction. This is called anisotropy. For example, muscle tissue is more elastic in the direction of its fibres than perpendicular to them. [19]

2.2. Testing Methods

Multiple methods exist for assessing the mechanical characteristics of human soft tissue. These properties are determined by tensile strength, elongation, elasticity, Young’s modulus, and bending stiffness. These parameters are crucial for accurately representing tissue in digital reconstructions. Note that each tissue type requires a distinct testing approach, and obtained values only apply to the tested individual. Some studies use simplified models based on 3D scans and MRI to identify tissue regions. In these models, bones are rigid bodies, while soft tissue is approximated as linearly elastic, homogeneous, and isotropic, with directional dependence. [20] In FEM human modelling, the HUByx model by Altair is a notable example. It is based on CT scans, incorporating organs, skeleton, and

material behaviour from literature. Primarily for ballistics research, this FE model simulates bones, organs, and fluids and focuses on replicating ballistic impacts on the torso. [21]
An alternative method to assess tissue softness for simulations is using a standardised technique to detect yielding. This is done by applying contact pressure using a specialised apparatus designed for this purpose. Notable devices for this include the 'Tissue Elastomer' and the technology developed by VitalFit, which can capture in vivo properties.[4] The paper "The human touch: measuring contact with real human soft tissues" from Dinesh K. Pai et al. [22] presents a novel handheld device for the direct measurement of mechanical properties of the human body, addressing the intricate challenge of simulating human body deformation in interactions with external elements. Through the introduction of a comprehensive pipeline encompassing measurement, modeling, parameter estimation, and finite element simulation, including the proposal of the sliding thick skin model, the study provides insights into the realistic behavior of the human body.
The measurement of the mechanical properties of soft tissue in vivo presents a unique challenge, as the conventional method of testing can only be performed on tissue samples obtained from a subject. However, 4D scanning and motion tracking techniques are employed to record the potential movements of bodily tissues. These methods enable the capture of deformations in the body during motion or while wearing tightly-fitted clothing, compared to the subject's static image or natural shape. This approach draws inspiration from animation, where a realistic dynamic body shape can be simulated using a second-order auto-regressive model. This model utilises previous deformations to predict soft tissue deformations. [23]
The most pragmatic and non-intrusive approach to generating a soft avatar for simulating the deformation characteristics of soft tissue under the influence of clothing in fit testing is by employing modelling techniques based on scans. This approach allows for precise determination of the soft avatar's geometry of various tissue structures.

3. Experimental Setup

A female participant was chosen to conduct the initial set of experiments. The surface area of the test person's body was captured using a three-dimensional scanner. The scan was conducted while the participant was in a state of relaxation. To ensure consistency in calf circumference measurements and prevent any influence from muscle contractions, both legs were positioned firmly and hip-width apart on the floor during the scanning procedure. The recordings of the calves in this stance served as the baseline for the development of compression-free test socks.

Pattern construction based on UV-Mapping: The test stockings were developed based on the 3D surface of the participants' calves, aiming to achieve compression levels close to zero. Utilizing the surface development technique resulted in a superior fit compared to the traditional pattern construction method [24]. The prevention of fit inadequacies is particularly crucial in the design of the test socks, as it helps to eliminate measurement errors caused by uneven compression.
The subsequent definitions of fit for test stockings were defined:

- Every point of the fabric must correspond to a point on the body.
- In the digital fit evaluation, stretching is permissible and should be evenly distributed.
- The tension in the material should exhibit minimal variations across the calves.

