

Article

Advanced Virtual Fit Technology for Precision Pressure Application in Medical Compression Waistbands

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Abstract: The design of medical-grade compression garments is essential for therapeutic efficacy, requiring precise pressure distribution on specific body areas. This study evaluates the effectiveness of virtual fit technology, focusing on CLO3D, in designing these garments. Simulated strain and pressure values from CLO3D were compared to experimental measurements, alongside the development of a CP model using CLO3D's digitized stretch stiffness (Youn's CP model). Using a 3D-scanned manikin, the mechanical behavior of eight knit fabrics, including composite structures, was assessed under strain of 5%, 10%, 15%, and 20%. The results showed that CLO3D's built-in pressure simulation overestimated the pressure, especially in plaited fabrics such as SJP and INTP, with discrepancies of up to 10 kPa at strain levels above 15%. In contrast, the experimental pressure measurements using the Kikuhime and PPS sensors varied within 0.13 to 2.59 kPa. Youn's CP model provided a closer fit to the experimental data, with deviations limited to within 1.9 kPa. This finding highlights the limitations of CLO3D for precision-required applications and underscores the need for more advanced, customized algorithms in virtual fit technology to ensure reliable compression garment design, particularly in medical contexts, where precise pressure control is critical for patient outcomes.

Keywords: computer-aided design (CAD); virtual fit; compression garment design; virtual fit; contact pressure; pressure simulation; strain simulation; manikin scanning; digital twin



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1. Introduction

Compression garments have numerous therapeutic benefits in medical and clinical settings, such as enhancing blood flow, reducing swelling, preventing hypertrophic burn scars, and aiding in wound healing [1]. These garments are engineered to apply targeted pressure at specific body locations to achieve the intended therapeutic outcomes. The compression level is carefully calibrated to meet specific medical needs, making these garments crucial in managing conditions like venous disorders, lymphedema, and post-operative recovery [2,3]. Their efficacy in promoting venous return, reducing edema, and improving wound healing through improved microcirculation is well documented [4,5]. This strategic application of mechanical pressure underscores the need for precision in garment design to optimize clinical outcomes. Despite their effectiveness, compression garment design must strike a balance between therapeutic pressure and wearer comfort [6]. Poorly designed garments can negatively impact both the comfort and therapeutic effectiveness. Insufficient pressure limits the garment's therapeutic benefits, while excessive pressure can cause discomfort or numbness or even impede movement and breathing [7]. Compression garments are typically categorized based on the pressure that they exert, which is measured in millimeters of mercury (mmHg) and can be converted to kilopascals (kPa) for precision. The pressure ranges considered in this study include mild (1–1.9 kPa), moderate (2–2.66 kPa), firm (3–4 kPa), extra firm (4.1–5.3 kPa), and prescription-level (5.4–6.6 kPa). These ranges are critical in treating conditions such as mild to advanced

venous insufficiency, lymphedema, and post-surgical recovery [8,9]. The effectiveness of each pressure range depends on the pathology being addressed and the specific therapeutic outcomes required [7,10]. Recent advancements in virtual fit technology, particularly 3D garment simulation (3DGS), have shown significant promise in addressing the challenges of accurately simulating fabric behavior and enhancing garment performance. In this context, 3DGS enables the precise modeling of garments under various real-world conditions without extensive physical testing. For instance, Youn, et al. (2024) demonstrated that the virtual fabric parameters closely aligned with the physical properties in their comparative study of physical versus virtual drape tests using commercial 3D garment software, CLO 3D (Version 7.2, CLO Virtual Fashion, Seoul, South Korea) [11]. Although 3DGS is widely used for visual garment prototyping, there are few studies focused on developing functional garment designs, utilizing 3D fashion design software for medical or functional garment design purposes, due to the unverified accuracy of mechanical property simulations [12,13]. To address this gap, researchers have begun exploring virtual mechanical representation in terms of garment stress, strain, and pressure using various 3D garment simulation programs, including Browzwear, Optitex, CLO3D, and Lectra [11–14]. Recent studies, such as those by Brubacher et al. (2023) [14], have explored the potential of 3DGS to replicate the actual garment pressure in both static and dynamic settings. Their research utilized the Optitex Pattern Design Software (Version 11, EFI Optitex, Rosh HaAyin, Israel) to simulate the fit of compression garments, like sports tights and tops, on virtual avatars. Their study involved comparisons across 13 body scan avatars, measuring the pressure at 22 specific points in both in vivo and virtual settings for a single female model. The findings indicated a general lack of correlation between the virtual and in vivo pressure values, except at the shoulder blade location. Additionally, other research using Vstitcher has highlighted challenges in simulating complex men's compression tops, showing mixed results in accurately simulating the pressure distribution across the torso [15]. While these efforts have been comprehensive, the correlation between the simulated and experimental pressure remains a challenge. For instance, a study utilizing CLO3D's garment stress representation developed a contact pressure prediction model (CP model) that incorporated digitized stretch stiffness and simulated strain data to predict the contact pressure more effectively [6]. This model has been validated with expanded materials and showed promise in improving the simulation accuracy [16]. However, despite these innovations, there is still a lack of published comparisons between simulated and experimental strain and pressure values on human-shaped manikins using the CLO3D software (Version 7.2 or earlier). In addition, given that CLO3D's updated version (Version 7.3) includes its own pressure simulation function, it has not been thoroughly evaluated for the comparison of the simulated pressure with the experimental contact pressure using various pressure sensors alongside Youn's CP model [6,16]. Therefore, this paper aims to evaluate the practicality of using virtual fit technology in the design of medical-grade compression garments, focusing on three aspects.

- (1) Strain Measurement Validation: Evaluating the correlation between simulated strain values and experimental strain values exerted on compressional knit materials on a 3D-scanned manikin to ensure reliable strain representation in the virtual environment.
- (2) Pressure Measurement Validation: Evaluating the accuracy of the new CLO3D's pressure measurement features against experimental data obtained from pressure sensors and Youn's previous CP model for materials on physical manikins and virtually scanned avatars.
- (3) Practical Application in Medical Compression Band Design: Assessing the practicality of using virtual fit technology for pressure optimization in designing practical medical-grade compression garments, specifically focusing on the composite application of advanced smart materials in compression garments.

2. Experimental Methodology

This study aimed to evaluate the practicality of virtual mechanical representation techniques by comparing data from both virtual and physical environments. The physical properties of the textile samples—including the weight, thickness, stretch, and bending characteristics—were measured following the CLO3D KIT guidelines, as outlined in our previous study [11]. The methodology included the 3D digitization of textile materials, importing a 3D-scanned manikin, and conducting strain and pressure measurements using CLO3D's built-in features. These virtual measurements were then systematically compared with corresponding experimental data collected from real-world tests. An overview of the experimental methodology is illustrated in Figure 1. In this study, we utilized CLO3D (Version 7.3, Clo Virtual Fashion, Inc., Seoul, South Korea), a specialized software platform for garment simulation. The software allows for the digital creation and manipulation of garments, providing tools to simulate fabric behavior under various conditions. CLO3D uses finite element analysis (FEA)-based algorithms to predict how fabrics stretch, bend, and interact with different body shapes. The strain simulations are highly sensitive to fabric properties like the elasticity, density, and knit structure, which are input directly into the software to ensure accurate modeling. The experimental methodology is described in detail below.

