# Validating a Cloth Simulator for Measuring Tight-fit Clothing Pressure

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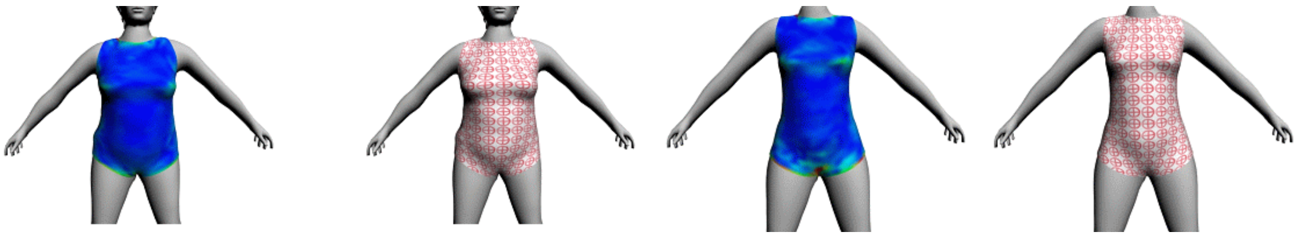

**Figure 1:** *Measurement of tight-fit cloth pressure on differently sized 3D mannequins.*

## Abstract

Tight-fit cloth pressure provides important clue on how well a cloth fits to a body and thus on how comfortable the wearer feels with the cloth. Traditionally-used pressure sensor devices are expensive, sensitive to the experimental environment, and difficult to reproduce. In this paper, a physically-based cloth simulator has been tested for its usability as to measuring the cloth pressure, in order to replace physical measurement of cloth pressure that requires careful operation of pressure sensors. We use existing cloth simulator based on a particle system and measure spring forces exerted on each particle along its normal direction, divided by the summed area of triangles adjacent to that particle. To quantitatively validate the pressure values from the simulator, we have conducted comparative analysis on a set of thin-shell cylindrical tubes − clothing pressure values have been measured by theoretical estimation and physical experiments using pressure sensors, and compared with those measured by the simulation. While their absolute pressure values differ from each other they exhibit a consistent tendency. From these comparative studies we concluded that cloth simulator can actually be used to measure tight-fit cloth pressure, and further conducted the clothing pressure measure on 3D human body models using the simulator.

**Keywords:** tight-fit cloth pressure, cloth simulator, quantitative analysis

## 1 Introduction

Functional cloths must protect human body from hazardous environment and, at the same time, support mobile functionality and comfort when worn by the wearer. Measurement of clothing pressure is one method for evaluating activity (mobility) of the cloth under design. It thus is also an important factor for clothing comfort, which is closely related to cloth mobility. Clothing pressure is the pressure applied on the body when wearing a cloth. It varies according to the design, pose of the wearer, garment material, wearers body shape, etc. The design of sportswear (for cycling, skating, or swimming) and foundations for body shape correction can benefit from appropriate clothing pressure. Presently, there are two ways of measuring cloth pressure. First is to use pressure sensor devices, directly on a body wearing a cloth. Second method is by observing the deformation of the garment and the curvature of skin surface in the cloth. While recently available air sensors exhibit good performance, they are expensive, and require direct contact with the wearer. The non-contact method has been first proposed by Kirk and Ibrahim [Kirk and Ibrahim 1996] but it had some limitations to be used in practice at the time of its publication, since no technology was available for systematic observation of patterns on clothes. It is only recently that their method has been reinvestigated by several researchers, who have tried to replace conventional tape measure for clothing with now-became-available 3D technologies. Indeed, 3D technology can be useful for morphology of tight-fit, functional cloths, because accurate 3D body data not only provides invaluable information on how to design 2D cloth patterns, but also guidance to estimate the clothing pressure.

In this paper, we propose to use a cloth simulator for measuring clothing pressure. In order to validate our method, we first carry out real-world measurements using pressure sensors on simple cylinder objects. These are then reconstructed in the simulator in which pressure values are calculated. The measured and the calculated pressure values are then compared. The high degree of consistency between the two experiments has been obtained, which indicates that the cloth simulator can replace physical pressure measurement. Finally we provide some analytical results.

### 1.1 Previous Work

In computer graphics, deformable objects such as cloth and skin have been the subject of interest for many years. Mechanical models for garment simulation have been investigated, in particular in the area of physically-based computer animation. However, the focus has been on obtaining realistic visual simulation and, validating the quality of the simulator has been almost always left unsaid. Mostly, garment simulators have been measured on the simulation speed, stability, or, simulation results have been visually compared to real images that are taken in similar real-world environments to the simulation ones.