The socks used for testing purposes were created with a highly flexible knitted material, which required the implementation of geometric mapping algorithms to create the design. In this method, each point on the socks' three-dimensional surface was assigned a corresponding two-dimensional coordinate. Therefore, we used LSCM (Least squares conformal map) Algorithm to create the corresponding UV Map as a Pattern [25]. For verification of the suitability of the test stockings, the Software CLO3D [26] was used. The avatars representing the initial 3D models of the individuals were utilised, and the actual material properties were assigned as physical parameters. To enhance the accuracy of the outcomes, a non-linear simulation was conducted with a particle distance of 5mm.
During digital fitting, the influence of the seam line was not considered. Given that a highly elastic 4 thread - 2 needle overlock stitch was used in the physical assembly process, this can be neglected for the digital fitting. Upon careful examination of the pattern, it becomes clear that during the initial digital fitting, the flattened pattern effectively guarantees a uniform distribution of pressure, as intended in Figure 1. The identification of prominent pressure points serves as confirmation that the goal of achieving complete contact between the fabric and the entire body has been successfully achieved. The strains that arise within the material remain within the initial strain of the specifically chosen material, thereby exerting no impact on the intended tests.

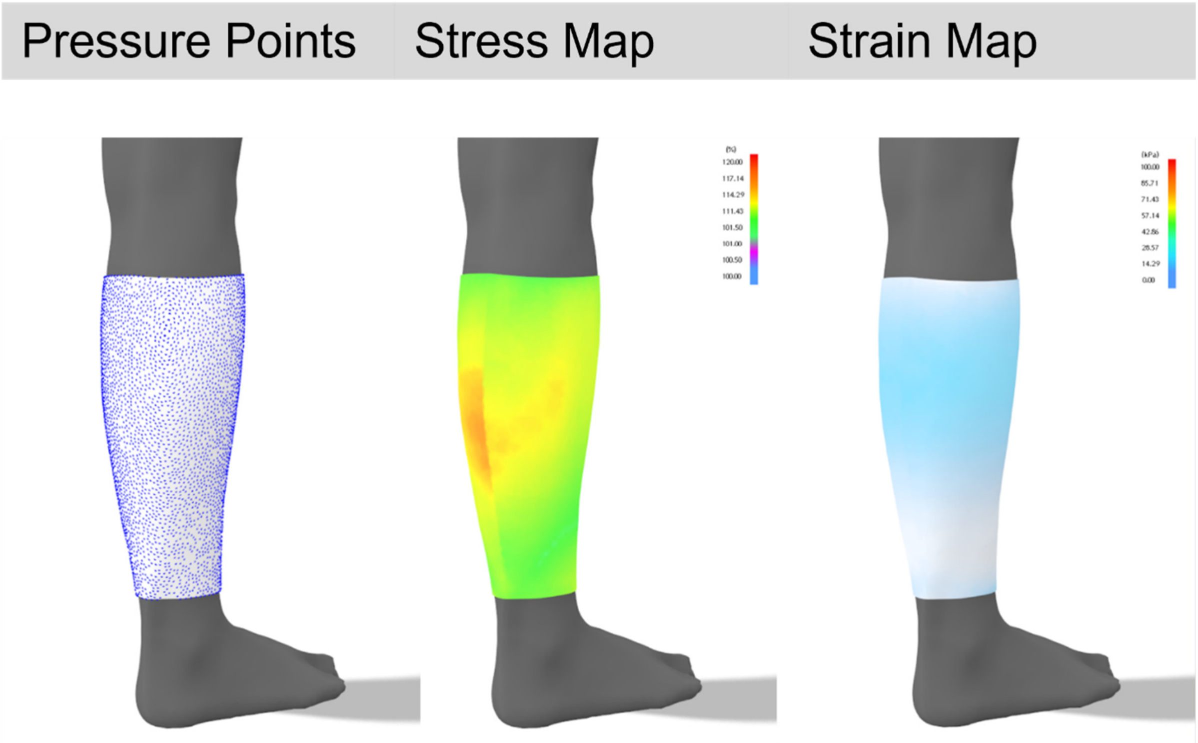

Figure 1 Fit evaluation of test pattern without ease: Pressure Points, Stress Map, Strain Map

Negative ease: The generated basic pattern was then provided with three different levels of negative ease, so three load cases could be produced. For this purpose, the flattened pattern was reduced in the warp-direction by -10, -20, and -30%, respectively. After the construction of the patterns, they were cut and sewn for the experiment. For this purpose, an elastic white material made of 100% polyamide was used.