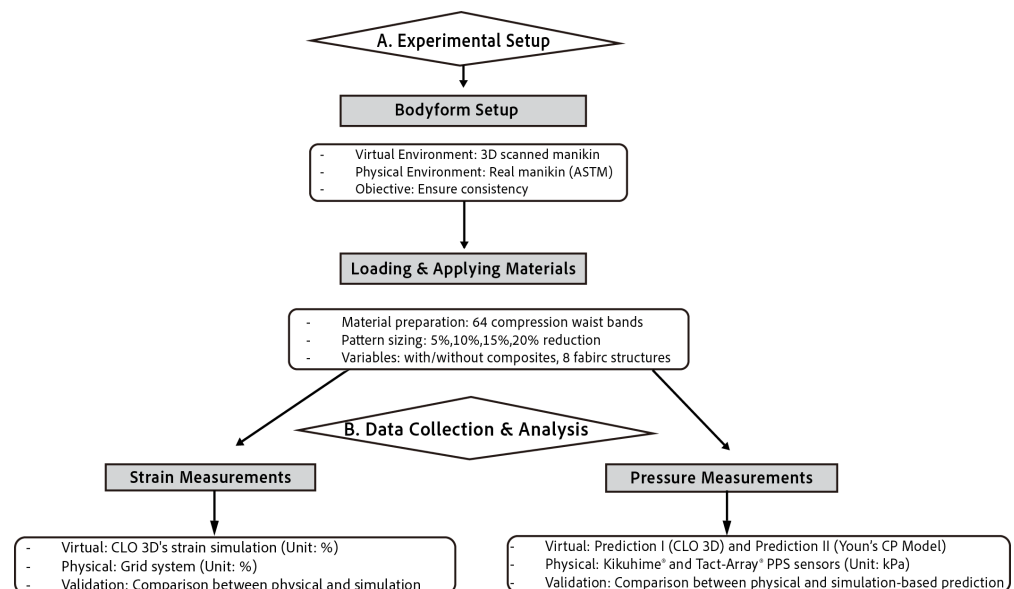
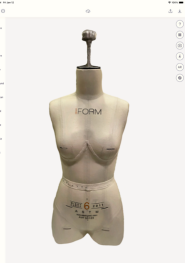


Figure 1. Overview of experimental methodology.

2.1. Scanning of the Manikin

A half-scale miniature Full Torso AlvaForm (Missy Curvy 6, compliant with ASTM Standard D5585-11e1 [17]), produced by Alvanon Inc. (New York, NY, USA), was 3D-scanned using an iPad equipped with the Polycam Pro® application (Polycam Inc., San Francisco, CA, USA). The photo mode in Polycam Pro® was used to manually capture over 200 images around the manikin from every angle, ensuring detailed surface texture data. The captured data were exported as an FBX file and imported into CLO3D as an avatar, ensuring that it matched the actual size of the physical manikin. The accuracy of the imported scanned manikin was confirmed by measuring the circumference of the scanned manikin's body at three locations: the bust line, waist, and hip line. These measurements were compared to those of the actual manikin, with the percent differences between the physical and scanned manikin's dimensions being minimal, within the range of 5.6–5.86%. The overall process of scanning, exporting, and importing the manikin into the virtual environment is shown in Table 1.

Table 1. Process overview for scanning, exporting, and importing of manikin into CLO3D.

Step 1: Target Manikin	Step 2: Scanned Manikin Image	Step 3: Exported Scanned Image to CLO3D
		

2.2. Knit Specimens

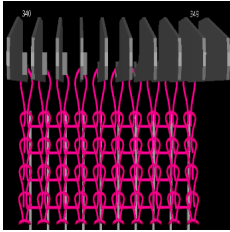
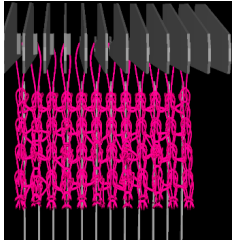
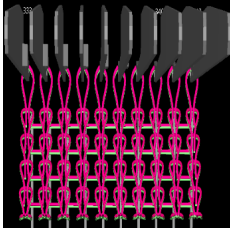
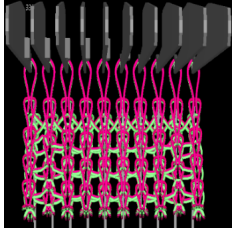
Eight knit samples were developed for this study, considering variations in the knit structure and filament density for compressional material engineering. These samples were tested to assess their suitability for medical-grade compression garments, specifically in terms of their ability to apply controlled pressure. The samples used in this study included both non-plaited and plaited counterparts with elastane yarns. Knit programming was developed using SHIMA SEIKI's SDS®-ONE APEX3 design system (Version 3.0., SHIMA SEIKI MFG., Ltd., Wakayama, Japan). and performed on a Shima Seiki Knitting Machine (Model: SVR123.SP) with the stitch loop length set at 30. Tables 2 and 3 summarize the knit materials used in this study. Table 2 provides detailed information on knit structures, ground yarns, elastic yarns, and whether the yarns were plaited with elastane for each sample used in the study. The samples were further categorized using a coding system to denote specific configurations. For example, SJ1: Single jersey with high filament density ground yarn (150d/96f). SJ2: Single jersey with low filament density ground yarn (150d/48f). The filament density codes differentiate between high ("1") and low ("2") densities while maintaining a consistent linear density for ground yarns. Table 3 visually represents the knit structures corresponding to each code listed in Table 2.

Table 2. Knit materials used in this study.

Code	Structure	Ground Yarn	Elastane Yarn	Plaited with Elastane Yarn?	Purpose
SJ1	Single Jersey	Polyester 150d/96f	-	No	Local strain and pressure tests for accuracy of simulation
INT1	Interlock	Polyester 150d/96f	-	No	
SJP1	Single jersey plaited with elastane yarn	Polyester 150d/96f	Spandex blends ¹	Yes	
INTP1	Interlock plaited with elastane yarn	Polyester 150d/96f	Spandex blends ¹	Yes	
SJ2	Single Jersey	Polyester 150d/48f	-	No	Validation of the study
INT2	Interlock	Polyester 150d/48f	-	No	
SJP2	Single jersey plaited with elastane yarn	Polyester 150d/48f	Spandex blends ¹	Yes	
INTP2	Interlock plaited with elastane yarn	Polyester 150d/48f	Spandex blends ¹	Yes	

¹ Polyester/Spandex blends with an 80/20 composition, featuring a yarn specification of 150 denier for polyester, 120 denier for spandex, and 96 for filaments.

Table 3. Knit materials' structure used in this study.