As it becomes now more realizable to have garment simulators that are capable of dealing with complex garments and offering mechan-

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ical accuracy at the same time, the interest of adopting cloth simulators for garment prototyping [Volino and Magnenat-Thalmann 2005] or retail has increased by garment industry [Cordier et al. 2003]. Most existing tools available for garment prototyping today, however, focus on accurate draping simulation, and only basic body-cloth interaction is supported, such as collision detection. As mentioned earlier, cloth pressure is important especially for functional cloths, but little has been done on this matter. Recently, Volino and Magnenat-Thalmann have reported their work on virtual tensile tests in the course of validating the accuracy of their mechanical model [Volino and Magnenat-Thalmann 2005]. While their work addresses significant achievements of garment simulator, tests on garment alone may not be sufficient. In our work, we focus on a more complex problem of clothing pressure, an example of interaction between garment and skin. However, our aim here is not addressing issues on developing a robust garment simulator that fulfills requirements of garment production. Rather, we focus on a framework for adopting and validating a garment simulator as a pressure measure.

In the domain of clothing and textiles, people have tried to measure the clothing pressure in many ways. Yu et al [Yu et al. 2004] have developed a soft mannequin to simulate cloth contact pressure. Their mannequin has been composed of bones, muscles, and skin, in order to model human body as accurately as possible. Some of the work that is closely related to ours is Lees thesis work [Lee 2005]. In that work, she proposed a method for estimating tight-fit cloth pressure by analyzing circular patterns stamped on the cloth worn by a 3D mannequin. They measured and compared the estimated and physically measured pressure on plaster and human body. Parts of our work adopts similar approach but on more simple objects (such as cylinder), on which analytic calculation of pressure is also possible. Jung [Jung 2006] has calculated curvature distribution over whole body scan data, and reasons about the optimal design of 2D patterns for bicycle clothing.

### 1.2 Overview and the organization of paper

The overview of our work is as follows. We describe the cloth simulator we have adopted and the method we use to calculate the clothing pressure in Section 2. In Section 3, we introduce the idea of estimating clothing pressure by analyzing pattern deformation. Section 4 gives a description of our experiments on cylindrical objects. After a set of physical experiments, we reconstruct them in simulation settings and perform simulation to calculate clothing pressure. Then, theoretical verification follows in Section 5. The main purpose of adopting simulator for calculating clothing pressure is to be able to use it for a human model, which is described in Section 6. After discussing results in Section 7, we conclude the paper in Section 8.

## 2 Cloth Simulator as a Pressure Measure

### 2.1 Mechanical Model

The cloth simulator we use is based on mass-spring system as described in [Volino and Magnenat-Thalmann 2000], where a garment is approximated as a thin surface composed of mass points (vertices) interconnected with springs. Different types of springs are used for modeling the mechanical behavior such as in-plane and curvature elasticity. In order to simulate the in-plane elasticity, the model integrates the strain-stress relationship by accurately modeling the simultaneous interactions between the three particles corresponding to each triangle. The curvature elasticity is computed with angular springs located at every edge between adjacent triangles. This mechanical model has been shown to be far more accurate than the mass-spring system based on regular grids with diagonal and leapfrog springs. In addition, this model allows for arbitrary triangular mesh, not requiring for a regular grid.

For the integration we have used is the fourth-order Runge-Kutta method, which is known to be very accurate if the simulation time step is sufficiently small. We refer to their paper [Volino and Magnenat-Thalmann 2005] for a detailed description of the mechanical model.

### 2.2 Cloth Pressure Measurement from Forces

At every simulation loop the force exerted on each mass point is calculated. Figure 2 illustrates the forces applied on a mass point. In order to calculate pressure (force per unit surface area) on a vertex **v**, we sum up all forces along the direction of vertex normal ($\sum \mathbf{f}_i \cdot \mathbf{n}$) and divide that force by the summed surface area of every triangle that is adjacent to **v**.

