COMMUNICATIONS IN
DEVELOPMENT AND ASSEMBLING OF TEXTILE PRODUCTS

Development of an elastic leg model for textile product optimization

Summary of the IGF research project 01IF23104N

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INFO

CDATP, ISSN 2701-939X
Communication
2026, Vol. 7, pp. 68-75
https://doi.org/10.25367/cdatp.v7.a246
Received: 25 June 2026
Accepted: 25 June 2026
Available online: 29 June 2026

Keywords
Compression, Compression stockings,
Product development,
Pressure measurement,
Quality control,
Soft tissue, Elasticity

ABSTRACT

The development of modern compression products involves assessing the appropriate product design, the correct level of medical or sports compression, and ensuring an acceptable level of comfort. As part of the 'Elastic Leg Model' research project, a novel system for evaluating all these parameters was developed. This paper presents a summary of the results of this project.

1 Introduction

Venous disorders, particularly in the legs, are a widespread condition in Germany. Only 10% of the population show no signs of the condition, whilst as many as 59% of the total population display visually noticeable symptoms, such as spider veins [1]. Over 2.8 million patients suffer from advanced stages of the condition and are, amongst other things, reliant on consistent compression therapy. A significant part of this involves the use of medical support and compression stockings. These are subject to high functional and quality standards, such as DIN 58133 and RAL GZ 387. In addition to the functional aspect, comfort during use is a key criterion for the adoption rate and the correct wearing of the hosiery, and is therefore essential for therapeutic success. To date, comfort has often been assessed via company-proprietary subject tests rather than in test rigs that comply with standards. In terms of test rigs, compression measurements using rigid leg geometries (MST Professional Mark IV [2]) or via multi-segment tensile testing (HOSYcan [3]) represent the state of the art and describe the applied compression in a fixed position in accordance with the standard. As a result, the effects of movement, such as creasing, or comfort parameters cannot currently be recorded or evaluated. Particularly in view of the increasing use of compression textiles in occupational settings and in sport [4], dynamic measurement and a quantifiable assessment of comfort are also gaining importance in non-medical contexts. This is essential to ensure the achievable success of compression therapy for patients, so that the socks are viewed not merely as a medical necessity, but as a comfortable aid.

2 State of the art

2.1 International State of the art

Medical and non-medical compression garments are subject to high quality standards, which must be ensured both during product development and subsequently in the production process. Testing using suitable apparatus is therefore essential. The HOSY device from Hohenstein is currently widely used for this purpose. The compression stocking to be tested is clamped into the apparatus and a tensile force is applied, which then provides information on the compression force and its profile. An alternative to this is the Swisslastic device, which is based on the standard (see Figure 2). To carry out the test, the stocking is pulled over a static leg model and pressure sensors are used to measure the compression and its distribution. The methods used to date are static and, due to their crude model-like nature, can only replicate individual patients' legs with great difficulty. These methods fail to take into account the patients' movements, the dynamics in the joints and many other aspects, such as how the stocking is put on. In terms of comfort, the 'Sherlock' manikin provides a measuring device for thermal comfort that closely approximates leg geometry. A stocking fitted onto the manikin can be tested in several positions, as this testing device allows for movement of the leg joints. However, this measurement method does not provide any information about the compression effect. Furthermore, the measurement methods do not allow conclusions to be drawn about ergonomic wearing comfort, which is influenced by multiple factors. Another aspect of existing measurement methods is the failure to account for the mechanical deformation of human tissue resulting from compression. In practice, this means that compression stockings may fall within the specified compression limits, yet the wearer may still find the actual comfort of the stocking unpleasant. In the past, this has led to customer dissatisfaction and complaints, for example due to an unsatisfactory fit. Approaches to solving this problem already exist in the field of prosthetics, which realistically attempts to replicate human tissue and skin, and in the additive manufacturing of phantoms with heterogeneous material properties for radiology training.

Various thermophysiological investigations into footwear, particularly the shoe/sock system, have been carried out using simulation units, such as SWEATOR and CYBOR. The human foot is modelled by a rigid, immobile test specimen with a perforated or semi-permeable surface [5,6]. The application of heat and moisture to the sock, or to the sock/shoe system, takes place under static conditions. To investigate and evaluate ergonomic aspects, such as fit and creasing, which only become apparent during movement, it was necessary to rely on various human trials involving wear tests on instrumented test subjects during walking and running trials, as well as field studies with complex experimental designs. Additional material tests established a correlation between pressure load, moisture transport and skin/sock friction, which was then compared with the test subjects' subjective assessments of the thermophysiological and ergonomic effects. This knowledge of the mechanisms of action identified in socks is very helpful for the planned investigations regarding the positioning and integration of suitable sensors, e.g. for temperature and moisture, into the elastic and flexible leg assembly to be developed. Using the numerical and physical simulation model for a lower limb, in future it should be possible to carry out tests on socks and knee-to-ankle stockings in both static and dynamic conditions, significantly reducing or even eliminating the need for human subject trials.

