Methodology for Analysis of the Deformations of a Wetsuit Using 4D Scanning and FEM Simulation

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Abstract

As a recently established field, 4D body scanning offers significant potential for application in the clothing development. It enables various forms of analysis of the movement of a body, without having to physically interact with it or destroy it. The objective of this study is to identify the most optimal sequence of stages for preparing a sample for analysis and following scanning and FEM analysis. A body-clothing interaction between a neoprene surfing wetsuit and a person was taken as an example scenario to apply the steps on. The chosen example outlined various weak spots in the methodology at every stage of the process. The following issues were identified and subsequently addressed: failure of the homologous mesh generation process following 4D scanning, suit detection failure during scanning, suit digitalization, and complications associated with the simulation modelling process. Two separate material testing techniques are applied, ensuring that accurate material properties are obtained for the simulation phase. Each stage is discussed, outlining all assumptions and limitations taken into consideration. The results present a proposal of the most efficient analysis algorithm, including all issue workarounds. The methodology presents a method for improvement of higher performance wetsuits, by establishing precise simulation models and using high speed (4D) body scanning techniques.

1. Introduction

This paper introduces a recently emerging field of engineering that has gained traction due to its potential for application in a multitude of technological domains. The field of 4-Dimensional (4D) Object Scanning (3D + time) involves the digitalization and analysis of a 3-D body through capturing entire movement sequences, while maintaining the exact physical dimensions of the specimen.

An area where this approach finds a lot of application is the study of body-clothing interaction, especially in the field of sports, where all focus falls on the dynamics of a system. The higher the level of a sport, the greater the demand for better performance. Each particular sport has its dedicated set of equipment and when one is attempting to push the limit, the equipment matters.

Being a relatively new field, 4D scanning has not been researched and optimized as much as its predecessors. One of the biggest problems in that sphere is finding the most efficient sequence of operations, beginning from the harvest of an object and its movement, leading up to a detailed loading analysis and application.

In order to optimize and study the scanning process, the body-clothing interaction between a person and a surfing wetsuit has been taken as an example. Surfing is an extremely physically-demanding sport, where unrestricted movement is crucial and can be the difference between life and death.

Firstly, this study gives an overview of the current state and level of the scanning technology. Typical problems and workarounds are described and considered later in the process. Afterwards, a detailed methodology section follows, where each stage of the scanning analysis sequence is described, including any issues, solutions, and assumptions. Every stage unlocks a piece of the most optimal algorithm for the process, concluding with a finalized version of it.

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2. State of the Art

For the engineering development of functional clothing, body data has to be obtained from a static or dynamic body scan, then garments need to be created and finally their interaction with the body needs to be studied or simulated. The most crucial aspect to consider is the identification of the most prevalent movements typically undertaken within the operational context of the evaluated garment[1]. In addition, many papers focus on identifying the most critical pose with regards to the amount of deformation present in the clothing [1]. This step is crucial as every garment is designed to be used in a given environment, with some expected level of performance. This post-scan data capture and editing process has shapeshifted substantially throughout the last two decades. Paper [3] is one of the earlies studies published on the topic of clothing analysis through 3D scanning. That study utilizes a 2-camera scanning set up, which captures the front and the back of the model, resulting in poor detail capture. In order for garments to be created, precise body dimensions are necessary. These are extracted from the scans manually and purely mathematically by segmenting the scanned body into a set of circumferential curves. Even though more convenient approaches are available, some studies [2-5], apply tedious data analysis and extraction methods. Garment deformation is still largely monitored through extraction of vertex position and length change calculation between different frames of the captured movements. This is a restrictive approach, which requires substantial amounts of data and it does not provide adequate accuracy, due to possible mismatch in mesh element position [5].

One common approach to meshing and garment creation, which has been utilized since the first studies in the area, is the modelling of garment patterns straight off of the body scan [2, 5-9]. The garment patterns are necessary to create 2D flattened drawings of each clothing component. This would allow to manage the fit of the garment prior to manufacture. Initially, a mathematical approach has been utilized, where surfaces are approximated to fit the shape of a part of the body, while constrained by some known circumferential measurements such as bust or waist [3]. In almost every clothing-body interaction analysis paper, one can notice that the patterns have been modelled directly from the scanned human model. This means that every piece of clothing or segment extracted from it, fits the shapes and curves of the model perfectly. While being suitable for simulation, as it greatly eases the dressing of the clothing onto the mesh, this perfect fit is unrealistic. Real-life clothing always includes some gaps or folding, which are not considered when the patterns are generated from the human scan. In [6] the main issue is the discrepancy between measured and predicted results due to the perfect fit being unrealistic. Another drawback to that approach is evident in [4], where the deformation of the clothing is monitored through the distance change of mesh vertices between frames. For this method to work, the topology of each generated garment section needs to be identical for every frame. The algorithms presented in this paper offer a solution to all of these current issues, by adding a clothing reconstruction stage to the post-scan analysis process. The reconstruction stage generates the patterns from a static scanned pose where the clothing is pre-loaded by being worn. Each garment segment is then extracted from the dressed mesh and the clothing is reassembled in a simulation software, where the fit of the garment mimics the real fit, it was scanned with.

Simulating or analysing the response of a piece of clothing to loading is what the majority of studies aim to achieve. Proper garment generation is essential for the completion of this stage. Furthermore, sufficient information about the materials used in the physical is crucial, therefore this paper describes a thorough tensile testing process of several pieces of wetsuit neoprene.