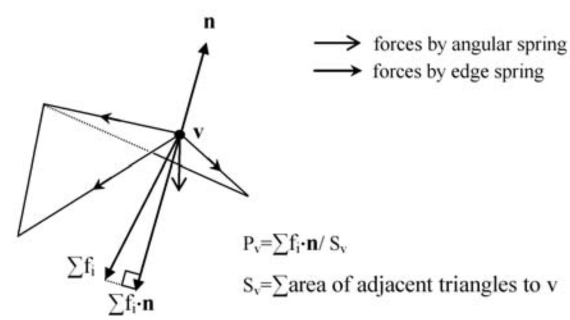


**Figure 2:** *Calculating the pressure on a vertex v. Forces are summed up along the normal direction of v, and is divided by the summed area of its adjacent triangles.*

## 3 Estimating Clothing Pressure by Analyzing Pattern Deformation

Kirk and Ibrahim (1966) noted that the warping of textile and stress applied on it are closely related. The pressure of a thin sphere is written by:

$$P = \frac{\sigma(2t)}{r} \tag{1}$$

where $P$ is the pressure (gf/cm$^2$), $\sigma$ tensile force per unit area (or tensile stress) (gf/cm$^2$), $t$ the thickness of the thin sphere (cm), and $r$ the radius of the sphere (cm) This estimation can be modified so that it applies to more complex yet locally ellipsoidal surface such as human body. That is, the pressure as defined in Equation (1) can be divided into horizontal and vertical direction:

$$P = \frac{\sigma_H t}{r_H} + \frac{\sigma_V t}{r_V}, \tag{2}$$

where $\sigma$ is tensile stress (gf/cm$^2$) and $r$ the radius of curvature (cm) $H$ and $V$ respectively represent horizontal and vertical direction.

Lee [Lee 2005] has modified the above equation so that principal stress and principal directions are used instead of the two orthogonal directions. That is, tensile stresses and radii of curvature are measured along maximum and minimum principal directions, as expressed by:

$$P = \frac{\sigma_{P\max} t}{r_{P\max}} + \frac{\sigma_{P\min} t}{r_{P\min}}. \quad (3)$$

Consider an object that goes under deformation with some external force. By the principal directions it is meant the direction of maximum and minimum normal stress when it reaches equilibrium. Note that the principal directions may not be orthogonal to each other, as shown in Figure 3. This estimation is more practical and accurate when measuring clothing pressure on human body. Later in our paper, we derive estimated pressure values on cylinder objects from this equation.

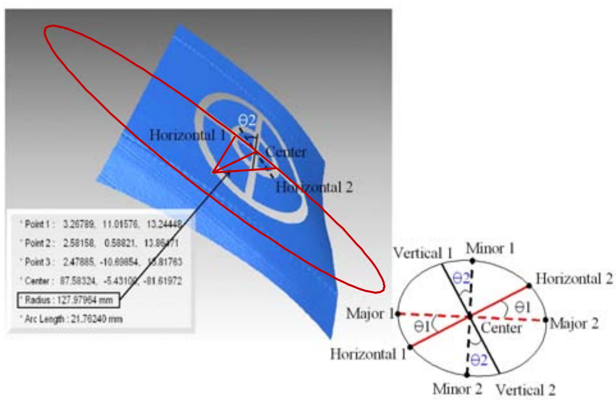


**Figure 3:** *Pressure estimation on the center of the circular stamp.*

## 4 Experiments on Cylindrical Objects

**Figure 4:** *The garment (left) and the cylinder we use for the physical pressure measure(right).*

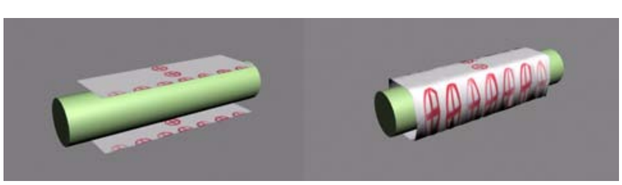

**Figure 5:** *The initial configuration of the pattern and the cylinder object (left) and the early stage of the simulation (right).*

In our first experiment, we begin with a simple cylinder object and make a garment wrap around it, as shown in Figure 4 and Figure 5. Cylinder has been chosen mainly because of its simplicity, which allows us to perform identical experiments both in physical and simulated settings. Moreover, it is also possible to make theoretical verification, by deriving analytic solution. Ignoring the influence of gravity, the clothing pressure on the cylinder surface is expectedly uniform. The size of the garment and the radius of the cylinder can vary, which we discuss later in this section (4.4 and 4.5).