Singe Jersey (SJ)	Interlock (INT)
	
Single Jersey Plaited (SJP)	Interlock Plaited (INTP)
	

2.3. Strain Measurements and Validation: Experimental vs. Simulation

Strain measurements were conducted on the textile samples to evaluate their mechanical behavior under controlled conditions. The compression garments were designed to apply pressure in clinically relevant ranges: mild (1–1.9 kPa), moderate (2.66 kPa), and firm (4 kPa). These pressure ranges are aligned with clinical applications for the management of medical conditions such as venous insufficiency, lymphedema, and postoperative recovery. To compare the experimental and simulated strain measurements, we applied a standardized grid system to both the physical samples and their virtual counterparts. The grid was marked at 1 inch intervals in both the wale and course directions, as depicted in Figure 2a. A template was employed to mark the grid on the textiles [18]. This method allowed for the precise calculation of changes in the grid dimensions before and after the fabric was stretched using the following equation [6]:

$$\text{Strain (\%)} = \frac{\text{Stretched length} - \text{Original length}}{\text{Original length}} \times 100$$

For the experimental setup, strain measurements were performed by stretching a compression waistband in the course direction on a manikin, at strain levels of 15% and 20%. The strain measurements were conducted in three directions: the course direction (axial strain), the wale direction (transverse strain), and the bias direction, considering that the waistband was stretched in the course direction accordingly (Figure 2b). The textile's strain was evaluated by applying the load around the manikin, with the stretch facilitated using Velcro (as depicted in Figure 2c). Specifically, a strain measurement tool in CLO3D was used to simulate and record the local strain corresponding to the applied strain levels in the axial, transverse, and bias directions (Figure 2b) at consistent 1 inch intervals between the grid points, ensuring alignment with the physical measurements (Figure 2d). By using both real-world grids and virtual strain predictions, this study validated CLO3D's accuracy in simulating textile deformation under controlled conditions.

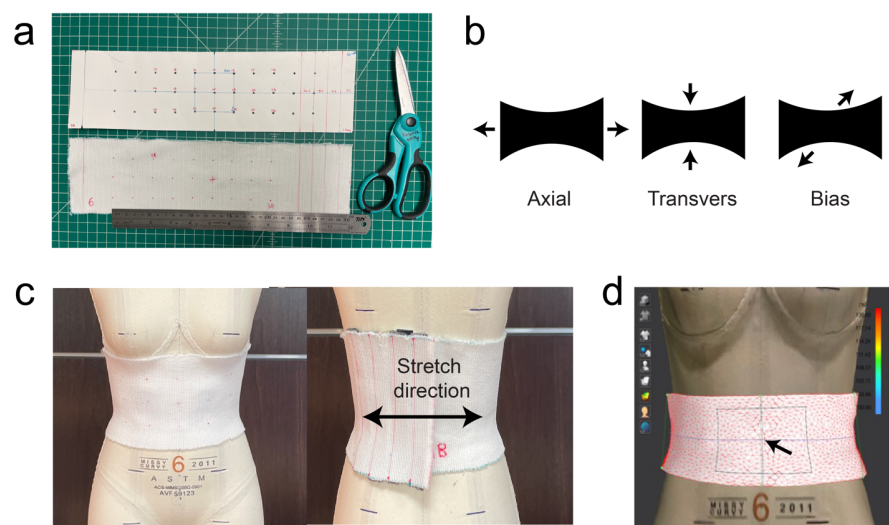


Figure 2. (a) Grid system setup with a template to accurately measure the sample’s strain. (b) Schematic representation showing the dimensions and orientation (length, width, bias) used in the sample. (c) Loading fabric on a manikin. (d) Simulation strain map after applying 20% strain.

2.4. Pressure Measurements and Validation: Experimental vs. Predictions

Pressure data were gathered using both physical sensors and virtual simulations. The experimental pressure readings were obtained with the Kikuhime® and TactArray® sensors, chosen for their ability to measure static and dynamic pressure, respectively. Pressure readings were conducted under identical conditions in both the virtual and physical environments, targeting specific locations on the manikin for consistency. CLO3D’s built-in pressure simulation was then used to predict the pressure, which was systematically compared with the experimental results. In addition, Youn’s CP model, which integrates the simulated strain and digitized stretch stiffness from CLO3D, was used for CP prediction as follows [6,16]:

$$\text{Youn’s CP model} = \frac{t}{2\pi r}(\epsilon_s \times \text{SS})$$

where t is the thickness of the specimen (m), r is the radius of a cylinder (m), ϵ_s is the simulation strain, and SS is the stretch stiffness in the specific direction (warp, weft, or shear) obtained from the digitized physical property (g/s^2) [6,16].

Table 4 details the pressure evaluation methods used in this study.

Table 4. Pressure evaluation equipment and methods used in this study.

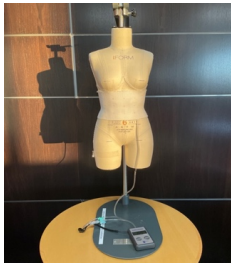
Method	Equipment Used	Details	Setup Image
A. Experimental pressure	A-1. Kikuhime® pressure sensor (TT Meditrade, Denmark)	Measures point-specific pressure using air-filled bladders; converts to kPa.	
	A-2. TactArray® pressure sensor pad (PPS, PPS UK Limited, UK)	Captures distributed pressure using a matrix of pressure-sensitive cells.	

Table 4. Cont.

Method	Equipment Used	Details	Setup Image
B. Simulated pressure	B-1. CLO3D® Pressure Simulation (CLO Virtual Fashion, South Korea)	Built-in function in CLO3D (v. 7.3) that simulates pressure.	
	B-2. Simulation-Based Pressure Prediction (Youn's CP Model)	Uses CLO3D's built-in strain measurements and digitized stretch stiffness to predict pressure via Youn's model [6,13].	

3. Results and Discussion

3.1. Experimental Strain Measurement

Local strain measurements were conducted across four textile structures under varying applied strain levels, determined by reducing the pattern size of the waistband using the Velcro method. The Velcro strips, attached to the fabric's edges, allowed for controlled reductions in the waistband size by overlapping the strips, simulating strain levels of 5%, 10%, 15%, and 20% without distorting the material. Figure 3 illustrates the strain behavior of the four fabric structures—SJ, INT, SJP, and INTP—under controlled strain levels of 5%, 10%, 15%, and 20%. When the fabric was stretched, the local axial strain increased consistently, reflecting the inherent stretchability of knit fabrics. Even at an initial 5% applied strain, the local axial strain exceeded 15% in all fabric samples. As the strain increased to 20%, the local axial strain expanded to values between 25% and 40%, varying based on the knit structure—single jersey (SJ), interlock (INT), and elastane yarn inclusion through the plaiting technique (single jersey-plaited (SJP), interlock-plaited (INTP)). The results show that the SJ fabric exhibited the highest local axial strain, with values increasing up to 40% at 20% applied strain. In contrast, the interlock (INT) fabrics displayed more controlled strain behavior, likely due to the increased structural stability inherent in the INT fabric. The incorporation of elastane yarn in the plaited structures (SJP, INTP) had a moderating effect on the strain behavior. Figure 3c,d show that the local axial strain was lower for both the SJP and INTP fabrics, indicating that the elastane reduced the degree of stretchability. It should be noted that, in Figure 3b,d, the data points are limited due to material constraints. Due to the inherent stiffness of these materials, they were unable to stretch beyond 10% on the mannequin without risking damage to the fabric's integrity. This limitation resulted in fewer data points and reflected the material's inherent properties, emphasizing its rigidity under strain.