4D Scanning procedure: For the digital recording of the test persons' tissue dynamics under 0 and 3 different pressure levels, the 4D scanning procedure is an advanced method of capturing and displaying 3D objects over time. Unlike traditional 3D scanning, which provides a static image of an object, 4D scanning technology captures the spatial structure of the object in motion or change. This enables a more accurate representation of dynamic processes, shape changes and movements. [27] For this study, the test subject was recorded without and with the three different compressing stockings in A-Pose, each with a variable degree of reduced width.

4. Evaluation and Digitisation

The measurement test carried out deals with the change of calf circumference under different conditions for one test person. The measurements were taken at different heights of the calf cross-section.

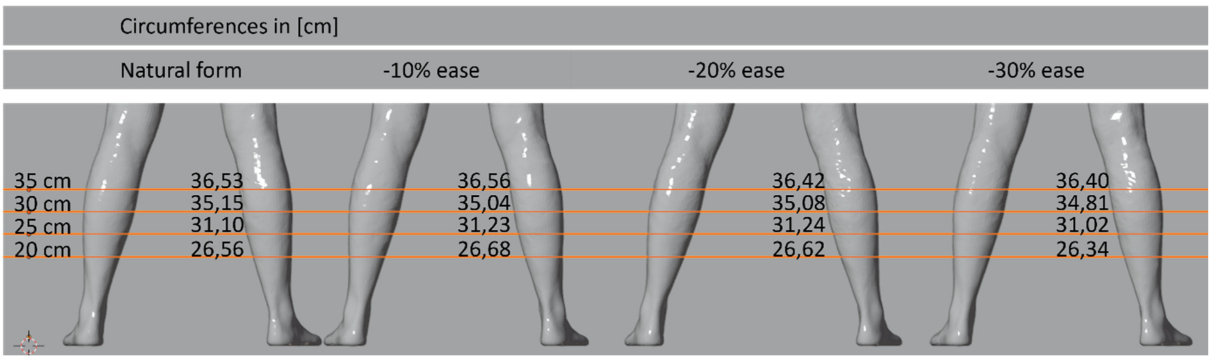

Figure 2 Measurement Height Levels

They were starting at 20 cm from the base level in 5 cm increments up to 35 cm above the baseline level of the scans, as documented in table 1:

Table 1 Measurement Circumferences Scanning Experiment

Measurement Height [cm]	Natural form in [cm]	Negative ease - 10% in [cm]	Negative ease - 20% in [cm]	Negative ease - 30% in [cm]
20	26,56	26,68	26,62	26,34
25	31,10	31,23	31,24	31,02
30	35,15	35,04	35,08	34,81
35	36,53	36,56	36,42	36,40