### 4.1 Physical experiments

We have measured pressure on a number of locations on the cylinder using an air pack type pressure sensor [AMI3037-2 ]. The specification of the sensor is summarized in Table 1. Prior to seaming, we print circular stamps on the garment. The outer radius of this circle is 2 centimeters, and we place them in two orthogonally crossing lines as shown in Figure 4. After seaming and placing the garment around the cylinder so that one stamp line on top aligns with the axial direction, we measure pressures on 11 locations on the cylinder, at the center of each stamp. We measure on two differently sized garments (the larger garment is named as '4_5T' and the smaller one 'T'). For each garment we vary the radius of the cylinder, applying different strains on it. Each of these experiments has been reconstructed in a simulated environment, in which pressures are calculated using the method as described in Section 2. We hypothesized that the pressure should increase with the radius and with the reduction of the garment, as is also verified in Section 3 and Section 5. As presented in Sections 4.4 and 4.5, the calculated pressure measures did increase with the increase in radius and, for the same radius, with the decrease of garment size.

| Model | AMI 3037-2 |
|---|---|
| Air pack diameter (mm) | 15 |
| Range (gf/cm$^2$) | 0.0 – 70.0 |
| Accuracy (gf/cm$^2$) | ±1.5 |
| Air tube length (m) | 1.5 |

**Table 1:** *Specification of air pack type clothing pressure sensor.*

### 4.2 Garment material parameters

Garment materials are defined by a number of curves (weft, warp and shear strain-stress curves). Cloth simulators require their users to input mechanical parameters of the garment under simulation. In our case, we have acquired those parameters from a number of physical tests. In order to compare the pressure value measured physically, we carefully measured and reproduced the dimension of the textile as well as its mechanical properties measured by modified ASTM D2594 as suggested by [Ziegert and Keil 1988]. Tensile force and Yong's modulus have been acquired using tensile tester (R&B, Unitech). Table 2 summarizes the test results of the garments we used in our work.

The Poisson coefficient of the garment is nonlinear, that is, it changes as the strain changes. So we take different coefficients each time, with the expected strain on the garment.

### 4.3 Simulation settings

Figure 5(left) shows the initial positioning of the garments relative to the cylinder object. Since the garment width is smaller than the circumference of the cylinder, we divide the garment (whose dimension is from the actual garment used for the physical experiments) into two pieces and seam them together around the cylinder. As the simulation proceeds, the garment is gradually relocated closer to (Figure 5(right)), and tightly wraps around the cylinder. Pressure values are measured around the garment vertices once the simulator reaches stability, that is, the movement of garment vertices becomes unnoticeably small. Below we describe each element in detail.

| | unit | 500g (4.9N) | | 1000g (9.8N) | |
|---|---|---|---|---|---|
| | | Wale | Course | Wale | Course |
| Original length ($l_0$) | cm | 20.0 | 20.0 | 20.0 | 20.0 |
| Deformed length ($l$) | cm | 31.5 | 27.0 | 36.5 | 32.0 |
| Strain, fabric stretch | % | 57.5 | 35.0 | 82.5 | 60.0 |
| Strain ($l$-$l_0$)/$l$ | | 11.5 | 7.0 | 16.5 | 12.0 |
| Extension ratio ($\alpha$=$l$/$l_0$) | | 1.575 | 1.35 | 1.825 | 1.6 |
| Tensile force per unit length | N/cm | 0.245 (4.9/20) | | 0.49 (9.8/20) | |
| Young's modulus × thickness (*Et*) | N/cm | 0.7 | 1.3 | 0.7 | 1.3 |
| Poisson coefficient ($\upsilon$) | | 0.3499 | | 0.2021 | |
| Thickness (t) | cm | 0.039 | | | |
| Density (mass per unit area) | kg/cm$^2$ | $1.057 \times 10^{-5}$ | | | |

**Table 2:** *Garment properties acquired from physical tests.*

- 2D pattern : We have made a pattern whose size and texture is identical to the one used for physical pressure measurement using sensors. In order to facilitate the simulation, this pattern has been divided into two halves, which has been placed on the opposite side of the cylinder, respectively. Note that the distance between these patterns and the cylinder must be small and identical, in order for the simulator to reach the stable status as soon as possible.

- Cylinder : Cylinder object is modeled as a rigid object, which means it does not change its shape because of the cloth pressure. Once the textile wraps around it and start to be stable, we progressively apply non-uniform scale on it until the desired dimension is obtained.

- Those two patterns are connected by seam lines at the four corners, resulting in a cloth that wraps the cylinder. Prior to the actual simulation, the patterns have been converted into mesh, using Delaunay triangulation. In our cylinder experiments, the average edge length of the triangles has been 0.7cm 0.8cm.

- Simulation method: At the very beginning of the simulation process we have used a method that ignores velocity (Quasi-static), so the system can arrive quickly to the stable status and avoid divergence. Runge-Kutta method has been used for the rest of the simulation.