2.2 Our own preparatory work

The Chair of Development and Assembly of Textile Products at ITM has many years' experience both in the field of processing textiles to meet specific performance requirements and in purely digital product development. Extensive preliminary work (e.g. ZIM ZF4008301RP5) has investigated the adhesion between elements manufactured using the FDM process and various textile fabrics. The completed research project 'Orthopaedic Aids' (IGF No. 19757 BR [7]) encompasses the development of novel orthopaedic aids produced using the Composite Filament Fabrication (CFF) process. For customised production, thermoplastic and continuous-fibre-based reinforcements are applied additively and directly onto textile surfaces based on 3D body data. The objectives pursued included, amongst other things, locally adjustable stiffness and strength tailored to specific requirements, as well as the realisation of structurally integrated solid-state joints. The process chain was further developed to enable the conversion of CAD or simulation data sets of complex shapes into machine data for biaxial flat knitting. By combining additive manufacturing with textile materials, the developed process offers great potential for customised products (batch size 1).

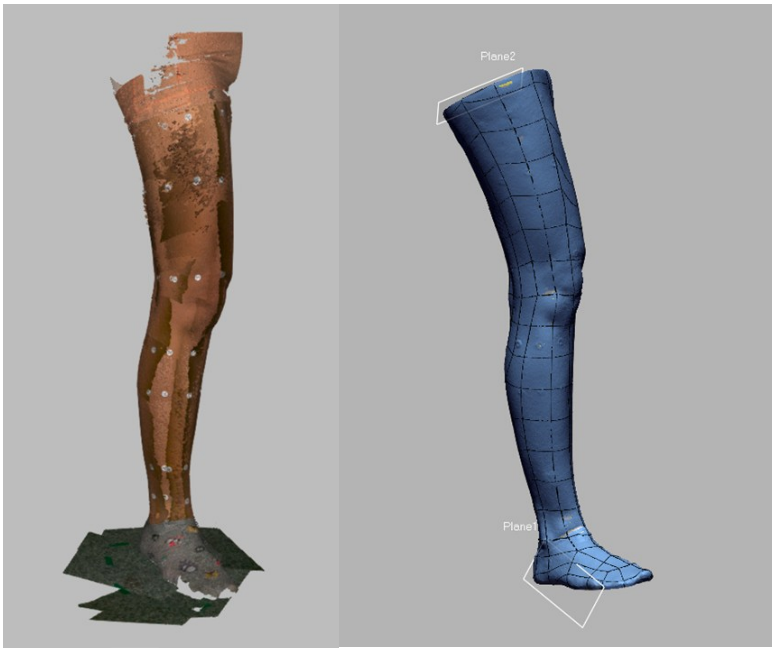
Furthermore, methods for fit-based product development for close-fitting garments, particularly knitted fabrics, were established, with a particular focus on fit whilst taking into account the textile properties of knitted fabrics. To this end, a novel approach was developed to analyse the pressure exerted on the body's surface, as this parameter is directly linked to fit and wearing comfort. In addition, a new, previously unused measurement principle was developed and implemented in the form of the split-cylinder measuring device. It has the advantage of being particularly suitable for measuring small pressures between the skin and close-fitting garments. The optimal test procedure and the parameters to be measured were defined. As part of the interdisciplinary basic research project RO 1303/2-1, the effect of compression garments on arterial blood flow in the upper limbs was investigated [8]. The aim was, on the one hand, to investigate the relationships between the material and design parameters of the garments and the forces exerted, and, on the other hand, to examine the biological effect of these forces on blood flow. The results are intended to provide the scientific basis for designing garments with a blood flow-modulating effect, which may subsequently be used in the sports and fitness sectors and in medicine.

In the IGF project No. 17355 BG [9], kinematic human models were developed for the product development of clothing. The kinematic model enables the user to move the model's joints into the required posture using precise angular specifications. Furthermore, movement sequences corresponding to the typical use of a particular garment can be recorded and reloaded at any time. This enables the patternmaker to take into account the effects of posture on pattern construction. Particularly in the development of functional sportswear and medical textiles, existing difficulties – such as fit problems – can be overcome. In project IGF No. BR1296/20 (Softavatar), the aim was to model virtual deformable bodies for the realistic representation of close-fitting garments. The results of this work were used as preparatory work for the creation of the simulation models [10].

