A Comparative Study of 3D Simulation and Scanning Technologies for Virtual Fabric Testing Laboratory: Tensile Tester

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Abstract

The textile and apparel industries are undergoing a digital transformation, leveraging three-dimensional (3D) apparel prototypes to increase efficiency and reduce costs. While 3D scanning and simulation technologies have advanced significantly, the development of virtual fabric testing equipment is still in its early stages. A virtual fabric test laboratory represents a promising solution to the challenges associated with traditional testing methods, such as high costs, extensive labor requirements, and material waste.

This study aims to bridge the gap between 3D simulation and real fabric appearance by comparing mesh-based models obtained through 3D scanning and simulation technologies. The goal is to evaluate if 3D simulation can accurately represent the real-world tensile behavior of fabrics. To achieve this, we created a virtual tensile tester in 3DS Max and used it to stretch virtual fabrics to obtain 3D models in CLO 3D software. We then contrasted the 3D simulated fabric—digitized from physical property tests using the CLO Fabric Kit—with results from 3D and 4D scanning. These comparative findings are anticipated to lay the groundwork for devising a virtual tensile test that accurately mirrors real-world fabric behavior, thereby bringing the virtual testing environment closer in visual resemblance to the physical one.

Keywords: 3D simulation, 3D scanning, Virtual modeling, Mesh models comparison, Virtual prototyping, Virtual fabric test

1. Introduction and Research objectives

In modern textile and fashion industries, virtual tests have emerged as an increasingly popular method, owing to their ability to conserve materials, reduce costs, and minimize labor, in contrast to traditional testing methods. [1] Although there's increasing literature on the current state of digital technologies in the textile and fashion sectors, research into virtual fabric testing remains rare. Most studies have centered around examining the fit performance discrepancies between real and digitized garment representations [2]. Yet, there's a gap in addressing an objective comparison of the appearance and mechanical behavior of real fabrics versus their digital versions—especially given that humans tend to prioritize visual information [3].

Furthermore, technical challenges often arise during fabric digitization, leading to potential mismatches between virtual and physical fabrics due to errors in the digitization process or challenges in capturing intricate textures and patterns [4]. As such, perfecting virtual testing methods is paramount to ensuring accurate representation and comparison between digital and real fabrics.

The primary objective of this study is to assess the accuracy of 3D simulation technology in replicating the tensile behavior of actual fabric within a virtual environment. To do this, we compared the 3D simulation against results from both 3D and 4D scanning, under the assumption that these scanning techniques offer the most reliable capture of real-world fabric behavior.

This study potentially lays the foundation for creating a tensile tester in 3D simulation, paving the way for a comprehensive virtual fabric testing lab. The research also intends to offer significant support to users of 3D clothing and fabric simulations, particularly to fabric and apparel developers who incorporate 3D simulation technologies into their product design and development processes.

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2. Experimental Method

2.1. Materials and Textile Digitization

In this study, a plain knit fabric was used as the sample, as shown in Table 1.

Table 1. Material characterization and digitized parameters for simulation

Material Characterization	Thickness (mm)	0.41
	Weight (g/m^2)	119.70
	Fabric construction	Plain rib
Digitized Parameters	Stretch Stiffness (weft, g/s^2)	23698
	Stretch Stiffness (warp, g/s^2)	56123
	Stretch Stiffness (bias, g/s^2)	93641
	Bending Stiffness (weft, g·mm^2/s^2/rad)	182
	Bending Stiffness (warp, g·mm^2/s^2/rad)	504
	Bending Stiffness (bias, g·mm^2/s^2/rad)	581

To virtualize fabric, it is required to measure the fabric's physical properties and then digitize these properties through an emulation process. In this study, CLO Fabric Testing Kit 2.0 was employed to measure the fabric's weight, thickness, bending, and stretch properties, as guided by the kit's manual [5]. For maintaining consistent control conditions, the CLO stretch tester from the testing kit was employed to stretch fabric samples, subsequently serving as the basis for our simulations. We selected the CLO stretch tester primarily due to its portability, making it more convenient to be scanned than other specialized fabric-stretching equipment. The CLO Fabric Testing Kit comprises a suite of instruments developed by CLO to digitize fabric for utilization in their 3D clothing design software [6]. As outlined in the Fabric Kit Manual by CLO, the stretch tester evaluates fabric stretch by analyzing the correlation between the stretch length and the exerted force. To conduct a test, users secure the fabric swatch at both ends on the fabric bed. With the digital force gauge turned on, the fabric is pulled to specific lengths, and the force applied during each interval is recorded. A minimum of three and a maximum of five measurements are recorded per swatch, ensuring accuracy. In this testing methodology, the fabric sample was extended from one end. For the purposes of this study, the stretching technique was employed to incrementally stretch the fabric. We executed five stretches, elongating the fabric from 20 cm to 25 cm, with pauses at every 1 cm interval.

The fabric sample prepared as the specifications of the CLO stretch tester, measured 22 cm x 3 cm. As indicated in Fig.1, the 1 cm width portions on both ends of the fabric were used to anchor the sample to the tester. As such, these segments remained static and did not undergo stretching. Consequently, the effective length of the fabric sample subjected to stretching was 20 cm.