### 4.4 Incrementing stress by the scaling the cylinder

Once the simulator has reached its stable status, we start increasing the radius of the cylinder gradually and thus the stress applied on the textile. As shown in Figure 6, the pressure values measured from the force increases as the radius becomes larger. The deformation of the stamp as well as the shrinkage of the garment along the height of the cylinder looks consistent. Figure 7 shows the calculated clothing pressure as a function of cylinder radius.

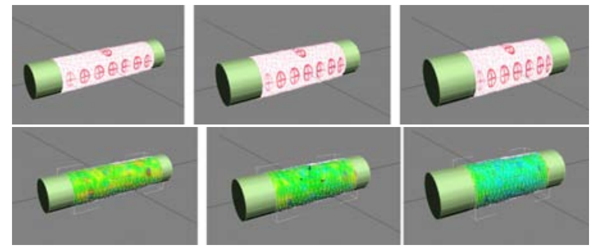

**Figure 6:** *The pressure of the same textile on differently sized cylinder.*

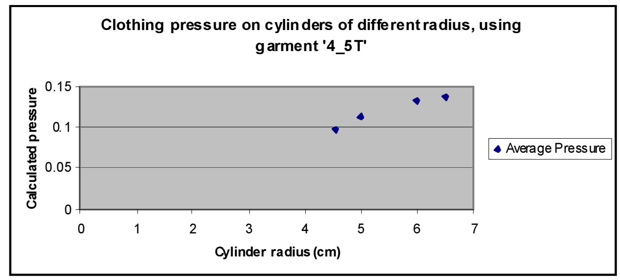


**Figure 7:** *Clothing pressure as a function of cylinder radius.*

### 4.5 Tests on differently sized garments

We have simulated two different sizes of garments on each cylinder. Detail information on geometrical properties of these two garments is provided in Table 3. From Equation (3) in Section 3 (and later in Section 5), we hypothesized that the smaller garment would exhibit higher pressure value for a given . Here, stands for the deformation ratio defined by the deformed length to the undeformed length. See Equation (6) for the detail. Our simulation result as shown in Figure 8 has assured us that such hypothesis is valid.

| | No. of vertices | No. of faces | Size |
|---|---|---|---|
| Larger garment (4_5T) | 575 | 1114 | 18.78cm × 24cm |
| Smaller garment(T) | 485 | 938 | 15.7cm × 24cm |
| Cylinder | 110 | 216 | Height: 24cm<br>Radius: 5cm |

**Table 3:** *Geometrical properties of two garments.*

## 5 Theoretical Explanation and Verification

We now discuss theoretical aspect of our experiments we described above. As shown in Figure 9, we model the garment as a long thin-walled cylinder, in order to derive theoretical explanation of cloth deformation and the internal cloth pressure, in accordance with the size of the cylinder. The internal pressure $P$ that deforms a textile of circumference $R_0$ to $R_f$ varies depending on the mechanical parameters of the textile. Here, we consider linear elasticity and Neo-Hookean cases.

Let us derive the internal pressure $P$ required for a garment to deform from $R_0$ to $R_f$. Two types of material properties are considered: First is the linear elasticity as described by linear stress-strain. The second is rubber-like material where Neo-Hookean model applies.

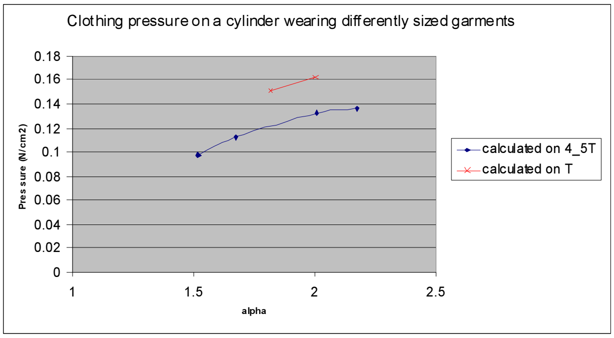


**Figure 8:** *Clothing pressure on a cylinder wearing two different sizes of garments.*

In case of a textile of linear elasticity and isotropic materials, the relationship between stress and strain for a thin-walled textile cylinder is defined by:

$$\sigma_h = \frac{PR_f}{t} \tag{4}$$

where $\sigma_h$ is the hoop stress and$t$is the textile thickness. Here, the thickness of the walled is assumed to be less and the 1/20th of the cylinder radius [Shigley and Mischke 2004]. The axial stress, $\sigma_a$, is 0 since there is no external force along the axial direction. Thus, from Hook's Law the hoop strain ($\varepsilon_h$) can be summarized as:

$$\varepsilon_h = \frac{\sigma_h}{E} - \upsilon\frac{\sigma_a}{E} = \frac{\sigma_h}{E} \tag{5}$$

where $E$ is Young's (tensile) modulus and $\upsilon$ Poisson ratio. Note that it is irrelevant to Poisson ratio (linear elasticity). Now from the definition of hoop strain ($\varepsilon_h$), we have:

$$\varepsilon_h = \frac{2\pi R_f - 2\pi R_0}{2\pi R_0} = \frac{R_f}{R_0} - 1 = \alpha - 1. \tag{6}$$