Building on the understanding of the experimental local strain test results, the simulation test outcomes are presented as dotted lines in the same Figure 3. Both the SJ and SJP fabrics demonstrated relatively accurate predictions of the local strain, as represented by the simulation model (Figure 3a,b). The INT fabric also showed good alignment between the experimental and simulated strain up to an applied strain of 15%. However, at an applied strain of 20%, although the experimentally observed local strain in the axial direction for INT was 28.67% ($\pm 3.77\%$), the corresponding simulation value was significantly higher at 38.93% ($\pm 1.95\%$) (Figure 3c). A similar overestimation was observed for the INTP fabric, as shown in Figure 3d, indicating potential limitations in the simulation model's ability to accurately capture the nonlinear mechanical behavior of double-knit textile structures under higher levels of applied strain (beyond 15%) [6]. Moreover, the observed differences

in the transverse and bias strain behaviors have important implications for fabrics' performance in applications requiring controlled deformation, such as compression garments. The greater structural stability of the INT fabric, as evidenced by its lower transverse strain values, suggests that it may offer better consistency in maintaining compression over time compared to the SJ fabric. Similarly, the reduced transverse and bias strains in the elastane-plaited fabrics (SJP and INTP) highlight the role of elastane in providing a more controlled strain response, which could be particularly advantageous in medical-grade garments. The simulation also represented this Poisson effect, aligning with the experimental results, particularly for non-elastane plaited fabrics like SJ and INT.

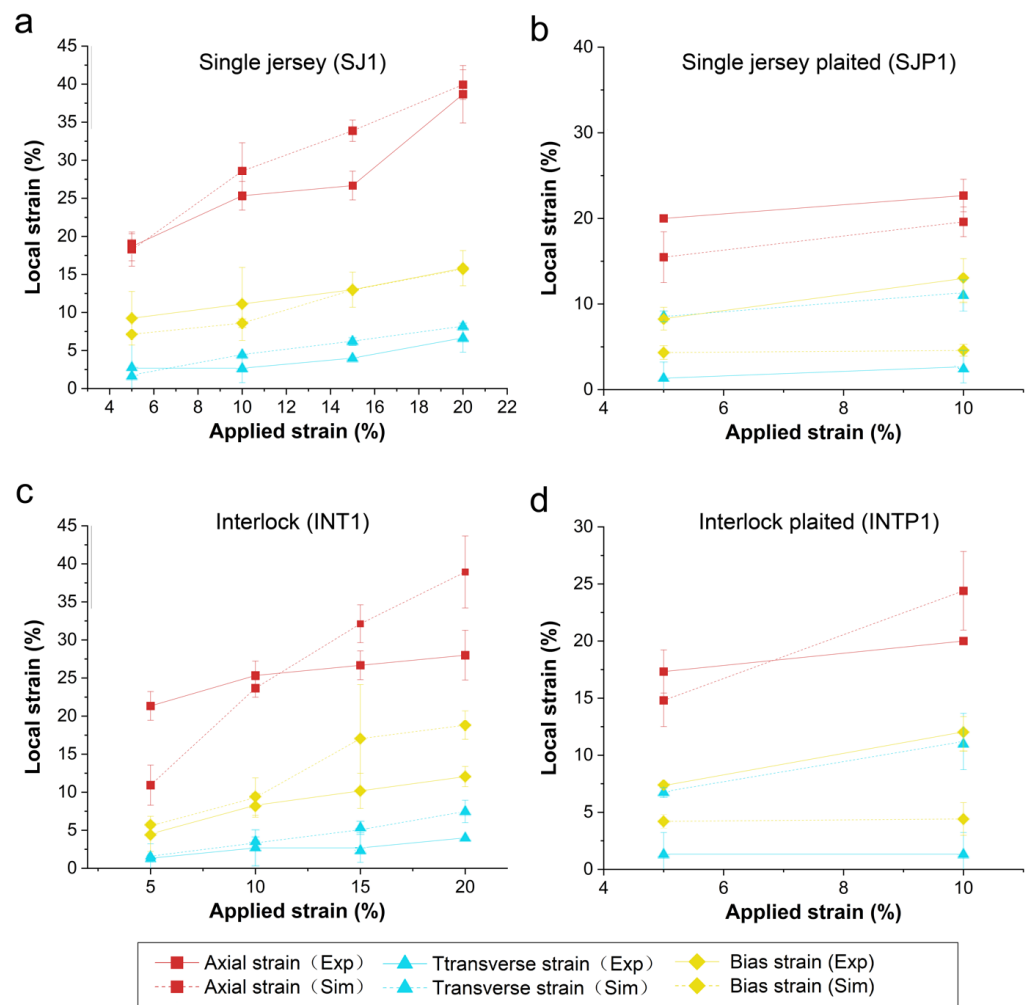


Figure 3. Comparison of physical and virtual strain measurements across four fabric samples: (a) single jersey, (b) single jersey plaited, (c) interlock, and (d) interlock plaited. The solid lines represent the experimental data, while the dotted lines represent the simulation results.

3.2. Validation of Pressure Measurement: Experimental (Kikuhime, PPS) vs. CLO3D

The PPS and Kikuhime sensors were employed as reference standards to validate the pressure measurements and compare their outputs with the simulated pressure values generated by the CLO3D built-in pressure feature. In Figure 4, the highlighted area (yellow) indicates the gap between the pressure values obtained from the PPS and Kikuhime sensors. Using two distinct sensors, each based on different measurement principles, allowed for a comprehensive assessment of the simulated pressure data. The PPS sensor utilizes capacitive sensing technology to capture the dynamic pressure distribution with a high spatial resolution, while the Kikuhime sensor measures the static pressure using an air-inflated mechanism, commonly used for compression garment evaluation. Due to these

different principles, the experimental measurements showed some variations, and we used this range as a threshold to validate the simulated pressure values.