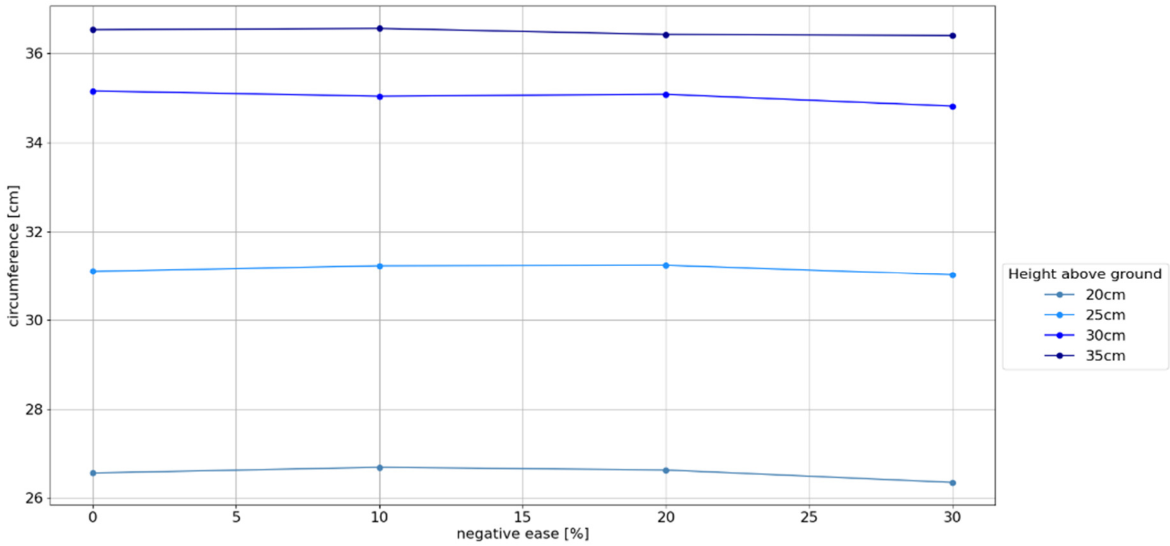

Figure 3 Course of the measurements of the 4 height levels at different compression levels

The partial increase in the data, as seen in figure 2, shows that the compressing clothing partially displaces the non-compressible tissue, which also explains an increase in the location of the measurement, and the water balance of the body can also be an influencing factor here.
Using the measured deformation response from the experimental test, the parameters of the Ogden model can be calibrated to represent the material's behaviour under different loading conditions. The strain energy potential function W describes the hyperelastic Ogden material model. For the n-th order Ogden model, the strain energy potential function is given by:

$$W = \sum_{i=1}^{n} \frac{\mu_i}{\alpha_i} \left(\lambda_1^{\alpha_1} + \lambda_2^{\alpha_1} + \lambda_3^{\alpha_1} - 3 \right) \quad (1)$$

This data-driven approach allows the formulation of a mathematical representation of the mechanical response of the material's hyperelasticity, which enables the prediction of deformations and stress distributions. By integrating the Ogden model with the collected data, the formula can be used to generate and apply the material parameters for our simulation. This contributes to a deeper understanding of how a garment might deform the participant's calf. The Lambda values are calculated from the experimental data, this is done by dividing the measured values of the experiment of the individual load cases by the measurement of natural form:

Table 2 Calculation Lambda Principal Strain Ratios from the Experiment

Lambda Calculation	Negative ease -10%	Negative ease -20%	Negative ease -30%
λ	2,001601325	2,00051055	1,994059806

The calculated values for the principal strain ratios can then be digitised in Blender and entered into the Ogden material model. In order to be able to use the capabilities of Blender for the simulation of a soft avatar with human mechanical properties and to be able to digitise own experimental data, a tissue calculator was developed that integrates the Ogden material model specifically for this experiment.

This process involved integrating the mathematical formulations of the stress-strain relationship of the Ogden model into the Blender framework. A user interface was developed that allows users to define the required material parameters and select the appropriate conditions for their specific simulation scenarios. For example, basic values researched from the literature [21, 28] are stored for α and μ and the λ values can be used. Here α represents the tensile strength of the tissue components. It describes the ability of the tissue to respond to stretch with tension and maintain its shape. In the Ogden model, the symbol μ represents the stiffness inequality of the tissue components. It describes the deviation of the strain response between the different tissue layers or components in the material.
The add-on interacts with the existing Blender physics engine and allows users to apply Ogden material properties to their simulated objects to more accurately replicate real-world deformations. In contrast to Blender's conventional soft-body physics, this constructed add-on offers an approach that takes into account an important criteria: the incompressibility inherent in human soft tissue. This consideration is consistent with the biomechanical reality that human soft tissue has minimal compressibility, which is critical to achieving accurate simulation results. As shown in figure 3, the material parameters calculated in the add on can then be applied to the leg, here in orange as the selected object, to create the soft body material.