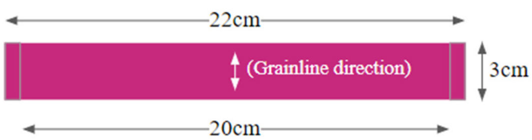


Fig. 1. Fabric sample dimensions

2.2. Simulation technique

In echoing the CLO stretch tester's operation, an animated two-stick model was developed in 3DS Max (version 25.3.3.6012) to produce virtual tester 3D object files. As illustrated in Fig. 2, the initial separation between the two sticks was established at 20 cm, reflecting the active stretch length of the actual fabric sample. While one stick remained stationary throughout the simulation, the other was animated to undergo translational movement, pausing at every 1 cm increment from 0 cm to 5 cm.

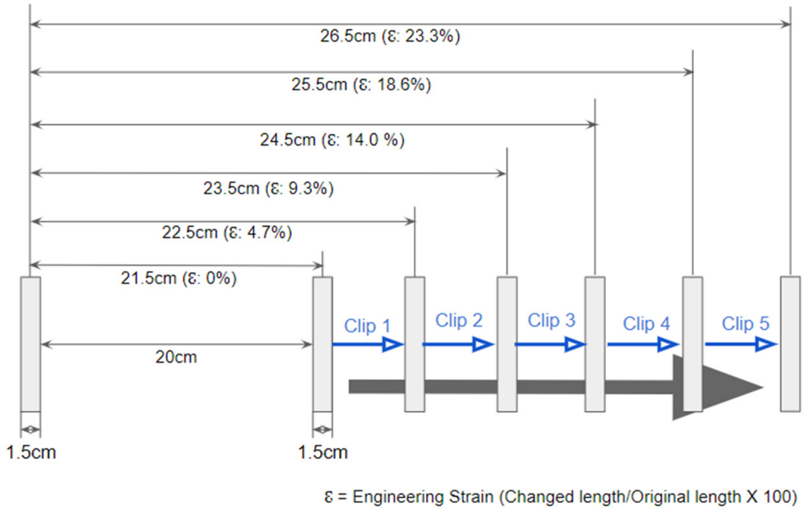


Fig. 2. Modeling and animation principle of the virtual stretch tester

This dynamic stick was configured to progress at a uniform speed, covering 1 cm in 6 seconds. This animation was for integration into the CLO software to facilitate the fabric stretching simulation. The "nonlinear simulation" option was activated within CLO settings to ensure precise elongation simulation [7].

To consider the potential influence of the digitally attached fabric on the stretching dynamics, two virtual tester prototypes were devised based on the two-stick model:

- The first prototype, as illustrated Fig. 3,consisted of two sticks, each 3 cm in length. Within CLO, a wrap was rendered to envelop the sticks, allowing the simulated fabric to be attached (or "virtually sewn") to them. These wraps were modeled using a trim material, denoting its rigid nature devoid of the soft fabric's pliability.
- The second virtual tester, as illustrated Fig. 4, incorporated two sticks, each 9 cm in length. A loop structure was crafted in CLO, comprising two rigid black sections (similar in material to the first tester's wrap) and two fabric segments. The top fabric section was the focus for comparison, while the bottom segment ensured structural stability during the stretching simulation. At the beginning of the simulation, the rigid sections aligned centrally with both sticks.