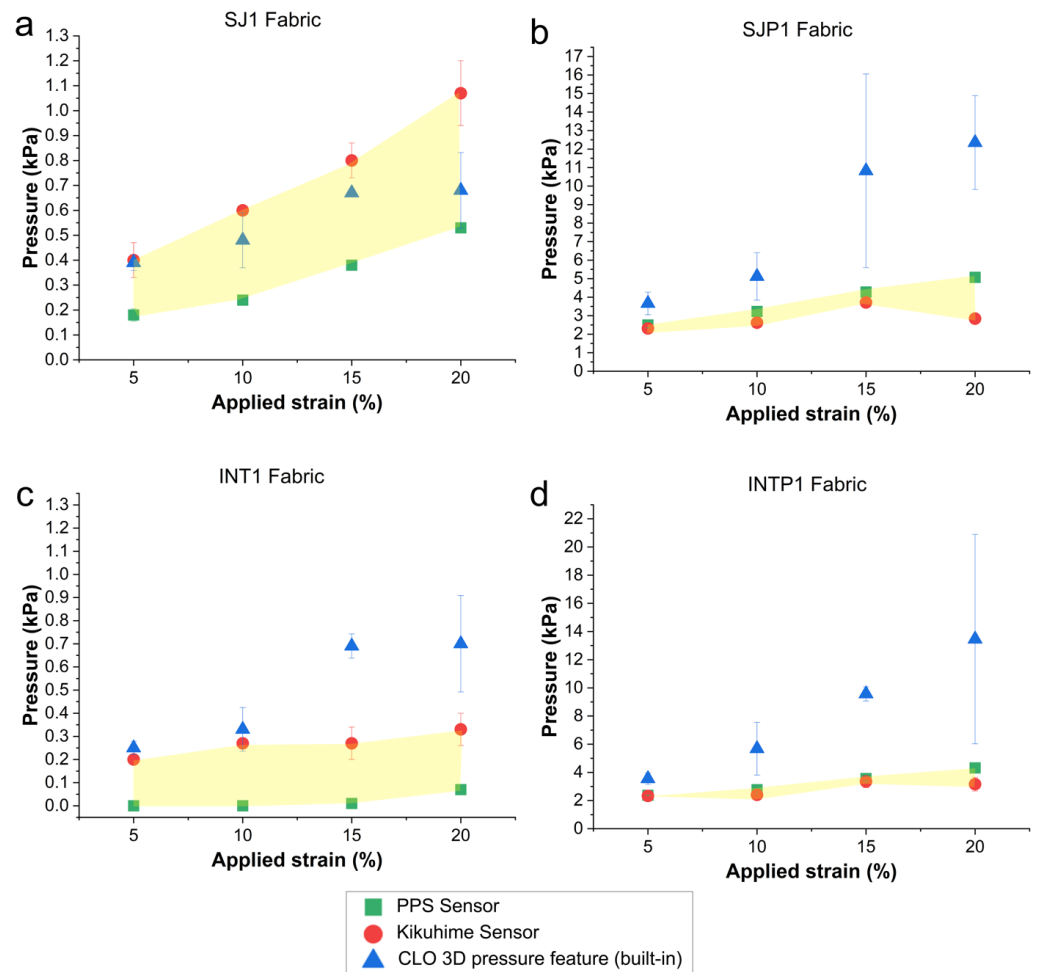


Figure 4. Experimental pressure measurements (Kikuhime, PPS) and simulated pressure measurements obtained from CLO3D. (a) single jersey, (b) single jersey plaited, (c) interlock, and (d) interlock plaited fabric. The highlighted area represents the gap between the pressure values obtained from the PPS and Kikuhime sensors, indicating the range of experimental pressure values.

The experimental pressure measurements between the Kikuhime and PPS sensors exhibited differences ranging from 0.13 to 2.59 kPa across the four knit samples. The most significant discrepancies were observed in the plaited structures, such as SJP and INTP, followed by the SJ fabric, whereas the INT fabric showed better alignment between the two sensors. This variation suggests that the pressure distribution in single jersey and plaited fabrics may be less uniform, likely due to structural differences in the fabric, as compared to the more stable interlock structure. These differences may result from how each sensor interacts with the fabric surface, leading to inconsistencies in measurement. The range of pressure values established by the PPS and Kikuhime sensors was used as a benchmark to validate the CLO3D-simulated pressure values, as highlighted in the yellow area. When comparing these experimental results to the simulated values, the CLO3D model generally overestimated the pressure, except for that of the SJ fabric, where the simulation closely matched the experimental data. The overestimation of the pressure was particularly observed in plaited structures such as SJP and INTP, with approximately 10 kPa differences beyond the 15% applied strain, which shows the inaccuracy of the current pressure model. This trend may be related to the local strain measurements, which also showed discrepancies between the simulation and experimental data at higher strain

levels. In this study, we found that the CLO3D model may struggle to account for the nonlinear mechanical behavior of fabrics under large deformation, particularly in more complex structures like plaited knits. Factors such as yarn interactions, the fabric density, and elastane inclusion contribute to the complexity of the pressure distribution, which the current CLO3D model does not fully capture. These findings suggest that the CLO3D simulation, in its current form, may require further refinement to accurately predict fabric mechanics at higher strain levels, especially under increased tension.

3.3. Validation of Pressure Measurement: Experimental vs. Simulation-Based CP Prediction (Youn's Model)

The pressure predictions from Youn's model were compared to the experimental pressure measurements obtained from the PPS and Kikuhime sensors. Youn's model utilized simulation values obtained from CLO3D, including the local strain measurement and digitized stretch stiffness, applying a modified version of Laplace's law for pressure estimation [6]. Figure 5 shows that Youn's model aligned better with the experimental pressure results, particularly for the SJP and INTP fabrics, than the built-in CLO3D pressure values.

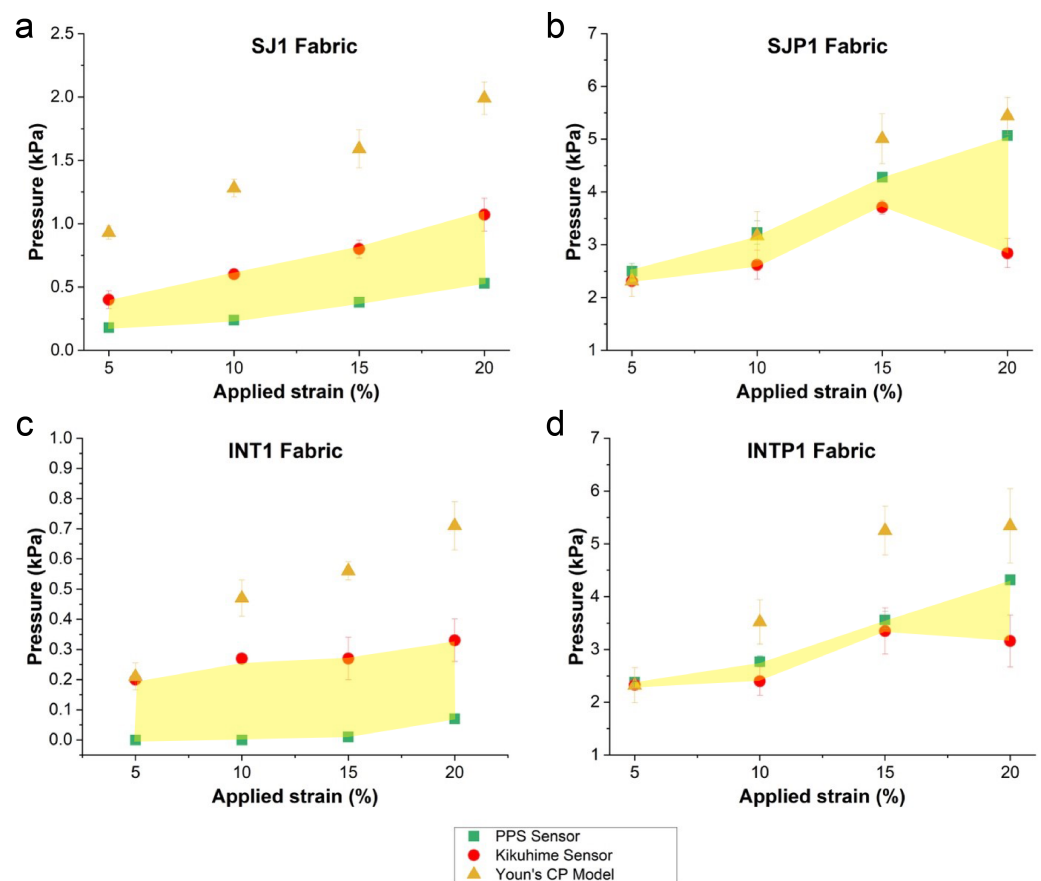


Figure 5. Experimental pressure measurements (Kikuhime, PPS) and predicted pressure values obtained from Youn's model using CLO3D. (a) single jersey, (b) single jersey plaited, (c) interlock, and (d) interlock plaited fabric.