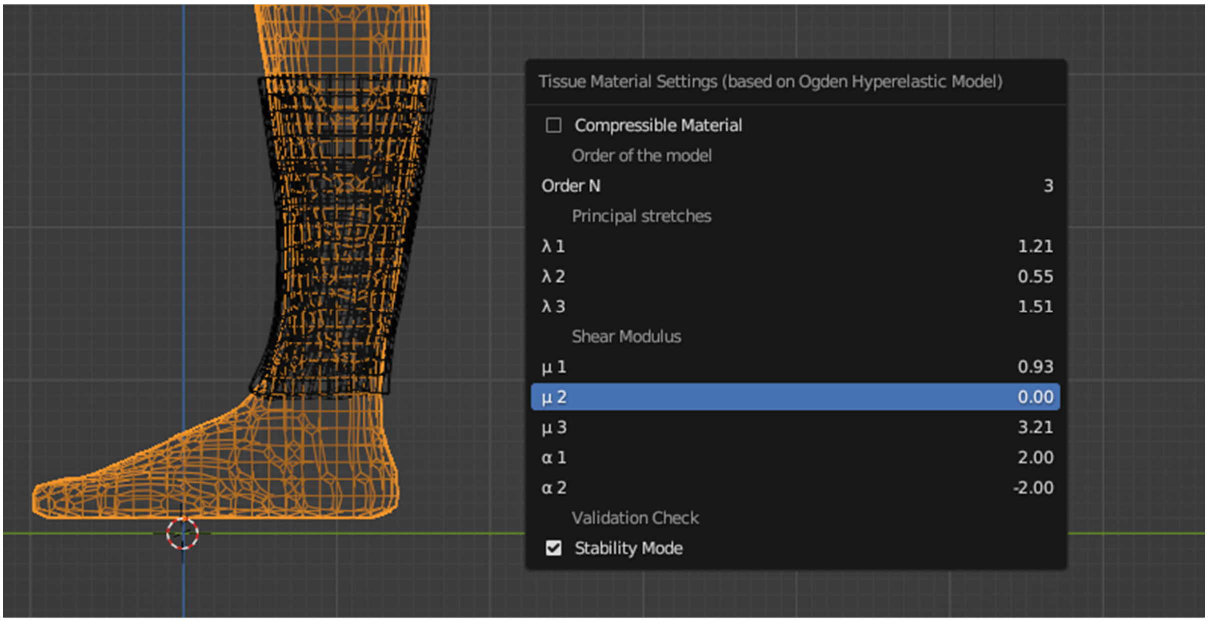

Figure 4 Ogden tissue settings

5. Results

We conducted a analysis utilising 4D scans paired with varying levels of compression stockings. By meticulously examining the deformations and changes in calf circumference resulting from different pressure levels, we successfully derived the principal strain ratios indicative of tissue softness. Furthermore, we developed a purpose-built Add-On for the Blender software, tailored to calculate deformation energy based on the Ogden model.
This novel tool allows the input of experimental strain data and subsequently simulates deformable tissue material within the Blender environment. Our findings offer valuable insights into the mechanical behavior of soft tissues under compression, providing a means to assess their response to varying pressure scenarios. The developed Add-On not only extends Blender's capabilities but also facilitates simulation of complex soft tissue mechanics, furthering our understanding of the interaction between the human body and tight-fitting clothing.