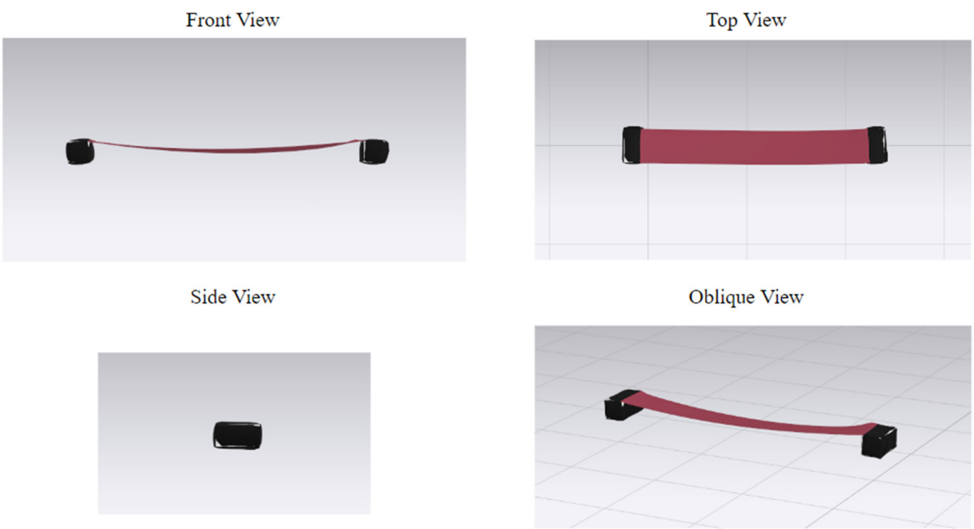


Fig. 3. The first virtual stretch tester proposed

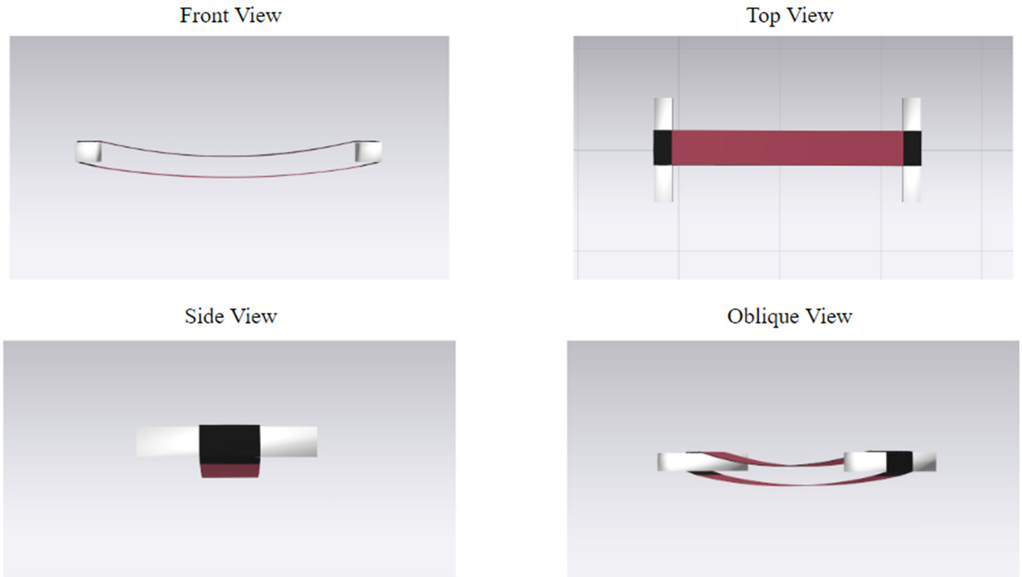


Fig. 4. The second virtual stretch tester proposed

Through a subjective visual assessment relative to the appearance of the physically stretched fabric, the loop configuration in the second tester exhibited more visually coherent comparisons. The key distinction between the two tester prototypes is the deformation observed along the two ends of the fabrics. The first model employing a virtual sewing technique, manifested pronounced distortions when stretched a lot. Fig. 5 shows the difference between the two testers when the fabric was stretched to its maximum length of 25 cm in this investigation. Notably, this deformation was significantly different from the characteristics observed with real fabrics when secured by the tester's clamps and stretched. Conversely, the loop method used in the second tester was much closer to how real fabric behaves. Therefore, we selected the devised second tester (or called “loop tester”) for the tensile testing simulation.

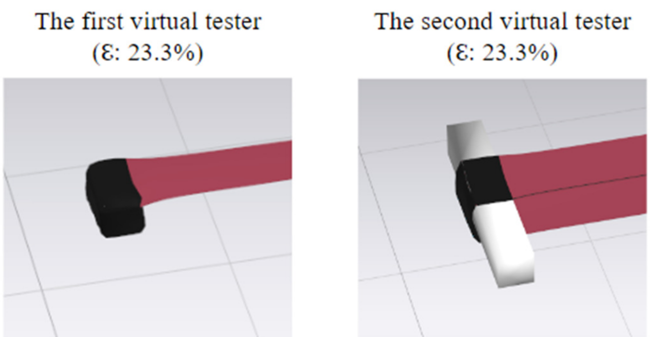


Fig. 5. Comparing the two virtual stretch testers proposed (Ɛ: 23.3%)

2.3. Scanning Techniques

2.3.1. 3D Scans

The Artec Leo handheld scanner was employed to capture 3D scans of the CLO stretch tester as it stretched the actual fabric sample. The scanner demonstrated a commendable accuracy especially in obtaining data from hard-to-access areas and in merging multiple scans [8]. Such precision proved indispensable for this research, facilitating the creation of high-fidelity soft fabric scans [9].

The CLO stretch tester was positioned on a flat table surface. We successfully acquired five distinct scans, each corresponding to a 1 cm incremental stretch of the fabric, ranging from 0 cm to 5 cm. These five scans were conducted consecutively on the same fabric piece across five successive stretches.

2.3.2. 4D Scans

The MOVE4D scanner, accessible in Human Solutions of North America, Inc., was employed to obtain 4D scans. This device encompasses 12 scanning modules, capable of capturing motion with a spatial resolution as fine as 1 mm and at rates reaching 178 frames per second [10]. In this study, the fabric sample was subjected to five sequential stretches, each captured in its own scanning clips as illustrated in Fig #, which depicts the animation principle of the virtual stretch tester. For each scan clip—corresponding to a 1 cm stretch—we configured the settings to 30 FPS over a span of 6 seconds. Consequently, this yielded both simulated and 4D scanned clips that are dynamic models comprising a total of 180 frames across 6 seconds. Such a setup facilitates a direct frame-by-frame comparison between the two.