3. Methodology

3.1. Wetsuit Specifics and Limitations

For this study the chosen wetsuit surfing example imposes several limitations to the analysis process:

- The scanning lab environment represents 12 cameras, capturing any movement constrained in a 2x2x2m cube volume, therefore movement had to be precise and calculated.
- A surfboard cannot be scanned with the person, since it would have to be manually removed after, leading to an unnatural movement, therefore the ground was deemed sufficient.
- Used wetsuit specimen is several years old with some of its physical properties having deteriorated, therefore a brand-new piece of neoprene has been used for dry and wet material testing.
- Cameras are unable to capture matte black specimen such as the suit in use, therefore white powdered chalk has been utilized to enhance the reflectivity of the surface.

In order to support this analysis optimization exercise, a neoprene, 5mm-thickness, hooded surfing wetsuit is scanned (*Figure 1*). The exact model is "*Xcel 6/5 Drylock Hooded Wetsuit"*, with variable thickness. Chest and back areas are of 6mm thickness, whereas all extremities are covered by 5mm of neoprene.

	Shoulder	Chest	Waist	Hip
Circumference [cm]	127	105	80	100
Model Height [cm]	179			

Figure 1: Scanned Surfing Wetsuit and Model Body Measurements

3.2. Scanning Process

The initial scanning stage of the process is the most important one, as any data harvest issues or inaccuracies, could potentially lead to substantial result discrepancies during later stages. For the sake of proper analysis of the surfing wetsuit example, two of the most typical movement patterns have been captured by separating one motion into two sections. This 4D scanning approach requires an initial set of scans, where the model is only in underwear or very tight-fitting clothing. This ensures that when the garment is generated and put on the naked model, there would be no gaps, due to previously recorded clothing. Prior to the dynamic capture, static undressed and dressed "A" pose scans are to be harvested (*Figure 2*) in order to allow the scanning software to register the exact dimensions of the specimen for both regimes and to locate critical topology such as joints and eyeline. These features are necessary for proper mesh generation, which is discussed in the following chapter (*see Mesh Generation)*. *Figure 2* also depicts the first part of a surfing movement, which is the "pop-up" motion, where the surfer stands up on their board to ride a wave.

Figure 2: Scanned Static A-Poses and Dynamic Surfing Movement

Ten scans of 30 frames each were recorded both for naked and dressed person. The second set of movements is the ending phase of the entire surfing motion, which focused on the arm and shoulder rotation of the surfer while steering the board.

Both of these movement patterns were an appropriate test for the scanning system as several problems arose upon reviewing the scanning data. Being a system of 12 cameras working syncronously, the scanner is able to generate a point cloud by triangulating and cross-referencing the position of each node between each camera. However, the tested Polychloroprene (Neoprene) suit was almost completely matte black. This proved to be an issue due to the low reflectivity of that surface. This ended up generating a point cloud, which had substantial data gaps (*Figure 3*).

This visual issue was solved by tracking where the non-reflective areas are from the test scans and applying white powdered chalk evenly across these surfaces. This is the reason why the suit on *Figure 3* is black and white. The chalk allows the scanner to recognize the surface and to construct a denser point cloud. Secondly, due to the nature of the movement, where the model needs to be laying on a board or in this case - on the ground, the scanning begins below the 42cm level of the lowest camera. This proved to be a problem, due to the insufficient amount of information sent to the software while locating the eyes of the person. Without having located the eyes and major joints of the model, the software is unable to automatically generate a mesh and outputs an incomplete point cloud. An attempt to resolve the height issue was made by elevating the model on a table and executing the movement on top of it, simulating a surfboard scenario.

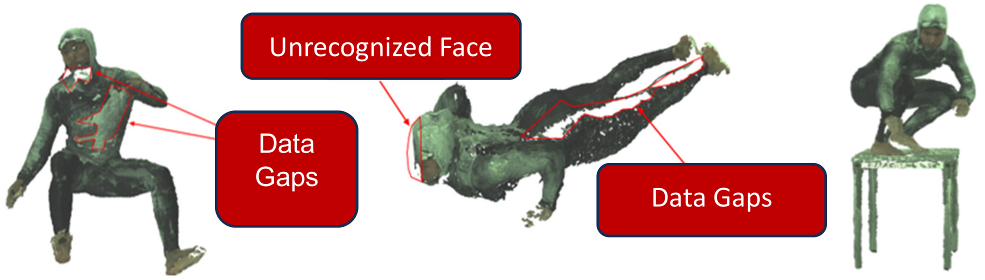


Figure 3: Post-Scan Reconstruction Data Issues and Adaptations

4. Mesh Generation

4.1. Automatic Mesh Generation

Following the scanning process, the collected data is to be filtered and a mesh is to be created. The Move4D scanner used for this paper comes with a software that runs all simplification, topology fixing, and meshing algorithms automatically. That is, provided that the scans were free from any issues, such as not being able to recognize the face of the model. The software creates a homologous surface mesh of the scanned specimen (see nomenclature for homology), which can be immediately used for some FEM cases. Typically, depending on the application, these surface meshes have to be transformed into volumetric meshes with internal elements, to obtain realistic FEM results. However, in the case of the dressed scans, the cameras were unable to recognize the position of the face, therefore the software failed to construct a homologous mesh for any of the movements. The homologous meshing was successful for the naked and dressed A-Poses, therefore those can be used throughout the paper for FEM, provided that they are taken through the necessary steps. This left us with two options, both of which have been explored in this paper, in order to show a complete spectrum of possibilities and solutions (Figure 4).