Therefore, the final expression of the internal pressure $P$ required for the garment to deform from $R_0$ to $R_f$ from Equations (1)-(3) is computed as:

$$P = \frac{Et(1 - R_0/R_f)}{R_0} = \frac{Et(1-\alpha^{-1})}{R_0}, \tag{7}$$

where $t$ is the thickness of the garment. Note that in case of linear elasticity, the pressure is a function of deformation ratio ($\alpha$), Young's modulus ($E$), and the initial textile circumference ($R_0$). It is irrelevant to Poisson ratio.

The rubber-like nonlinear garment material has larger deformation than the linear Hooks-like material. Rivlin (1948) first developed Neo-Hookean constitutive equation, which models well nonlinear case [Rivlin 1948]. In the case of a textile of long thin-walled rubber like materials which has the volume conservation property with Poisson ratio=0.5, the final expression for pressure can be well described by Neo-Hookean model, as described by:

$$P = \frac{Gt(1 - R_0^4/R_f^4)}{R_0} = \frac{Gt(1-\alpha^{-4})}{R_0} \tag{8}$$

where $G$ is Shear modulus.

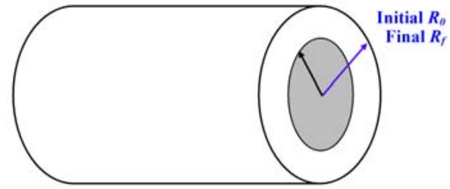


**Figure 9:** *Illustration of a long thin-walled cylinder.*

### 5.1 Equivalence of Equation (3) and Equation (7)

We note that from Equation (3) the pressure can be easily estimated on a cylinder. The $r_{Pmin}$ is infinite and we have $P$= $\sigma_{Pmax}t/r_{Pmax}$ where $\sigma_{Pmax}$ is the tensile stress (Young's modulus $E$ multiplied by strain $\Delta l/l_0$= $(2\pi r$-$l)/l_0$= $2\pi r/l_0$-1), and $r_{Pmax}$ is the radius of the cylinder. Note that $r_{Pmax}$ is the deformed radius as $R_f$ as shown in Figure 9. Therefore, we have:

$$\text{Equation}(3) = P = \frac{\sigma_{P\max} t}{r_{P\max}} = \frac{Et(2\pi r - l_0)/l_0}{r} = \text{Equation}(7)$$

This implies that when $l_0$, the initial garment circumference, is fixed and as $r$ increases, the pressure becomes smaller. Similarly, when radius $r$ is fixed, the pressure decreases as $l_0$ increases.

## 6 Experiments on Human Body Model

In reality, objects we would like to measure clothing pressure on are more complicated than cylinders. In such case analytical pressure calculation would be extremely difficult, if not impossible. Recently, we have conducted comparative measurements of clothing pressure, by analyzing circular patterns and by sensor devices on some selected locations of a plaster mannequin model. We refer the authors' other paper [Lee et al. 2006] for further details.

In this work, we have measured pressure values on a tight cloth worn by two differently sized mannequins. Additional comparisons with pressure values from the simulator are left as future work. The whole body modeler that we used for the generation of these mannequins is based on one of the authors previous work [Seo and Magnenat-Thalmann 2003]. After drawing and placing 2D patterns around the template body, we run the simulation so that these patterns are seemed together. As the simulation proceeds, the seemed patterns merge into a tight cloth worn by the mannequin. Once the system becomes stable, we start incrementally deforming the template into another individuals body by using the modeler. As the body mesh deforms, the cloth deforms accordingly, as a result of collision interaction between the two objects. After the deformation of the body is complete we wait for the system to reach stability, prior to calculating pressure values on the cloth surface. Figure 1 shows the result of our simulation. Deformation of the same cloth worn by two differently sized bodies is illustrated; also illustrated is the pressure distribution visualized using a color map. The use of circularly shaped stamp is particularly interesting, as it provides highly resourceful information on the pressure distribution. The fact that the simulator could be used to measure the pressure on a cylinder reliably assured us of the credibility of the calculated pressure values and their distribution. For example, the pressure is higher across the bottom of the breast and near the scapula.