2.4. Data analysis

In this study, 3D scans were derived and exported as OBJ mesh model files using Artec Studio 17 (version 17.1.0.141). Within Artec Studio 17, we refined the OBJ mesh models by removing erroneous frames, merging the remaining accurate frames, and fine tuning both mesh and texture. These resultant 3D models, high in precision, comprised approximately 75,000 meshes that focused on our fabric sample. On the other hand, 4D scans were directly exported as PLY cloud point files post-scanning. Given that the 4D scan software is mainly for human-scale scanning and data processing, appropriate ways to modify the exported 4D scans were elusive, so no alterations to these 4D scan files were made prior to subsequent data analyses. These 4D cloud-point models were also of high precision, containing around 11,000 points that focused on the fabric sample.

The CLO-based simulations were configured for a 5 mm particle distance. Simulations extracted from CLO were exported as standard OBJ mesh model files. Only the virtual fabric samples were encompassed within these mesh models, yielding medium-resolution 3D models with approximately 3,000 meshes.

Upon preparing the scan and simulation models, we employed CloudCompare (version 2.12.alpha, dated 07-05-2023) for visualization and comparison [11]. Both 3D and 4D scans underwent segmentation, isolating the fabric samples from extra elements, thereby facilitating alignment with the CLO-simulated mesh models. However, we faced an issue with the 3D scans. The fabric samples were very close to the fabric bed of the stretch tester, and the handheld scanner blended the two together during processing. This resulted in superfluous spatial data (attributed to the fabric bed) incorporated into the 3D scans during comparative analysis.

Comparing the 3D simulation to the 3D and 4D scans required initial alignment of the simulated and scanned models. This was manually executed, primarily because our alignment protocol — which focused on lining up the corners of the fabric samples and ensuring the holder side matched up — was hard to set up automatically in CloudCompare. Therefore, careful manual work was conducted to ensure accurate alignment. Fig. 6 gives examples of these alignment results using 3D and 4D scans.

Fig. 6. Examples of alignment results

Upon achieving alignment, the "compute cloud/mesh distance" function was utilized to determine distances [11].We set the simulated model as reference in these comparisons. Consequently, scalar field maps superimposed on the scanned model illustrated the spatial distribution and histogram of computed distances, alongside metrics such as average, minimum, and maximum approximate distances.

3. Results

3.1. Comparative Analysis Between 3D Simulation and 3D Scan

For the CLO-based 3D simulation, the animated two-stick model was devised to incrementally stretch the fabric by a consistent 1-cm interval. The side length of the simulated fabric strip, as illustrated in Fig. 7, was measured and compared with the 3D scans.

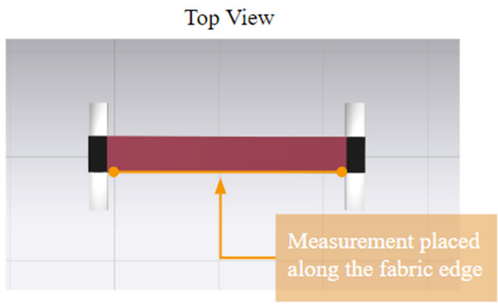


Fig. 7. Fabric length measured on simulation

The comparative measurements between the simulated fabric and the 3D scans are tabulated in Table 1.

Table 1. The measurement difference of the real, 3D simulated, and 3D scans according to the stretch variations

Stretching ratio (%)	0	4.7	9.3	14	18.6	23.3
Simulation (cm)	20.18	20.93	22.38	23.34	24.36	25.36
3D scan (cm)	19.88	21.01	21.94	22.75	23.76	24.86
Percent difference between 3D scan and simulation (%)	1.51	0.38	2.01	2.59	2.53	2.01

The central lengths derived from the 3D fabric scans align closely with the anticipated fabric stretching behavior, evidencing extensions to 21cm, 22cm, 23cm, 24cm, and 25cm. As delineated in Table 1, the 3D scans rendered measurements of 19.88cm, 21.01cm, 21.94cm, 22.75cm, 23.76cm, and 24.86cm. These values display a marginal percentage discrepancy ranging from 0.05-1.09% relative to the anticipated values, thereby endorsing the 3D scans as credible digital proxies of the real-world fabric samples.

Using the 3D scan results as a benchmark, differences in side length percentages between the 3D simulations and the 3D scans ranged from 0.38% to 2.59%. Such variations underscore the anisotropic behavior exhibited by the simulated fabric upon virtual stretching. Specifically, this suggests that the central width of the virtual fabric specimen contracted, rendering it comparatively narrower than the width at both clamped edges. This phenomenon is consistent with the bell-shaped deformation observed in the center of the simulated fabric upon stretching, as depicted in Fig.8.

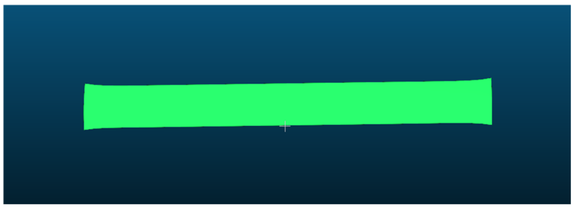


Fig. 8. The bell shape of the simulated fabric (Ɛ: 23.3%)

In our subsequent analysis, we meticulously quantified the mesh-to-mesh distance differences between the 3D simulations and the 3D scans across all extension states, spanning stretching ratios from 0% up to 23.3%. Table 2 delineates the evolution of average mesh-to-mesh distance values with progressive stretching, offering insights into the general deformation consistency between the 3D simulations and the 3D scans under identical stretching conditions.