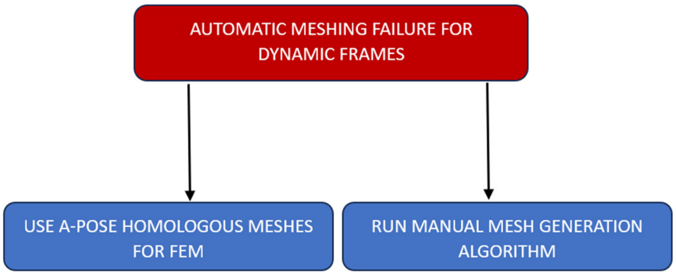


Figure 4: Two Mesh Generation Scenarios

4.2. Manual Mesh Generation

Due to the automatic mesh generation issue, a manual way to run an external point cloud to mesh algorithm had to be utilized. There are available open-source pieces of software such as MeshLab, which include several different meshing algorithms such as Poisson and Ball-Pivot. Figure 6 represents a surface meshes generated using the Poisson meshing algorithm in MeshLab. The generated mesh does not have topology, which is suitable for FEM, as the element sizes are non-uniform. After the surface mesh is constructed, a triangular or square retopology of the surface is applied to equalize the element sizes. This approach still creates a surface mesh, which is to be converted to volumetric if any loading analysis is to be conducted on the body.

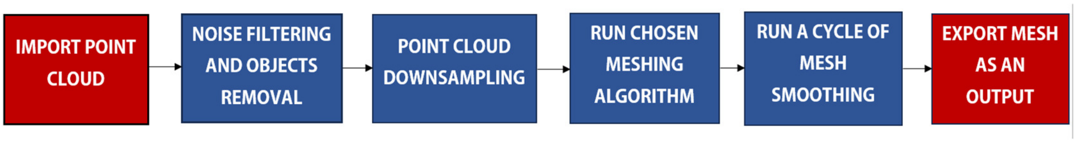


Figure 5: Manual Meshing Algorithm

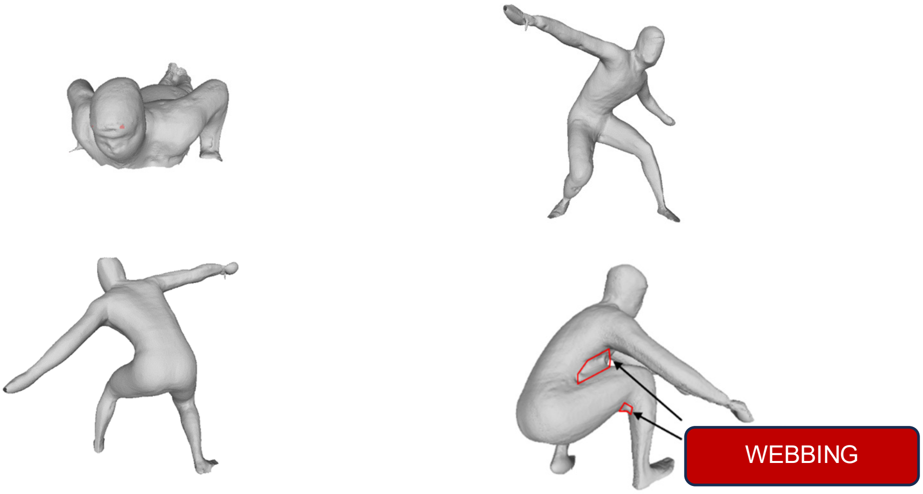


Figure 6: Manually Generated Meshes using Poisson's Surface Reconstruction Algorithm with Depth 12

4.3. Volumetric Mesh Generation, Issues and Assumptions

Regardless of the chosen meshing algorithm, any generated mesh is a surface mesh, meaning that the shape is hollow, with no internal elements. However, in the case of FEM, where loading might be applied on parts of the body, a volumetric mesh is crucial. The first option is assuming the surface mesh as a rigid hollow body for the simulation stage. This is an appropriate assumption, considering that we are interested in the response of the wetsuit to the body and it is the main assumption of this paper. As mentioned, the scanner software was successful in generating two sets of homologous meshes, one for the naked and one for the dressed case. This rigid assumption, allowed us to import sections of the homologous meshes into the simulation software instantly.

The second choice involves launching a volumetric mesh generation process, where the surface mesh is filled and segmented into internal mesh elements. This is so that when a load is applied, a more realistic protrusion of the deformation can be followed. There are several different pieces of software that generate volumetric meshes, however if this work path is chosen, a simple volumetric mesh would not yield realistic results. The creation of detailed testing dummies is a study area focusing on FEM simulation, where a body with its skeleton, joints, muscles, and organs is modelled. This is crucial for impact analysis, such as car safety tests, however for this example, that process is only described as a possibility.

5. Clothing Digitalization

Typically, every body-clothing interaction process involves a stage, dedicated to extracting the clothing from the dressed scan. This is done so that the specimen can be transformed into garment items, which can be imported into clothing analysis software such as *VStitcher* [13]. These programs enable the separate garments to be sewn together to form the clothing and dress the naked mesh. Through these steps one can manage properties such as the fit of the clothing, the pressure applied on the model, and the stretch of the material by adjusting the garment dimensions. The following algorithm represents the innovative approach of this paper, where all garments are stripped from the suit in the 3D modelling software *Blender* [12] (*Figure 7*).