For the SJP fabric stretched to 20%, Youn's model predicted pressure of approximately 5 kPa, whereas the CLO3D built-in feature predicted much higher pressure of over 11 kPa. Considering the experimental pressure range of 2.84 to 4.72 kPa, obtained from the PPS and Kikuhime measurements, Youn's CP model provides a more accurate estimate. Similarly, for the INTP fabric stretched to 20%, Youn's CP model predicted pressure of around 5 kPa, while the CLO3D built-in feature estimated significantly higher pressure of 15 kPa. Given the experimental pressure range of 2.84 to 4.72 kPa, Youn's CP model again demonstrates

greater reliability. However, it is important to note that Youn's CP model also tended to slightly overestimate the contact pressure, although the predictions were much closer to the experimental values than those provided by the CLO3D built-in feature. This deviation may be attributed to the use of CLO3D's local strain values, which were generally higher than the experimental strain results. The exact predictive mechanisms within CLO3D's built-in pressure feature remain proprietary and unclear. Nonetheless, Youn's CP model, which incorporates factors such as the digitized stretch stiffness, fabric thickness, and garment circumference into a modified version of Laplace's law, appears to offer a more suitable approach to predicting the pressure in compression garments than the pressure directly simulated by CLO3D. Additionally, the deviation between Youn's CP model and the experimental pressure obtained from the two types of sensors may be acceptable, given that pressure sensors themselves can have a standard deviation of up to 0.22 (pps) or 0.49 kPa (kikuhimi). This variation could be due to differences in the pressure distribution across the fabric surface and interactions with the manikin's body stiffness.

3.4. Practical Application in Medical Compression Band Design: Integration of Virtual Fit Technology and Electrode Composites

To validate the use of virtual fit technology in the design of medical compression waistbands, four new samples—SJ2, INT2, SJP2, and INTP2—were developed, distinct from those used in the previous strain and pressure assessments (SJ, INT, SJP, and INTP). A unique pattern design was developed specifically for this study, as illustrated in Figure 6a. The design incorporated electrode composites, adding functionality to the waistband by enabling e-textile features such as heating, a useful component in therapeutic compression applications [19,20]. Figure 6b,c depict the experimental setup for both the physical and virtual strain measurements of the waistband and composite. The waistband's dimensions could be adjusted using Velcro, reducing the fabric width by 5%, 10%, 15%, and 20% (Figure 6d).

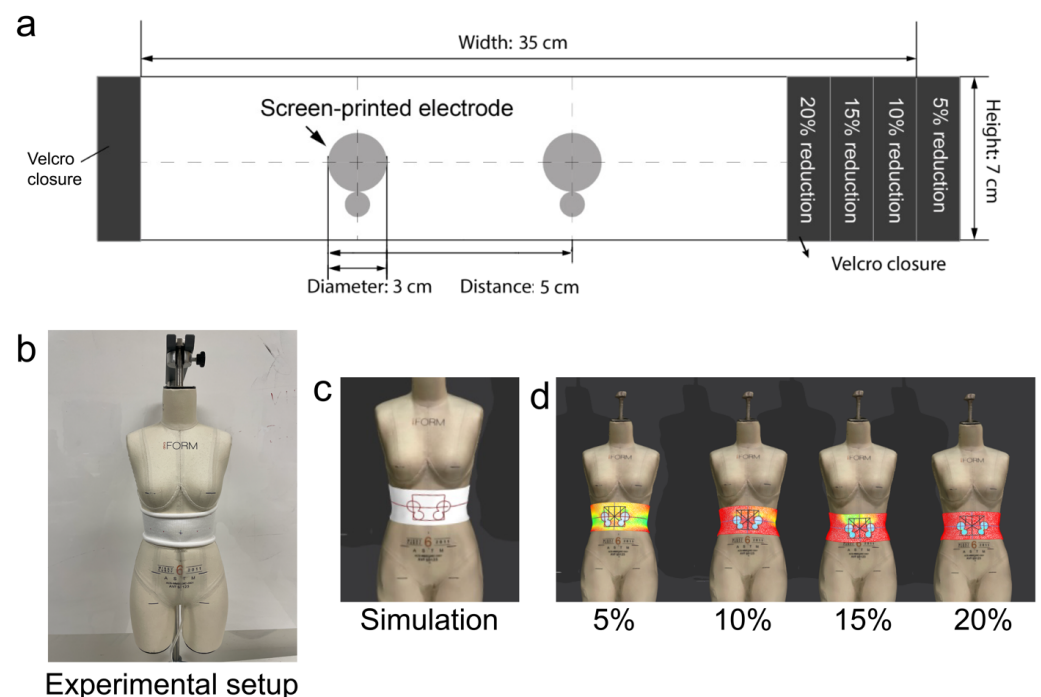


Figure 6. (a) Illustration of compressional band pattern design. (b) Experimental setup with manikin wearing the compressional band integrated with the electrode composite. (c) A 3D-scanned manikin visualized in CLO3D wearing the simulated compressional band with composite. (d) Simulated stress map in CLO3D, indicating pressure distributions at pattern size reductions of 5%, 10%, 15%, and 20%.

The results of the simulated pressure obtained from the CLO3D built-in feature and Youn's CP model, compared to the experimental values, are shown in Figures 7 and 8, respectively. Youn's CP model demonstrated closer alignment with the experimental values, with differences ranging from a minimum of 0 kPa (SJP2 at the applied strain of 5%) to a maximum of 1.9 kPa (INTP2 at the applied strain of 20%). In Figure 7, the CLO3D built-in result shows an unrealistically overestimated value for INTP 2 and SJP2, especially above the applied strain of 15%.