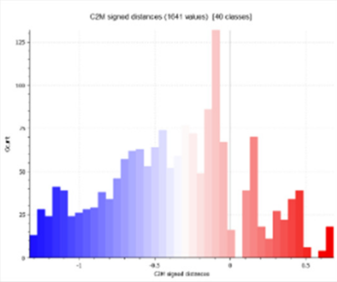
Table 2. Mesh-to-mesh distances between 3D simulation and 3D scans

Stretching ratio	Ɛ: 0%	Ɛ: 4.7%	Ɛ: 9.3%	Ɛ: 14.0%	Ɛ: 18.6%	Ɛ: 23.3%
Avg. (cm)	0.70	0.24	0.18	0.19	0.22	0.17

An elevated average value signifies a greater difference between the 3D scans and simulations, implying that the simulation may be less reflective of real-world behavior. As evidenced in Table 2, in the unstretched state (Ɛ: 0%), the mesh-to-mesh distances exhibit their peak average value, indicating the most pronounced difference between the 3D simulated fabric specimen and its real-world scanned counterpart. As the fabric undergoes further stretching, this average distance diminishes, suggesting that the visual attributes of the simulated fabric increasingly converge with those of the 3D scans.

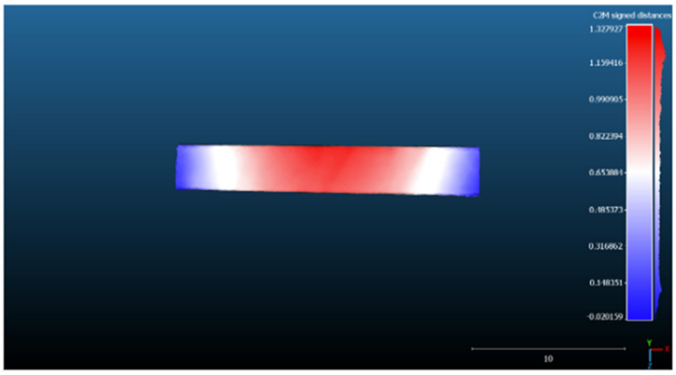
Moreover, we investigated the color scalar field maps and histograms which depicted the spatial distribution of mesh-to-mesh distance counts, thus providing insights into the deviations across the surface of the stretched fabric. The 3D simulation was designated as the reference for the comparison with the 3D scans.

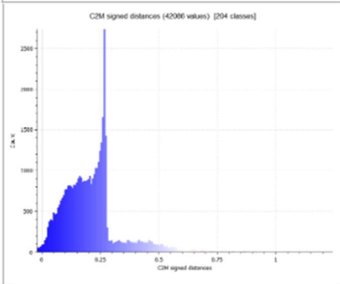
A more comprehensive comparison between the 3D simulations and 3D scans—including histograms, scalar field maps, and essential metrics—is presented in Fig.9, which accentuates strains at 0%, 4.7%, and 23.3%.