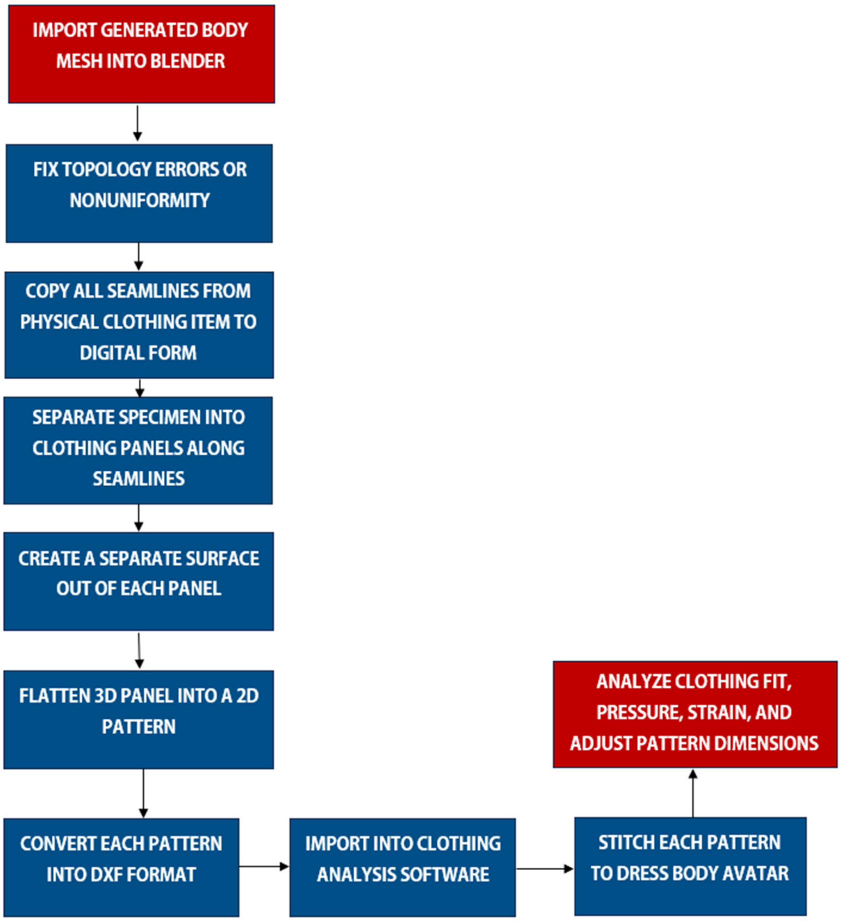


Figure 7: Suit Reconstruction Workflow

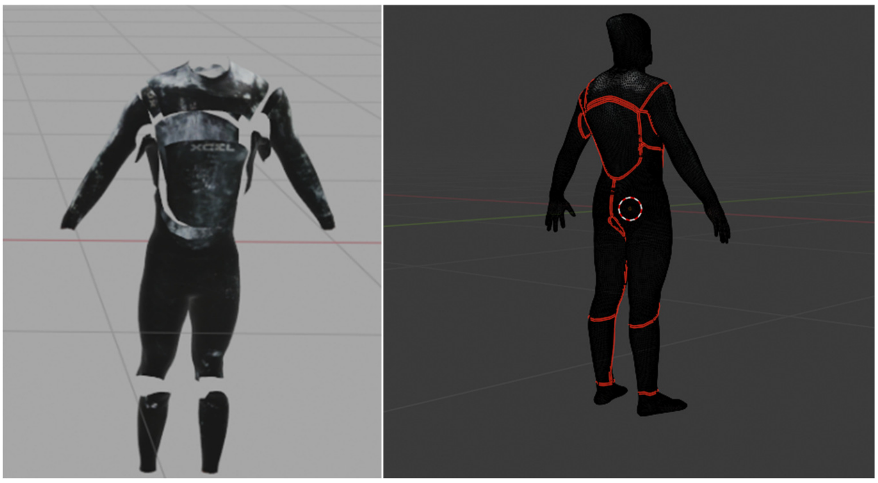


Figure 8: Suit Seam Mapping Separation into Panels Along Seamlines

This allowed us to follow the texture of the suit from the scan almost perfectly and prepare all samples for input into the clothing simulation software.

Lectra Design Concept [10] is a software that can flatten the created 3D suit pieces into 2D patterns, which are then cut out of a textile and sewn together. It allows us to make a complex shape 2D, export it in a specific format (.DXF AAMA), and then import each garment into a clothing response software such as *Vstitcher.* They are then assembled at the actual seamlines and are assigned material properties for realistic simulation results. Attaining accurate material properties is crucial for predicting the response of the clothing. The following section presents a comparison between a material testing method specific for body-clothing interaction scenarios and the traditional tensile test.