3 Overview of the project results

3.1 Methodology of the modular test rig: Elastic leg model

One of the project's objectives was to model the soft tissues of the leg on a test rig. For this application, a methodology was developed to produce a realistic model of the human leg. As an example, a leg in size 20/21 according to RAL GZ 387-1 was modelled as part of the project. First, various methods for determining the 3D geometry using a 3D hand-held scanner and a 4D motion scanner (MOVE4D) were carried out (Fig. 1a), evaluated and converted into virtual twins (Fig. 1b). For additive manufacturing, the model was modified to incorporate the sensors and adapted to the movement mechanism in the knee area, as explained in Section 3.2.



A b

Fig. 1 Virtual twin of a leg: a) unprocessed 3D scan with visible markers for the points; b) converted into a free-form 3D geometric model for further processing as a CAD model

As part of the adaptation, the leg geometry was divided into modular sections to ensure the future integration of advanced thermophysiological measuring devices, in accordance with DIN CEN/TR 16422, via measuring segments. Within the scope of the project, priority was given to dynamic compression measurement, as the main factor influencing the comfort and medical application of hosiery; see Chapter 3.4. The entire leg model was designed parametrically as a CAD model and can be adapted to a wide variety of leg geometries and characteristics, with a focus on maximum adaptability and ease of reconfiguration in the event of changes to leg characteristics. A partial view of the overall design, including the motion mechanism, initial knee prototype and motor control, is shown in Fig. 2.

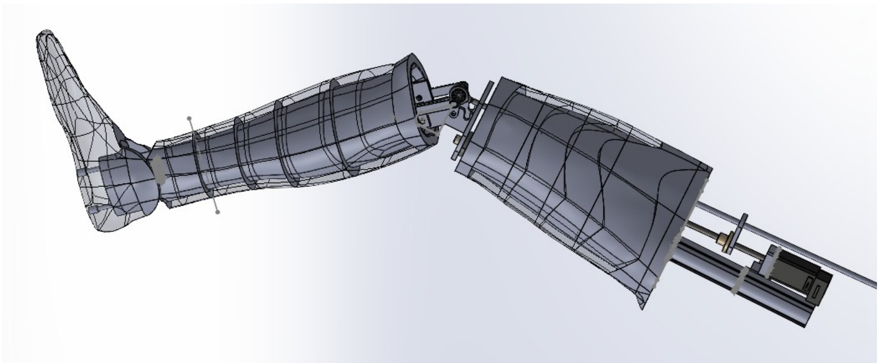


Fig. 2 CAD design of the leg, showing the drive motor

In terms of the overall design, the leg constructed in this way was incorporated into a test rig, and test methodologies have already been devised and validated for the application of compression measurement using current test prototypes, as described in Chapter 3.4.

Accordingly, a digital process chain was developed to create a personalised test rig for evaluating comfort and compression, and this was assessed, revised and validated using the design of a sample leg.

3.2 Soft-tissue imaging

In order to take account of the softness of the different areas of the leg in the measurement system and in simulations, the leg was divided into vertical and radial segments. Each segment consists of an inner, rigid, thin-walled structure (Fig. 3a, red structure). This structure acts as the supporting framework for the segment, providing support for the outer, more flexible structures and housing and protecting the internal measurement, drive and signalling technology; it also provides the necessary space for the actuators and motors adjacent to the knee and ankle joints. The soft tissues were manufactured using commercially available flexible TPU-based filaments, and were produced in the prototype version using a Prusa XL 2-filament extruder setup. The infill structures were mapped according to the leg's measured values and medical literature on leg anatomy; in future, automation using open-source slicer software, such as Slc3r, is conceivable and would be beneficial for a wider application of the methodology. Fig. 3b shows an example of a cross-sectional design with three different infill patterns, which correspond to the varying stiffnesses of the human leg in these directions.

a b

Fig. 3 Additively manufactured soft tissue segment of a leg: (a) visible layers representing bone (red) and soft tissue; (b) soft tissue segment with three different levels of elasticity achieved through different infill

The determination of soft tissue elasticity has been analysed in detail in previous studies, and it has been established that the IdentoPRO device, manufactured by thermotrigger.de, is currently the only device capable of simultaneously measuring penetration depth and reaction force at that depth [3] (Fig.4)

Fig. 4 Determination of soft tissue elasticity and penetration depth at a measurement point using the IdentoPRO device.

As part of the project, a method was developed in which a specific list of individual points is tested that are sufficient to provide an adequately accurate representation of the overall behaviour (Fig. 2). The data collected is mapped onto a 3D virtual twin geometry developed for this purpose and is subsequently used both to create FEM simulation models and as an initial data set for the elastic test rig.