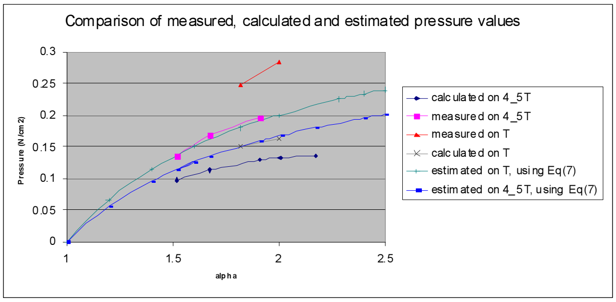


**Figure 10:** *Pressure values obtained from the physical measurement, calculation by simulation, and theoretically estimation.*

## 7 Results and Discussions

### 7.1 Pressure measure

Figure 10 shows pressure values obtained from the physical measurement, calculation by simulation, and theoretically estimation. In this figure, for the theoretical estimation, we used the average Et (Young's modulus time thickness) of wale and course direction in Equation (7). From Equation (7), the pressure is supposedly increased with $\alpha$ and is an inverse function of initial textile circumference $R_0$, since the Young's modulus remains the same throughout our experiments. Figure 10 shows the measured (from physical experiments), calculated (using the simulator), and theoretically estimated pressure values as a function of $\alpha$. All of them show the identical, expected tendency, that is, the pressure value increases asymptotically with $\alpha$. In addition, for the same given $\alpha$, pressure of the garment with smaller $R_0$(garment 'T') is higher than the one with larger $R_0$(garment '4_5T'). However, the absolute pressure values differ from each other. Such discrepancy could originate from several obvious reasons. First, the theoretically estimated pressure uses linear hook's law (Equation (7)) and assumed isotropic material property for the garment. In reality, the garment is nonlinear and most of garments manufactured today are anisotropic, this includes the garment used in our experiments. The simulator adopted in our work does support two Young's modulus (bidirectional material property), but accepts only one Poisson coefficient. Also, it approximates and models linear property of garments, while the garment we have tested is nonlinear (as is evident from Table 2). Second possible reason is the friction between the garment and the cylinder surface. Such friction has not been considered, both in theoretical validation and in the simulator.

Thus, we conclude that we could acquire consistent pressure values from the simulator in terms of its relation to $\alpha$ and $R_0$, although absolute values differ. The smallest pressure values have been obtained from the simulator, and the largest values from the physical measurements. The theoretical estimation using Equation (7) are in-between. As a result we found the strong possibility to use the current simulator as a pressure measurement tool from the similar trend qualitatively in pressure values from three different approaches. The discrepancy could be improved once we introduce the more accurate material model corresponding to the material used in experiments.

### 7.2 Stability of the simulator

The cloth pressure values must be measured once the simulator reaches stable status. If we measure the pressure values before that, the pressure values are either biased or show high degree of variation among neighboring vertices. For example, more than 5000 frames were required in order to acquire the result shown in Figure 6. Considering the calculation time of approximately 0.1 second for each frame (on a Pentium IV 3GHz PC under Windows, with 3ds max plug-in implementation), the total duration of simulation is approximately 10 minutes. Of course, this time is subject to change depending on the initial condition of the simulation. Figure 11 shows the pressure values calculated on a simulated garment, as a function of theta (The definition of theta is illustrated in Figure 12). The average pressure is taken as a result pressure.

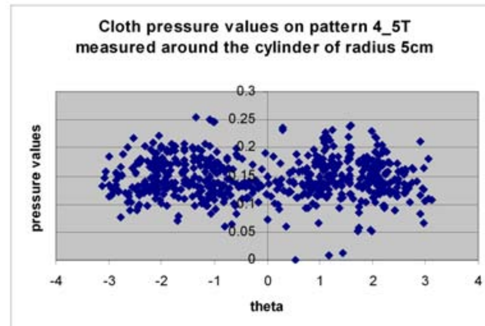


**Figure 11:** *Pressure values calculated on a simulated garment.*

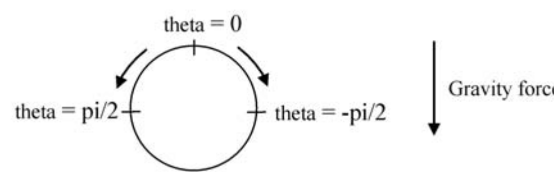


**Figure 12:** *Parameterization of the cylinder.*

### 7.3 Influence of gravity

Figure 13 shows the pressure values around the circumference of the cylinder when we enable the gravity force in the simulator. It clearly modifies pressure value, especially on those vertices at the top and the bottom of the cylinder. As theta becomes close to $\pm$pi/2, the angle between the normal vector and the direction of gravity force become close to 90 degrees, and thus the influence of gravity close to zero. In practice (physical pressure measurements or theory), the influence of gravity in pressure measurement is negligible. Hence we have excluded the gravity when calculating the pressure force. However, the gravity force accelerates the simulator to arrive at the stable status. So the best way would be to include gravity at the beginning of the simulation so that it becomes stable as fast as possible, and disable gravity thereafter.