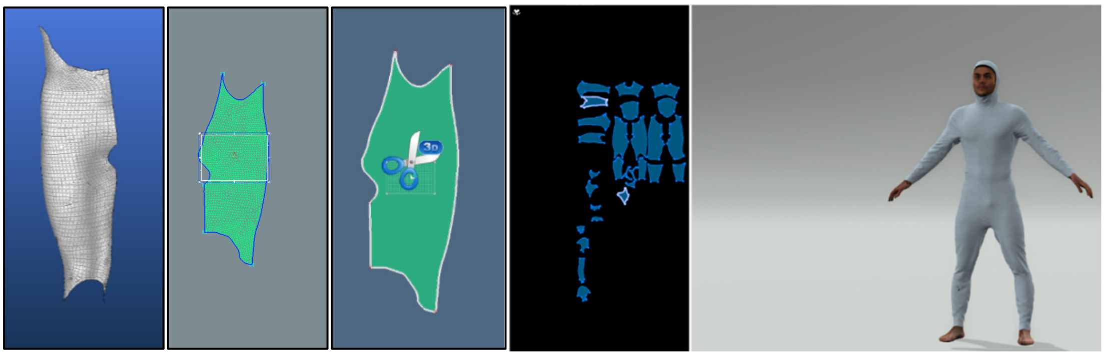


Figure 9: Garment Pattern Creation and Suit Assembly

6. Material Testing

Typically, whenever *VStitcher* is used for simulating a clothing interaction, the FAB (Fabric Analyzer by Browzwear) tester is used. It is specifically created to extract material properties and seamlessly integrate them within the software. It tests knitted and woven fabrics in tension and compression longitudinally, however almost all frequently tested materials have high stiffness. Neoprene, however, is a hyper-elastic polymer, which is created by pouring the molten material and letting it set.

FAB does not load the material to failure as well, which limits the scope of our analysis as any extreme simulation results cannot be validated. Therefore, FAB testing is not sufficient in representing the accurate material response of the specimen – it has only been used to monitor purely elastic elongation percentage for later calculation of the Poisson’s ratio of Neoprene. For that reason a second testing process was conducted, using a Zwick Z100 testing rig, manually extracting the necessary material properties. Here the process is standardized, taking the specimen to failure.

Three specimen orientations were tested – 0, 45, 90 degrees. Each direction was tested 3 times each, requiring 9 samples for each set of tests (wet and dry). Each sample is tested after being brought up to a pre load of 5N, which was then calibrated out of the raw data. The used samples were of the same dimensions (250x50x5mm) as the ones in the FAB test to obtain an accurate comparison. Surfing provides a naturally wet environment; therefore the material must be tested dry and wet to enable us to accurately capture the entire scope of material properties of neoprene.

After testing each dry specimen, the second set of 9 samples were submerged into distilled water and tested fully-soaked. Wetsuits are designed for operation in saltwater environment, where the density of the water is higher and is rich in different types of minerals such as magnesium, sodium, phosphorites and different organic compounds. Tap water could be used to emulate some contaminants in the sample, however, being completely pure, distilled water provides baseline results, which can be adjusted by changing the liquid properties later.

Three load-elongation curves were outputted for each direction. The data was then calibrated and checked for defects or outliers. An outlier can be a curve which differs substantially compared to the other two. Such outliers could result from not soaking the sample uniformly, leaving sections of it dry, leading to inconsistent loading response. Stress and strain were calculated from each loading curve and then each set of stress-strain values was transformed into an averaged one and the 0, 45 and 90 degrees were superimposed on a DRY and WET plot (*Figures 16 & 17*). Where for our example a lateral strain of ~22% was taken from the FAB testing and a 50% longitudinal strain at the end of the linear region of the tensile test curve.

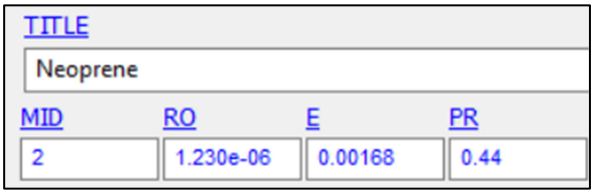
Figure 10: Separate Simulation Objects Mesh Segments (Part of the suit and fof the body)

Engineering strain was considered for these tests, since the elongation was large enough, where we did not focus on small imperfections in the resulting values. Almansi or Green strains can be considered for the testing on a material such as steel, which is substantially stiffer and the quadratic terms that these two strain types add, might make a difference. The reason why the average between each of the 3 tests for a given orientation was taken is that the material behaved almost identically for every specimen of a set.

The material properties obtained from the tensile testing and the stress/strain graphs are necessary for a realistic response of the object in a load simulation environment. The following section looks at modelling the response of a part of the wetsuit when it is being put on the body using *LSDYNA* [14]. For that to be as accurate as possible, the obtained parameters in the testing stages are crucial.

7. FEM Simulation

Combining all of the steps from the previous section, including the material properties from the testing section, is sufficient for making changes to the geometry of the garment in the 3D clothing software. This section, however, looks at how one can model the dynamic response of the suit to loading. Such simulations provide greater confidence in the performance of a piece of clothing prior to its manufacture. Ideally, both approaches would be used to ensure all factors of the design process are considered. One of the most daunting challenges in this simulation stage is putting the full suit mesh back on the avatar as a separate object. For that reason, a simplified simulation scenario was considered, where the motion of putting a leg into the wetsuit and monitoring its response is analyzed. This is appropriate as some of the highest values of strain do not occur when it is being used in the water, but when putting it on. *Figure 10* depicts the two mesh segments in LSDYNA.



TITLE

Neoprene

MID	RO	E	PR
2	1.230e-06	0.00168	0.44

Figure 11: Neoprene LS-DYNA Material Definition

The red mesh represents the leg of the user and is taken from the naked A-pose scan, which was a homologous mesh, generated by the scanner software. The green mesh is taken from the homologous dressed scan mesh and represents the section of the suit, where the leg comes into. Defining the two objects correctly is important for the solver to work as anticipated. The suit was defined as a solid shell with 5mm thickness and the leg was taken as a rigid body with 1DOF in the y-direction. Both bodies are given different material properties, with the leg being set as a dense and stiff material for the solver to work, and the suit was given the properties obtained from tensile testing (*Figure 11*).