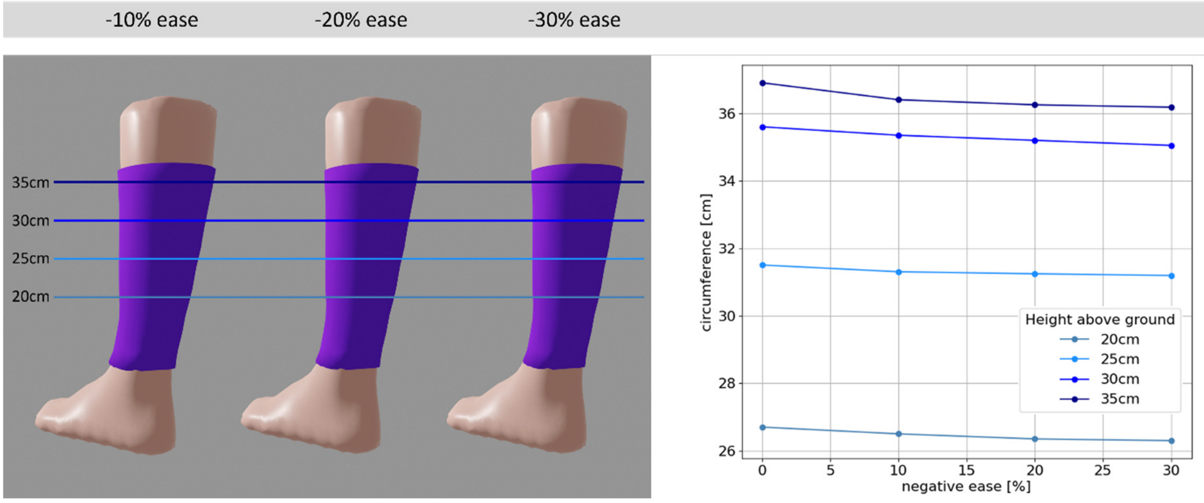

Figure 5 Simulation in Blender. From left to right: 10%, 20%, 30% negative ease

To validate the calculations of the softness parameters for the avatar's calf using the newly developed add-on, the test previously carried out in real life was repeated as a simulation. As shown in Figure 4, the calf was provided with the material parameters calculated by the add on and then the pattern was simulated with the different pressure levels. The simulation results reveal a continuous slight decrease in calf circumference when pressure is applied, whereas in the real test there was sometimes a slight increase or decrease. This apparent discrepancy between simulation and real test performance may occur due to the inherent incompressibility of human tissue, often resulting in a shift in tissue volume. Importantly, the simulation nevertheless provides valuable insight into mechanical behaviour, while not fully capturing real-world challenges such as varying factors and individual tissue responses.

5. Conclusion

In conclusion, the advancements in 3D CAD simulations have paved the way for more accurate and lifelike representations of human avatars, particularly in soft tissue dynamics. The innovative use of 4D scanning technology to digitise human tissue softness offers a promising approach to understanding better and simulating the interactions between apparel and the human body. By capturing the details of tissue deformability and elasticity, we can achieve a more realistic simulation that considers individual bodies' unique properties. This allows an actual analysis of the garment's fit to be performed digitally.
Above all, the aspect of speed of such a simulation serves to shorten the development time of closefitting garments. However, a notable limitation of the method presented is its specificity to the individual being scanned. While the approach can provide highly accurate results for that particular individual, it may not necessarily be generalisable to a broader population. For this it would be necessary to carry out a very large row of measurement surveys. The variations in deformation capabilities based on age, muscle mass, and body fat further accentuate this limitation. Nonetheless, as technology continues to evolve and our data sets expand, there is immense potential to revolutionise how we approach digital fit verification using soft avatars. This advancement offers a significant potential to replicate real-life deformations more accurately and to improve the precision of virtual fit testing. Future endeavours should focus on expanding the data set to encompass a more diverse range of individuals, ensuring a more holistic and inclusive simulation process.
It should be noted, however, that the water balance in the body shifts and thus the circumference of the calf can change by centimeters, depending on the status of the water in the body. The timing of the measurement is crucial for the water balance condition of the lymphatic system.
A 3D scanner can also be used for the research, but this research serves as the basis for the research of the impact after a jump. Based on this, the tissue movement is to be recorded and digitized. Therefore, the leg had to be scanned during the jump, the impact cannot be captured with a 3D scanner.

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