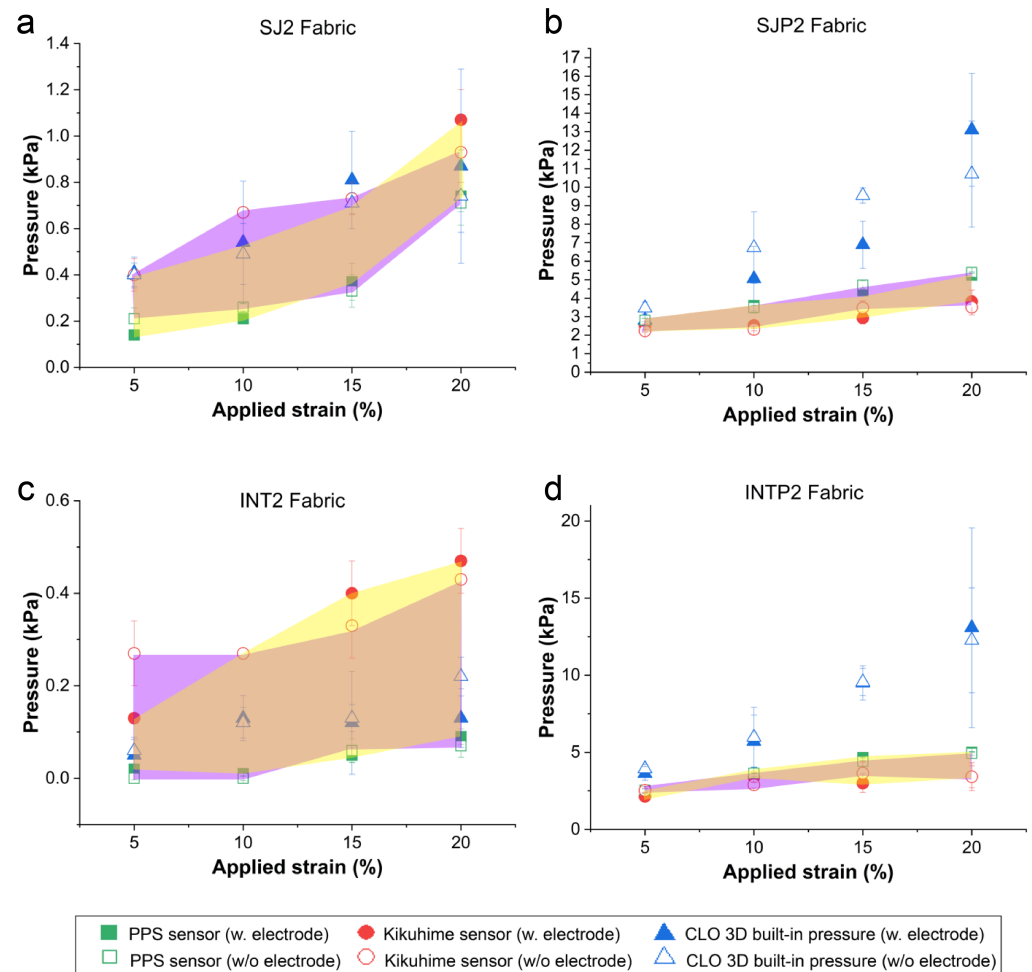


Figure 7. Comparison of simulated pressure values from the CLO3D built-in pressure feature and experimental pressure measurements obtained from PPS and Kikuhime, with and without electrode application, using four different samples: (a) SJ2, (b) SJP2, (c) INT2, and (d) INTP2.

In contrast, in Figure 8, Youn's CP model provides more accurate pressure predictions than the built-in CLO3D feature, likely due to incorporating additional mechanical properties such as the fabric thickness, stretch stiffness, and specific material properties, which are particularly observed in SJP2 and INTP2. The small differences in the pressure values suggest that the CP model could be a valuable tool for future developments in compression garments if they incorporate Youn's CP model.

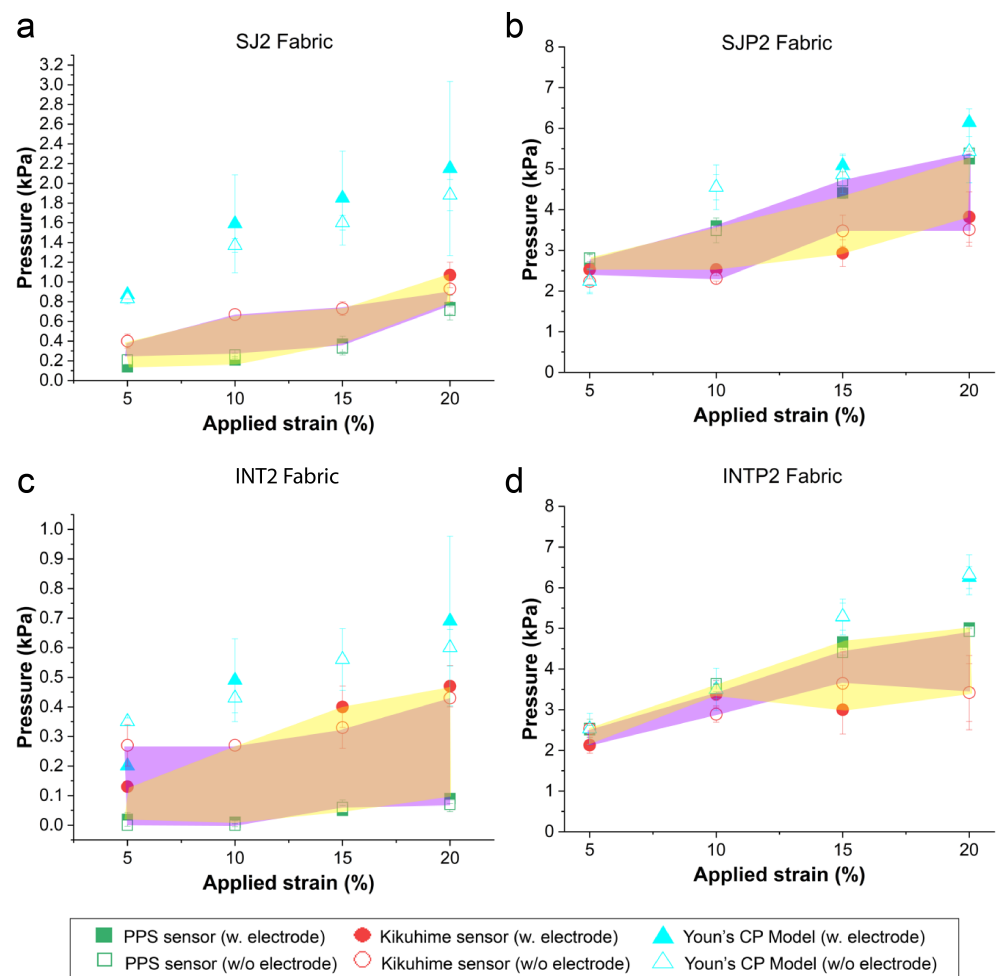


Figure 8. Comparison of simulated pressure values from the CLO3D-based Youn's CP model and experimental pressure measurements obtained from PPS and Kikuhime, with and without electrode application, using four different samples: (a) SJ2, (b) SJP2, (c) INT2, and (d) INTP2.

3.5. Pressure Distribution Result: Experimental (PPS) vs. CLO3D's Built-in Pressure Map

To further analyze CLO3D's built-in pressure feature, we compared its pressure distribution map with experimental measurements from the pressure sensor (PPS). The overestimation in CLO3D was particularly evident with the plaited composite knit structures like SJP2 and INTP2. As shown in Table 5, CLO3D consistently displayed a smooth and homogeneous pressure distribution with a color gradient indicating the pressure levels in kPa. However, the PPS pressure maps, in contrast, revealed more realistic, granular representations of the actual pressure distribution, with lower average pressure that aligned better with the physical properties of the fabric and its interaction with the body. Notably, the discrepancies became more pronounced at stretch levels exceeding 15%. While CLO3D showed continuous, smooth gradients with pressure exceeding 13 kPa, the PPS displayed more complex profiles with distinct peaks and troughs, typically in the 4–5 kPa range. This comparison highlights that the actual pressure distribution is far from uniform and is significantly influenced by the fabric characteristics and body contours—factors that CLO3D's algorithms may not fully account for. The overestimation in CLO3D likely stems from limitations in modeling the mechanical interactions between composite knits and the body, especially under higher fabric stretch.