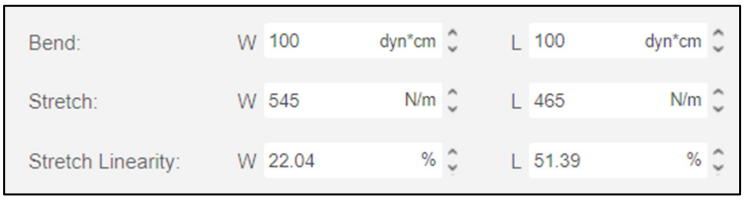
The most important part of the setup was the contact definition between the rigid body and the elastic wetsuit object. LSDYNA has a vast array of different contact types, each of which is specific for a testing scenario. For this example, since the focus was on the deformation of the suit, it was not important if there is any penetration into the rigid leg. Therefore, an ONE_WAY_SURFACE_TO_SURFACE contact was chosen where the software only checks for protrusion of the nodes of the leg into the suit and tries to counteract it. This allowed the explicit solver to simulate the most realistic loading scenario.

The following section represents the results of all sections of this body-clothing interaction process, which prepared and analyzed a wetsuit sample. At the end of the chapter the most optimal algorithm of steps for such an experiment is presented.

8. Results and Discussion

8.1. FAB Testing

This section presents the results of each step of the analysis process. In order to be able to reconstruct the suit in the clothing simulation software, accurate material properties are necessary. The FAB testing rig outputs very specific parameters, which are generally connected to the resistivity of the material to stretching (*Figure 12*).



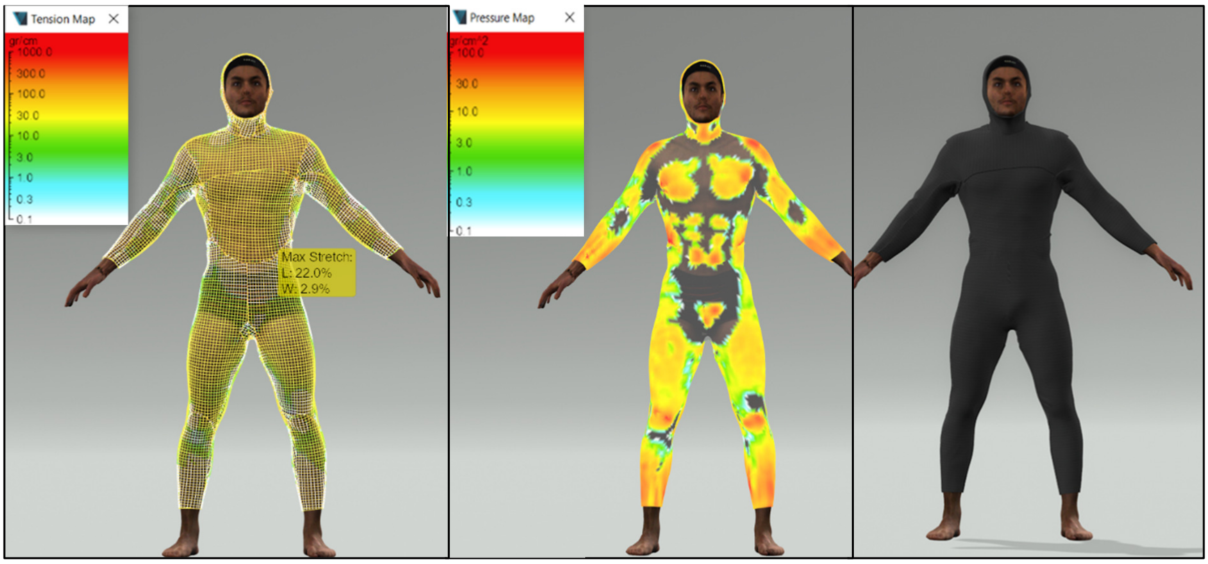
Bend:	W	100	dyn*cm	L	100	dyn*cm
Stretch:	W	545	N/m	L	465	N/m
Stretch Linearity:	W	22.04	%	L	51.39	%

Figure 12: FAB Testing Resulting Parameters

The only results from this testing regime, which were considered as a baseline, were the two stretch linearity values. Strain along the width of the sample was used in combination with the linear longitudinal strain to calculate the Poisson's ratio. After cross-referencing with the destructive tensile test, where the Poisson's ratio was calculated again, very similar values were received in the range of 0.44-0.46. This is assuming that the lateral strain value of 22.04% is accurate. Another drawback of this method is the lack of access to comprehensive raw load/elongation data, which prevents loading analysis off of plotted curves. Inputting the results of the FAB test into the clothing software and applying a pre-shrink of the suit of 22% generates a Fit Map, indicating how well the suit interacts with the body.

The 22% percent shrink was applied to simulate how the suit would react to being loaded only by the volume of the body inside of it, assuming that it will deform strictly linearly.

This is a way to reverse the captured deformation during the scan and this is the only reason why the FAB test is useful – it gives us a baseline value for stretch reversal. *Figures 13,14* represent how well the suit fits onto the body and the map of the pressure applied onto the body by the garment. *Figure 15* depicts the completed suit reconstruction in VStitcher with added material properties and textures.