1	Min dist.	0
2	Max dist.	1.41603
3	Avg dist.	0.703676
4	Sigma	0.388382
5	Max error	0.0786681

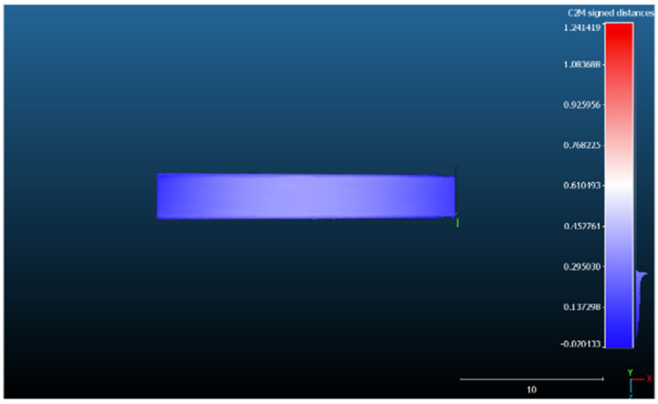
Ɛ: 0%

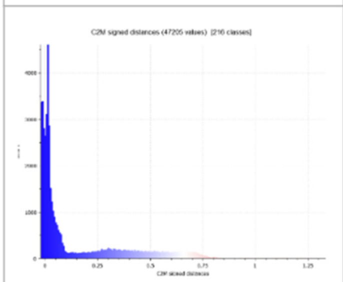




1	Min dist.	0
2	Max dist.	1.25106
3	Avg dist.	0.241159
4	Sigma	0.130429
5	Max error	0.0821359

Ɛ: 4.7%





1	Min dist.	0
2	Max dist.	1.4353
3	Avg dist.	0.167441
4	Sigma	0.262106
5	Max error	0.0995203

Ɛ: 23.3%

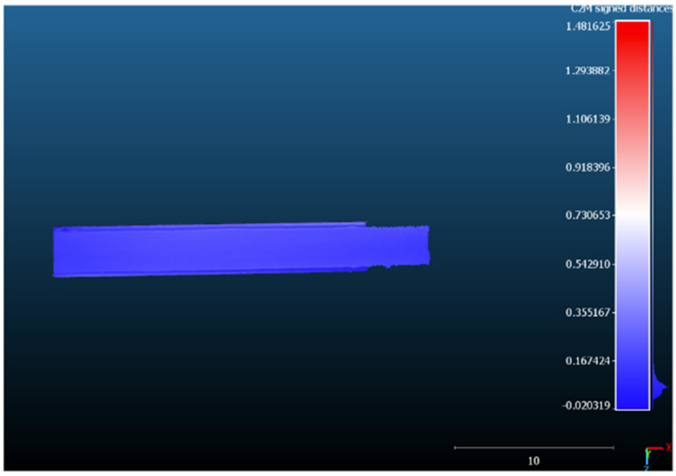


Fig. 9. Comparative analysis of 3D simulations and 3D scans: histogram, scalar field Maps, and key metrics (Ɛ: 0%, 4.7%, and 23.3 %)

As illustrated in Fig. 9, when the fabric remains unstretched (Ɛ: 0%), the histogram indicates a substantial range in distance distributions, spanning from -0.02 to 1.00 cm. The scalar field map, superimposed on the 3D scans, employs a blue-white-red-colored system to signify deviations: red signifies positive deviations relative to the reference, suggesting that the central segment of the simulated fabric strip is positioned about 1 cm lower than its real-world counterpart. Conversely, blue indicates negative deviations, revealing that the two ends of the simulated fabric are elevated by roughly 0.02 cm, compared to the real fabric sample. The neutral white zone, representing a distance interval between -0.5 cm and 0 cm, denotes the most similar regions between the simulated and scanned fabrics. In addition, at strains of 4.7% and 23.3%, the histogram reveals a diminished distance variation across its spatial distribution. This suggests an enhanced consistency between the simulated and the 3D scanned fabrics. This observation is consistent with the previously noted decrease in the average mesh-to-mesh distance value as the fabric stretches. It's essential to acknowledge that since the 3D scans incorporate segments of the fabric bed, the actual average distance would likely be even lower.

A more detailed examination of the scalar field maps at strains of 4.7% and 23.3% shows that at strains of 4.7%, the simulated representation aligns more closely with the 3D scan than of 23.3%. This transition can be visualized in the central region of the fabric strip where the mixed white-blue hue gradually shifts to a dominant blue from strain of 4.7% to 23.3%. This dominant blue hue in the scalar field map at a strain of 23.3% suggests that the simulated fabric appears slightly elevated compared to its real-world counterpart. This observation might indicate an over-extension in the simulation, suggesting the simulated fabric could be rendered too flat.

3.2. Comparative Analysis Between 3D Simulation and 4D scanning

We extended our comparison to a frame-by-frame analysis between the 3D simulations and the 4D scans. 4D scans were represented by point clouds, in contrast to the mesh models of the 3D scans. To determine the discrepancies between these point clouds and the simulated mesh, we utilized the Cloud-to-Mesh (C2M) computation function in CloudCompare. Table 3 delineates the average C2M distances at specific stretching ratios: 0%, 4.7%, 9.3%, 14%, 18.6%, and 23.3%.

Table 3. Cloud-to-Mesh (C2M) Distances between 3D simulation and 4D scans

Stretching ratio	Ɛ: 0%	Ɛ: 4.7%	Ɛ: 9.3%	Ɛ: 14.0%	Ɛ: 18.6%	Ɛ: 23.3%
Avg. (cm)	0.83	0.14	0.14	0.14	0.16	0.14

These ratios correspond to the same elongations that applied in the 3D scanning tests. As observed, with increasing fabric stretch, the average C2M distance reduces markedly, spanning from 0.83 cm at no stretch to a mere 0.14 cm at a 23.3% stretching ratio. This pattern mirrors the observations from our earlier comparison between the 3D scans and the simulation. Furthermore, the average distances in this 4D comparison are more definitive than in the preceding 3D scan-simulation comparison. This heightened precision can be attributed to the accurate point clouds of the 4D scans, which can be meticulously segmented within CloudCompare.

Moreover, upon closely examining the strain range from 0% to 4.7%—where the most pronounced change in average distance is observed— Table 4 exhibited that during the initial phase of stretching, spanning from 0% to 1.6% strain (equivalent to the first 60 frames over a 2-second duration), there was a significant reduction in the average C2M value; following this brief period, the behavior of the 3D-simulated fabric begins to align more closely with the actual behavior of the stretched fabric.