### 7.4 Pressure and the granularity of the cloth mesh

One criteria of a robust cloth simulator is its independence of the mesh granularity. That is, the behavior of the simulator must be consistent regardless of the density of triangles composing the garment. In our work, we have measured the pressure values on differently sized cylinders using the larger ('4_5T' in Table 3) garment. For each simulated experiment, we have made the second simulation, with increased granularity of the garment mesh (The number of vertices has increased from 575 to 1397 and number of faces from 1114 to 2738). Everything else in the simulation kept unchanged. In Figure 14, we have compared the calculated pressure values acquired from the two garments of different granularity. The

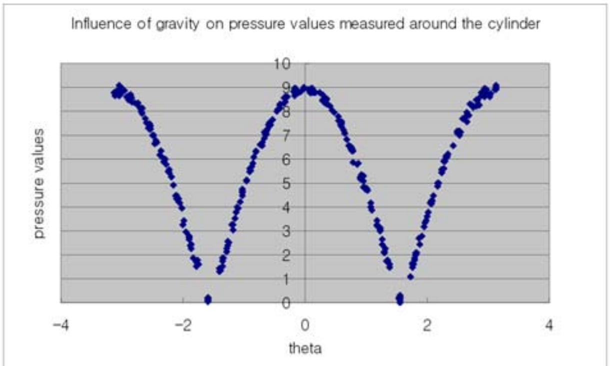


**Figure 13:** *Pressure values calculated on a simulated garment, with gravity force enabled.*

pressure value sets do not differ significantly, although the simulation time did increase with the increased granularity.

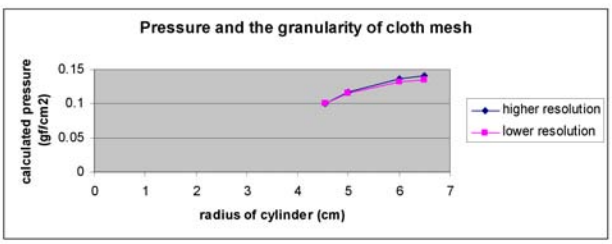


**Figure 14:** *Pressure values on variously sized cylinders, using higher and lower granularity of cloth mesh.*

## 8 Conclusion and Future Work

We have made various simulation tests and physical experiments using tight fit garments, with the aim of validating a cloth simulator as clothing pressure measure. Existing cloth simulator based on a particle system has been adopted. To compute the clothing pressure, spring forces exerted on each particle have been measured along the normal direction and divided by the summed area of triangles adjacent to that particle. In order to quantitatively validate the pressure values from the simulator, we have conducted comparative analysis on a set of thin-shell cylindrical tubes, on which theoretical verification is also possible to make. Clothing pressure values have been physically measured, calculated by using the garment simulator, and theoretically estimated.

When approximated as a function of $\alpha = R_f/R_0$, all pressure curves exhibit similar tendency although they differ quantitatively, which could be improved by adopting more realistic material models in the simulator. From these comparative studies we concluded that cloth simulator can actually be used to measure tight-fit cloth pressure, and further conducted the clothing pressure measure on 3D human body models using the simulator. In short, our work takes one step toward using simulator-based experiments as a replacement to physical experiments, which would be of great saver of time, effort and cost.

Combined with this work, more sophisticated, application-dependent approaches could be developed, to guide pattern fabrication that considers clothing pressure distribution. As well, we plan to extend our work to pressure calculation on various poses or moving mannequins. In addition we will study the tight-fit clothing pressure distribution on human body model by means of experiments as well as numerical simulations via the deformation of stamps as future work.

For simplicity, we have assumed the linearity of the cloth mechanical property, but most of the garments exhibit nonlinearity, so it would be immensely interesting to look at ways of calculating clothing pressure with a simulator that is capable of inputting nonlinear curves instead of a constant. Along with the nonlinearity of clothes, we are eager to model the nonlinear, viscoelastic property of human skin, as well as their interactions like friction forces.

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