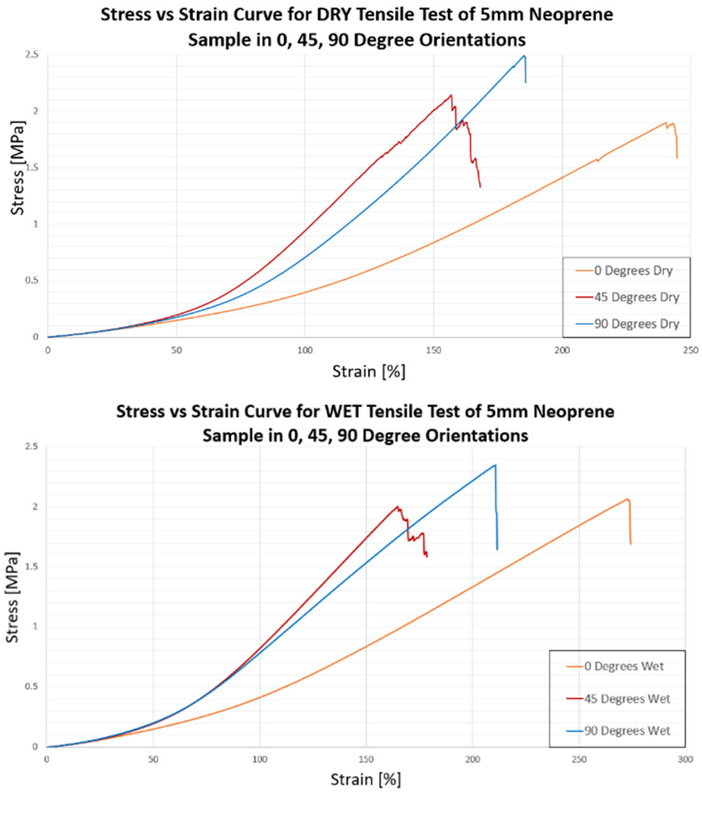
Figures 13,14 & 15: Suit Fit Map, Suit Pressure Map, Complete Suit Reconstruction

The highest longitudinal tension of the suit was around the shoulders with values of 280 gr/cm or 0.03N/m, which indicates that the 22% percent shrink results in an almost perfect fit. That also confirms that the FAB linear lateral strain measurement was accurate. The areas with the highest pressure were the curves of the body protruding out of the plane such as the shoulders, chest, and abdominal muscles.

These areas resulted in pressures of up to 9,8 kPa. [15] states that the range for high pressure-induced discomfort is between 60 and 100 gr/cm^2**.** In addition, research on the pressure exerted by waist trainers or corsets conducted [11], indicates that no discomfort is registered between 0-15 gr/cm^2 and that the uncomfortable sensation is evident between 15-25 gr/cm^2. The route which we were interested in started from the hamstring, though the glues, obliques, upper back and finished at the neckline. This is where the highest stretch occurs in the typical surfing movement. The highest-pressure values of 8.8kPa were at the obliques. These values are taken from a static A-Pose, since that was the only scan which outputted a homologous mesh. Greater pressure values are expected in the dynamic "pop-up" movement, where the body it curled forward, elongating the targeted route. Analogically, following all of the previously mentioned steps in the methodology chapter, one can get a similar analysis for a pose from one the movement sequences. Another possibility is importing a new avatar, which is in a dynamic pose and rearranging the suit to fit it. Changes to the fit and to the stress maps are done by adjusting the dimensions of the garment sections, making up the suit.

8.2. Destructive Tensile Testing

All graphs generated from the destructive tensile test are presented in the following pages, where 0-, 45- and 90-degree directions were superimposed on the same stress/strain curve for each testing configuration (DRY & WET). The following two *figures (16 & 17)* are the finalized stress/strain curves for each direction for both the dry and the wet sample tests. Looking at the graphs one cannot make a general statement about the material behavior. It is individual for each sample's cutting orientation. In the case of the dry testing, the 0-degree samples are the ones which have experienced the highest elongation, with values of up to 245% at failure. This is around 100% more than the 45-degree and 75% more than the 90-degree samples, which is a substantial difference. In terms of which sample was able to handle the highest amount of load, that was the 90-degree one. It handled stresses of 0.3-0.6 MPa more than the remaining 2 sets of samples.



Figures 16 & 17: Finalized Stress vs Strain Curves for the DRY and WET Samples

The second graph (*Figure 17*) are the finalized results of the WET test of the three sample orientations. Looking at the elongations it appears that when wet, samples experience higher elongations overall. The 0 and 90-degree samples have experienced exactly 1.15 times more elongation than the dry test, whereas the shear direction has stretched 1.05 times more. The 0-degree sample has become better at stress handling when soaked with water, compared to the dry test, however the 90-degree orientation has become generally weaker. These results are most likely due to the distribution of the water particles in the pores of the material. The overall consensus from the results is that the material allows for more strain, when used in its operating environment.

8.3. LS DYNA Simulation Results

Both testing sections served as a prerequisite for the proper material definition in the simulation stage of the process. It aimed at modelling the response of the clothing, using the generated meshes and material properties. After defining the wetsuit material with the properties obtained from testing, the simulation was run and the von Mises stress and the xy-shear stress and strain were recorded. Dry material properties were used as a wetsuit is typically put on while dry. The reason why the von Mises stress was taken was the fact that its yielding criterion is slightly less conservative compared to Tresca. Looking at the xy-shear stresses and strains was the more appropriate choice; due to the way the material is loaded. Neither the longitudinal, nor the lateral direction is loaded directly. Infinitesimal strains are typically considered, however that is under the assumption that low strain is expected, with respect to the size of the specimen. This would be an inappropriate assumption to adopt here, since the material was seen to experience deformations of up to 250% from the tensile test.