Table 4. Cloud-to-Mesh (C2M) Distances between 3D simulation and 4D scans (Ɛ: 0% - 3.9%)

Stretching Ratio	Ɛ: 0%	Ɛ: 0.8%	Ɛ: 1.6%	Ɛ: 2.3%	Ɛ: 3.1%	Ɛ: 3.9%	Ɛ: 4.7%
Frame	1	30	60	90	120	150	180
Avg. (cm)	0.83	0.50	0.24	0.21	0.17	0.17	0.14

Furthermore, we extended the analyzing approach used for the comparison between 3D scans and 3D simulations to examine the deviations distributed across the surface of the stretched fabric. This involved investigating scalar field maps and histograms depicting the spatial distribution of C2M distance counts across the five key stretching states, as shown in Fig. 10.

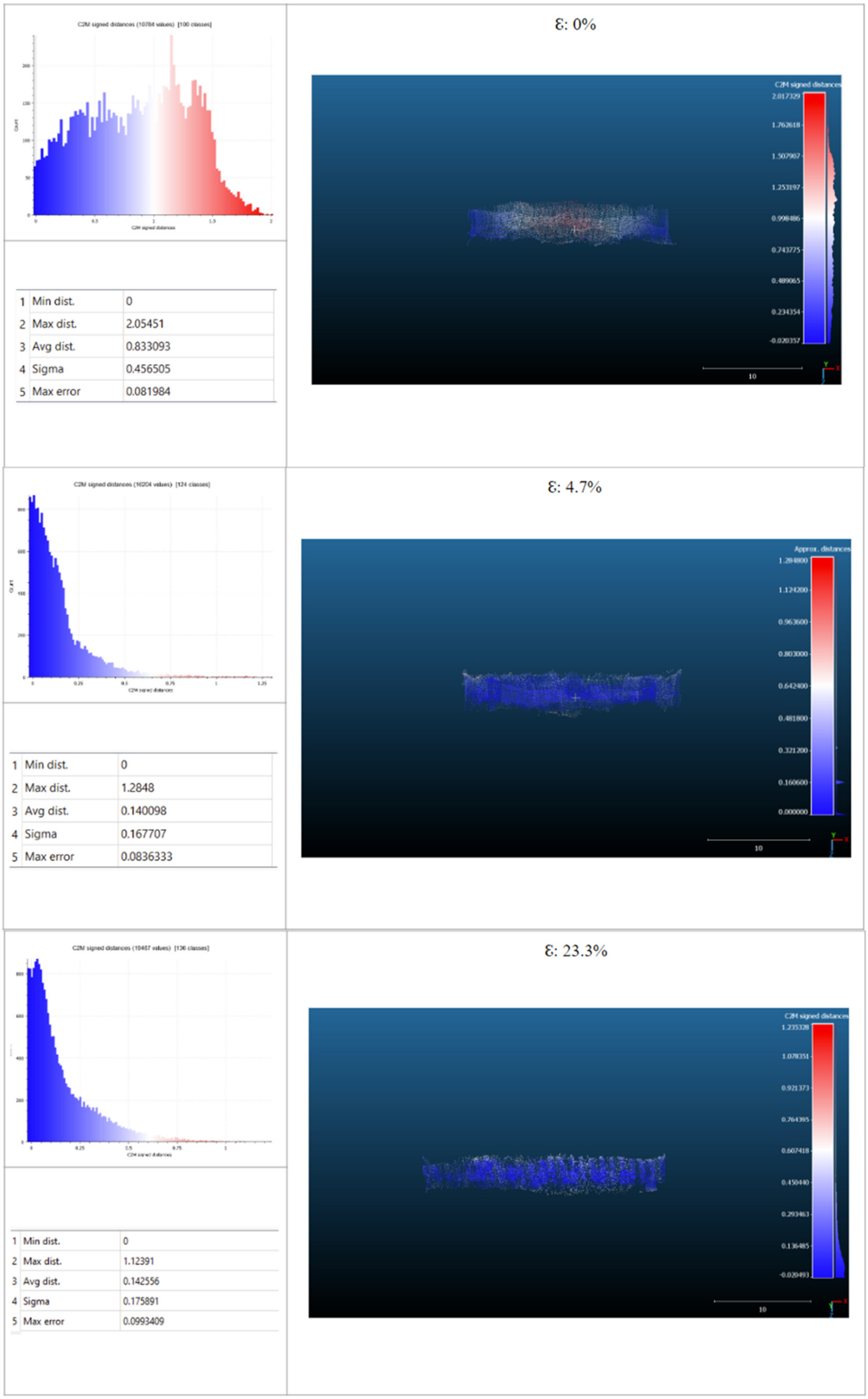


Fig. 10. Comparative analysis of 3D simulations and 4D scans: histogram, scalar field Maps, and key metrics (Ɛ: 0%, 4.7%, and 23.3 %)

The representatives of the stretching states are also characterized by strains of 0%, 4.7%, and 23.3%. As indicated in Fig. 10, the observation corroborated earlier findings, underscoring a similar stretching pattern wherein the variability in spatial distance distribution diminishes progressively from a strain of 0% to 23.3%. It's also observable that at a strain of 4.7%, the simulated fabric more closely mirrors the 3D scans than at a strain of 23.3%. The legend accompanying the scalar field maps on the right side of the figures, sheds light on this trend, indicative of the reduced distance variability at the 4.7% strain mark. However, the visual representation of superimposed cloud points doesn't offer a clear insight into the spatial distribution of varied distances—not with the clarity that solid color areas on 3D scans provide.