In order to achieve a surface as realistic as possible, various materials for coverings were extensively tested for their elastic behavior and coefficient of friction. Existing applications of silicone-based prosthetics, as well as textile solutions such as spacer knits and synthetic leather, were evaluated in terms of their coefficient of friction and functionality. In simple terms, a solution designed for dry skin was selected for the prototype. The best functional representation was achieved by the synthetic leather Lorica Soft®, which is already used in standardization as a material-based skin substitute (bfu test regulations R 9729 [12]). Due to the lack of elasticity in the imitation leather, a flexible knitted fabric is sewn into the movable intermediate zones for the prototypical implementation. In future, clamping solutions are planned for the individual segments, so that seams and transition structures affecting the coefficient of friction can be avoided and may no longer be necessary. In the summary prototypical implementation, the design and method validation described in Section 3.1 was carried out using the 3D printing process and the overlaid skin model, as illustrated in Fig. 5. Here, the segments are mounted onto a standard aluminum profile and the foot segment is manufactured in one piece on standard 3D printers, such as the Prusa XL. This was validated through comparative compression measurements using medical compression stockings and the human leg as a reference.

Fig. 5 Prototype lower leg and foot covered with skin-like fabric and elastic material in the joint area

3.3 Simulation

As part of the project, a digital twin of the test rig was created at the functional level, enabling compression products to be evaluated and optimized virtually prior to production. This was achieved using FEM simulations with leg models that were as realistic as possible. To this end, the HANS [13] and THUMS [14] human models were analyzed in detail and deemed unsuitable for this application. For example, the models contain significantly more detail about the human body than is required for textile product development and are therefore computationally too demanding for use in SMEs; furthermore, the necessary flexibility in the application and movement of the models has not yet been sufficiently implemented, meaning that the simulation method was further developed following the IGF project Softavatar (IGF 22435 BR) and the doctoral thesis by Tal [10]. Using a scanned leg geometry and the SMPL model, movements in the knee area were realistically simulated and the effects of compression were captured. This open-source-based approach is easy for SMEs in the textile industry to implement and was presented at the 10th International Digital Human Modelling Symposium in 2026 [15]

Measurement and sensor technology

The key focus of the test bench design was the integration of compression measurement technology with minimal impact on the leg geometry and the material behaviour of the 3D-printed soft tissue model under movement. To this end, standard in-situ measurement methods, e.g. using the Mircolab PicoPress® device [16] or Novel texsense [17], were evaluated in relation to the free-form phantoms of the leg model and presented at AUTEX 2026 [18]. In addition, a novel variation of FSR compression measurement using printed film sensors from project partner Flexoo GmbH was analysed, as this enables the least invasive installation beneath the skin and offers (almost) unlimited design flexibility in sensor positioning, which will enable spatial resolution in future, analogous to the simulation of the digital twin. The evaluation prototype, featuring various sensor sizes, is shown in Fig. 6.

Fig. 6 Innovative Flexoo sensor with 24 wet cells, shown here as a development prototype

The film-based sensor technology was subsequently incorporated into the leg design, including skin simulation, and conceptually integrated, as well as functionally validated on the prototype lower leg (see Fig. 4).

The initial request from some companies to integrate holistic comfort features directly into the leg proved to be uneconomical. In addition to the problem of measurement technology not currently being commercially available within the space constraints required for such a leg design, an adequate model of the leg in terms of thermal and water vapour transport is currently not feasible from either a design or financial perspective. As part of the project implementation, requirements for such measurement technologies, as well as initial specifications, have already been defined and can be used as lists of requirements in the form of a specification document for further research.

For an initial, metrologically quantifiable evaluation, a comfort score for compression textiles was therefore developed as an example, and a wide variety of thermophysiological measurement methods to be considered were evaluated for application to compression socks. For example, moisture transport was measured using specialised equipment such as the WickView (Moisture Management Tester) [19], softness was assessed using the Textile Sensation Analyser (TSA) [10], and air permeability, thermal resistance and water vapour transmission resistance were measured using standard commercial equipment.

4 Conclusion

The project has resulted in a complete development chain for the production of flexible, soft, articulated foot components capable of bending. The geometry can be tailored to an individual based on a 3D scan dataset, or used as representative geometry derived from the averaged geometry of a group of people. The elastic properties, such as softness (elasticity) and penetration depth, are systematically recorded and documented using a specially developed method, and are utilized for the production of 3D-printed geometries using a two-component printer, or for the creation of 3D simulations. The innovative measuring strips used enable the evaluation of pressure distribution across compression garments around the circumference of the leg and along its length, taking body elasticity into account. Building on this foundation, the development of compression products can achieve significantly greater precision, and quality assurance can lead to significantly higher customer acceptance.

Acknowledgements

Das IGF-Vorhaben **01IF23104N** der Forschungsvereinigung Forschungskuratorium Textil e.V. wurde über die AiF/DLR-PT im Rahmen des Programms zur Förderung der industriellen Gemeinschaftsforschung und -entwicklung (IGF) vom Bundesministerium für Wirtschaft und Energie aufgrund eines Beschlusses des Deutschen Bundestages gefördert.

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