Table 5. Discrepancies between CLO3D-simulated pressure maps and PPS experimental pressure maps across different fabric structures.

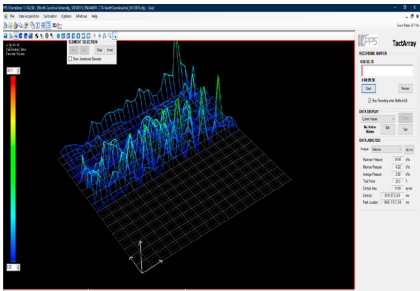
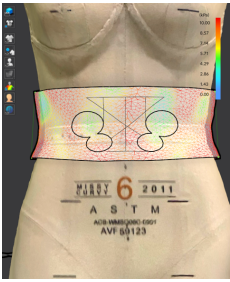
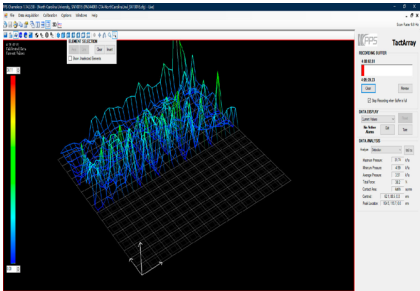
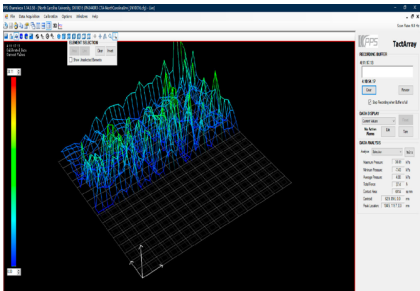
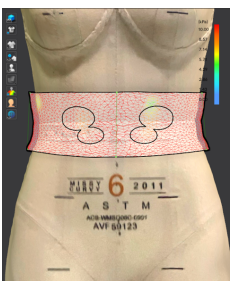
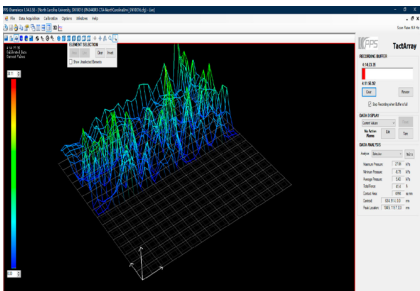
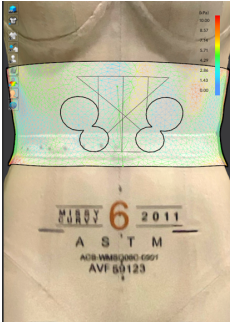
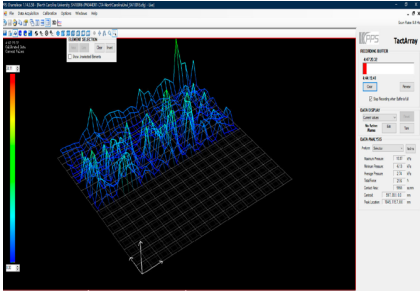
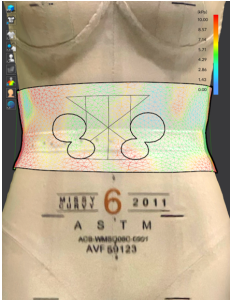
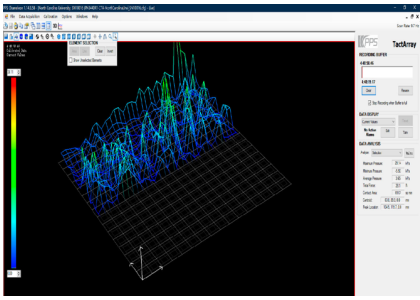
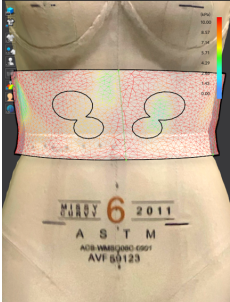
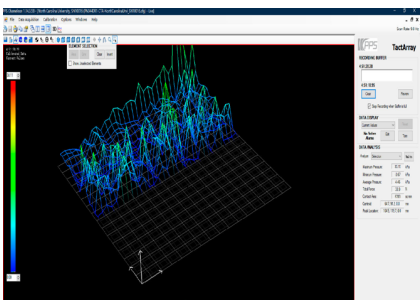
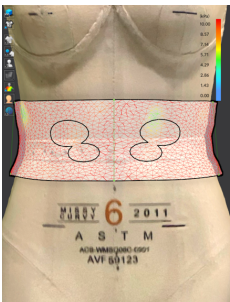
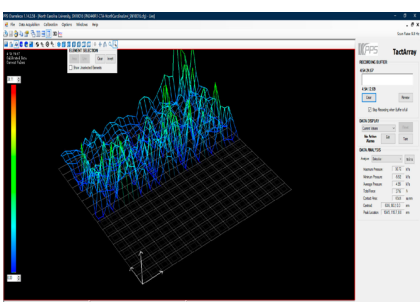
Sample	CLO3D Pressure Map	PPS Pressure Map
SJP2_5%		
SJP2_10%		
SJP2_15%		
SJP2_20%		
INTP2_5%		

Table 5. Cont.

Sample	CLO3D Pressure Map	PPS Pressure Map
INTP2_10%		
SINTP2_15%		
INTP2_20%		

These findings suggest that while CLO3D is helpful for general garment design, it requires cautious interpretation and supplementary validation when applied to medical compression garment engineering. Incorporating Youn’s CP model, which accounts for the digitized stretch stiffness, the fabric thickness, and the body’s circumference—factors influenced by a theoretical model (Laplace’s law)—could enhance the accuracy of pressure predictions and better reflect the complex interactions between the fabric and body in medical applications.

4. Future Research

Future research should aim to enhance the capabilities of the 3D garment simulation software by developing advanced algorithms that better account for the non-linear behavior of complex fabrics, particularly at higher strain levels. Improving the precision of virtual pressure predictions could significantly optimize the design of medical compression garments, reducing the reliance on physical prototypes. Additionally, integrating virtual fit technology with smart textiles, such as e-textiles for health monitoring, could expand the scope of medical applications. Conducting long-term in vivo studies would provide critical data on the durability and sustained performance of these garments.

5. Conclusions

This study aimed to assess the practicality of using CLO3D’s built-in pressure mapping feature to design medical compression garments. This study highlights the limitations

and potential of using CLO3D's built-in pressure mapping for medical compression garment design. While CLO3D provides a useful general framework for garment design, the overestimation of the pressure values—particularly with composite knit structures—underscores the need for more tailored simulations when designing precision-dependent medical garments. The comparison between CLO3D's pressure maps and the experimental data revealed significant discrepancies, especially at higher stretch levels, indicating that CLO3D's current algorithms may not fully capture the complex mechanical interactions between fabrics and the body. Incorporating more advanced models, such as Youn's CP model, which considers digitized parameters like the stretch stiffness, fabric thickness, and body circumference, can offer more accurate pressure predictions. This approach would significantly improve the reliability of virtual simulations for the design of medical-grade compression garments, reducing the need for extensive physical prototyping and leading to better patient outcomes. Moving forward, the further refinement of such simulation tools will be essential for the integration of e-textiles and for advanced functionality in therapeutic applications.

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