4. Limitation and Future Works

While this study provides valuable insights, there are some limitations that should be considered. Firstly, the comparative analysis between the simulation and 3D scans mentioned that the scans captured parts of the fabric bed. Due to mesh model processing constraints, differentiating the thin fabric sample proved challenging. Consequently, the exact deviation between the simulation and the 3D scans remains unidentified in our findings. Future research should focus on refining 3D scan processing to clearly separate such delicate fabric samples.

Secondly, the manual alignment process between the simulations and scans makes deducing the spatial relationship using minimum and maximum distances challenging. Subsequent studies should prioritize developing more precise and efficient alignment strategies.

5. Conclusion

Synthesizing the results, our main conclusions are as follows.

- Predictive accuracy of the virtual stretch tester: By analyzing the consistent stretching simulation patterns observed both in the comparison between simulations and 3D/4D scans, it's evident that our proposed CLO-based virtual stretch tester can reasonably predict the final state after stretching deformation. However, the entire deformation process remains a challenge for the simulation to forecast accurately. Specifically, in the initial phase, which lasts roughly two seconds from the onset of stretching, the simulation experiences the most difficulty in accurately reflecting real-world behavior, with an average deviation exceeding 0.24cm. This insight underscores the need for future research to finetune the initial settings of the loop tester to more closely emulate an actual fabric's static state.
- Overstretching in the simulation: The virtual fabric appears to be overstretched within the simulation relative to its real-world counterpart. This discrepancy raises questions about the stretching parameters used in the simulation, suggesting a need for recalibration.
- Mesh vs. Cloud-Point Models: While the mesh model provides a clear and efficient means of data processing, the cloud-point model might serve as a more precise representation of a fabric's intricate appearance, as the cloud-point model allows for the capturing of minute details. The granularity of cloud-point models, particularly those derived from 4D scanners, captures the finer details of real-world fabrics. Future studies should focus on integrating advanced data processing techniques to facilitate a more comprehensive frame-by-frame analysis, broadening its applicability across a variety of fabrics.
- This research has significant implications for 3D digital technology users, particularly fabric and apparel developers who utilize 3D simulation in design, development, and testing phases. A virtual testing platform that better replicates real-world conditions not only reduces costs and diminishes material waste but also enhances product quality. Additionally, this study resonates with Industry 5.0 principles, underlining the urgency to reduce energy consumption, labor, and material waste.

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Reference

[1] S. H. Shin & H. Lee, “The use of 3D virtual fitting technology: comparison between sourcing agents contractors and domestic suppliers in the apparel industry”, *International Journal of Fashion Design, Technology and Education*, Vol. 13, No. 3, 2020, pp. 300-307, https://doi.org/10.1080/17543266.2020.1797905.

[2] Teyeme, Y., et al, “Fit and pressure comfort evaluation on a virtual prototype of a tight-fit cycling shirt”, *Autex Research Journal*, Vol. 23, No. 2, 2023, pp. 153-163, https://doi.org/10.2478/aut-2021-0057.

[3] B. Shin, et al., "Development of a Simple Drape Measurement Method for 3D Virtualization." *Journal of the Korean Society of Clothing and Textiles,* Vol. 45, No. 5, 2021, pp. 881-891, https://doi.org/10.5850/JKSCT.2021.45.5.881.

[4] H. Kim, et al., "Indexing surface smoothness and fiber softness by sound frequency analysis for textile clustering and classification." *Textile Research Journal,* Vol. 91, No. 1, 2021, pp. 200-218, https://doi.org/10.1177/0040517520935211.

[5] S. Youn et al., "Simulation-Based Contact Pressure Prediction Model to Optimize Health Monitoring Using E-Textile Integrated Garment," *IEEE Sensors Journal*, Vol. 23, No. 16, 2023, pp. 18316-18324, doi: 10.1109/JSEN.2023.3293065.

[6] “Fabric Kit Manual,” www.support.clo3d.com, 2020, https://support.clo3d.com/hc/en-us/articles/360041074334-Fabric-Kit-Manual

[7] “Complete Nonlinear Simulation,” www.support.clo3d.com, 2023, https://support.clo3d.com/hc/en-us/articles/115000560308-Complete-Nonlinear-Simulation-

[8] “Wireless Handheld 3D Scanner | Artec Leo,” www.artec3d.com, 2020, https://www.artec3d.com/portable-3d-scanners/artec-leo#tech-specs

[9] “Test and Evaluation of an Artec Leo 3D Scanner,” 2020, https://repository.lib.fit.edu/bitstream/handle/11141/3218/REICHARD-THESIS-2020.pdf?sequence=1

[10] “Move 4D - Product,” Move 4D, https://www.move4d.net/product/

[11] Carew, Rachael M., et al. "A multi-method assessment of 3D printed micromorphological osteological features," *International Journal of Legal Medicine,* Vol. 136, No. 5, 2022, pp.1391-1406, https://doi.org/10.1007/s00414-022-02789-y.