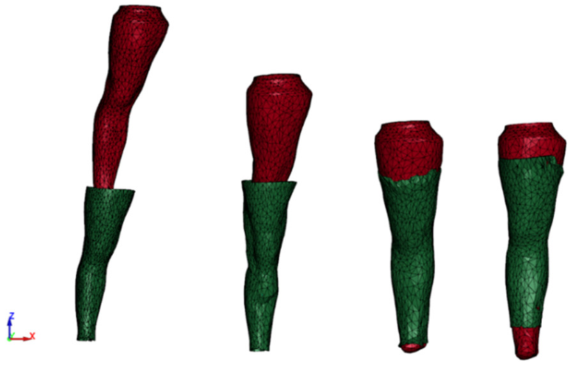
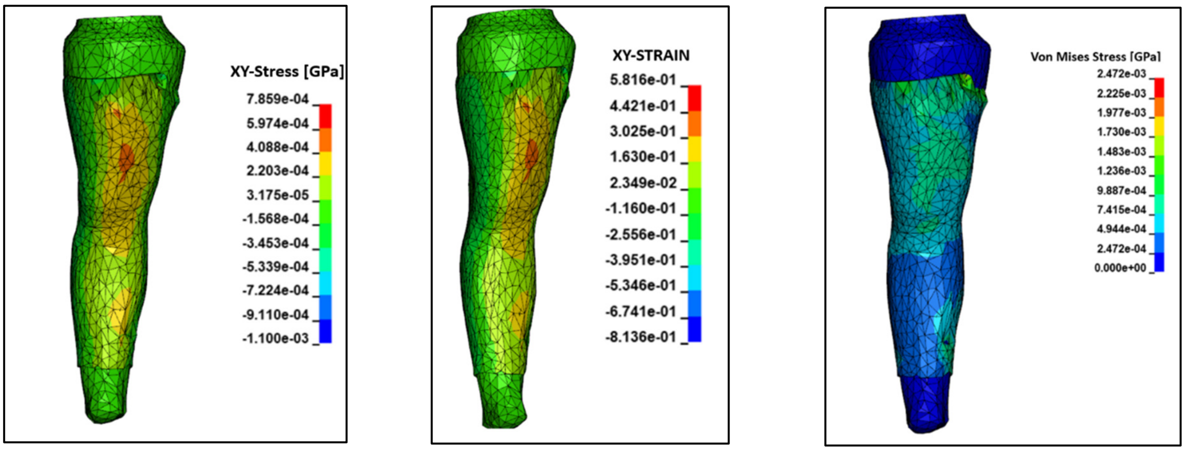


Figure 18: LS-DYNA Simulation Leg Movement Scenario

The figures below describe the simulation results for the frame with the largest deformation, where the maximum von Mises stress value was approximately 0.9 MPa. This is lower than the maximum tensile stress of the material, judging by the conducted tests, which is as expected, considering that the suit is just being put on the body. A flaw of this simulation scenario could be the way the leg is directed towards the suit. High initial velocity is given to the rigid leg, which generates a larger stress on impact. Alternatively, setting a prescribed motion to the nodes of the leg, would yield even a more unrealistic result, since the leg will not react to any resistance from the suit.



Figures 19, 20 & 21: LS-DYNA XY-Shear Stress, XY-Shear Strain, von Mises Stress

These results were completely expected and were also confirmed by the dry tensile testing plot, where looking at the maximum xy-shear values, they lay exactly on the 45-degree shear curve in the linear section. This is an important conclusion, indicating that the simulation was appropriate, resulting in a fully-elastic deformation of the suit. This deformation is best represented by analyzing the shear direction, where the material response mimicked the one obtained from the testing. Such linear behavior, while putting the suit on, is necessary to ensure continuous use of the equipment, without any loss of performance.

9. Conclusion

This experience aimed at establishing the most efficient sequence of operations involved in the analysis of a movement after a 4D scan. The chosen surfing example was successful in identifying drawbacks to the current methodology and finding alternative solutions at every stage of the process. Each section had its own array of unique problems, most of which were overcome in several different ways. The first simulation stage focused on obtaining the most optimal clothing fit, without exerting excessive pressure onto the user. On the other hand, the second simulation section, did not aim to provide the best fit, but to model the response of the wetsuit to a dynamic shearing movement. The experience was successful in completing its initial set of objectives, where assembling the most optimal data-handling algorithm for post-scan movement analysis was of highest importance. In addition, the typical approach to clothing simulation, where the shrink value of the garments is chosen somewhat arbitrarily, was challenged though extensive material testing. Such decisions, regarding the shrinkage of the clothing in order to ensure a better overall fit, are only to be made after carrying out both material testing methods. Working in tandem, they provide sufficient confidence in the response of the garment. The finalized algorithm is presented at the end of the paper.

This paper demonstrated an upgraded methodology for scan analysis, and also put forward the eccentricities of crucial sections such as mesh generation and tensile testing. All of the obtained results were as anticipated, confirming any made assumptions, apart from the grain orientation of the tested samples. One of the conclusions, which completely affirms the validity of the generated algorithm, is the fact that the dynamic simulation results mimicked the tensile testing response almost identically. The values for the linear deformation domain, corresponded to both the empirical data obtained upon testing the material, and the agreed upon values from literature. Testing the neoprene samples soaked in water, was crucial, leading to substantial differences in the material response. This also solidified the idea of always taking the operating environment of a system into account, when monitoring its performance. Had this not been done, any obtained results would not have been conclusive and should have been discarded.

Such experiences are an indispensable part of the development of every upcoming professional. Regardless of the exercise or the field of study, critical and creative thinking is necessary for achieving success. The more complex a skillset is, the further it can push the current technological limits.

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APPENDIX

Finalized 4D Scanning Analysis Algorithm