Practical Extension of Tensegric-Modeling-Based Soft Tissue Deformation

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ABSTRACT

Soft tissue deformation based on tensegric modeling is extended. This modeling is developed to apply for human females to reform/alter their body shape using tailor-made undergarments. A tensegric model is generated based on body data scanned from real female humans and covers around the bust and hips of the body. It simulates a physically-based deformation of the body shape based on pseudo forces. Variations of the undergarments are represented by different types of constraining lines, which behaves like rubber-bands. When an excessive constraint is imposed to the real body shapes, vibrations of deforming calculation are not negligible small comparing to that of a mannequin shape. Here, it is suppressed by controlling pseudo forces to perform stable calculation. Finally, the deformation result is correlated with a scanned body shape wearing an undergarment.

Keywords: women's shaping-undergarment, digital human, soft tissue deformation, tensegric modeling, FFD.

1. INTRODUCTION

Against imported low-cost and mass-produced clothing, the textile/apparel industry is urged to develop highly value-added products. One of the break-through is tailor-made garments based on information technology. Here, we focus on female undergarments which may not satisfy the users about reforming their body shapes, because mass-produced items are prepared for the typical body shape. We call this type of items as "shaping undergarments". We applied information technology on simulation of bust shapes being reformed by shaping-undergarments [1]. Fig.1 shows models for the simulation. A body shape of a customer is optically scanned by 3D measuring device *Cousette* [2] as a dense mesh model shown in Fig.1(a), the data is used to compose a control mesh as an approximated body shape (Fig.1(b)), a constraining line which behaves like a rubber band is set to represent a type of undergarments (Fig.1(c)), and a tensegric model is generated to simulate a physically-based deformation based on pseudo forces (Fig.1(d)). A tensegric model is composed of prestressed parts and tensile parts, that is, like rigid sticks and spring wires [3-10]. The entire shape of the tensegric model is decided by balance between the parts and external forces. According to the deformation of the tensegric model, the control mesh is modified then the body shape is deformed by using t-FFD [11]; a kind of FFD [12-14] using triangles as control handle. As the result of our previous work [1], the bust shape of a mannequin model seems to be deformed properly according to the imposed constraint. However, there remain some future extensions for real human's bodies, different types of undergarments, entire body parts other than bust, and correlation between simulation and real-world.

Our research objective is to develop a basic system to create a 3D view of the reformed body shape in real-time to use in practical fields, that is, apparel shops. For that purpose, exact calculations of soft tissue deformation are not necessarily, such as anatomy based approach [18-20], FEM [21-23], or mass-spring system [24]. The system is required to be stable, to give rapid response, and to have simple usage applicable to any body shapes. In this paper, we show the results of practical extension of tensegric modeling to real human body shapes about bust and hips with different types of constraints. When excessive constraints, such as too much tightened, are applied to real body data, vibrations occur during iterative calculation of deformation. We also develop a control method of pseudo forces to suppress vibrations and to converge the calculation as rapid as possible.

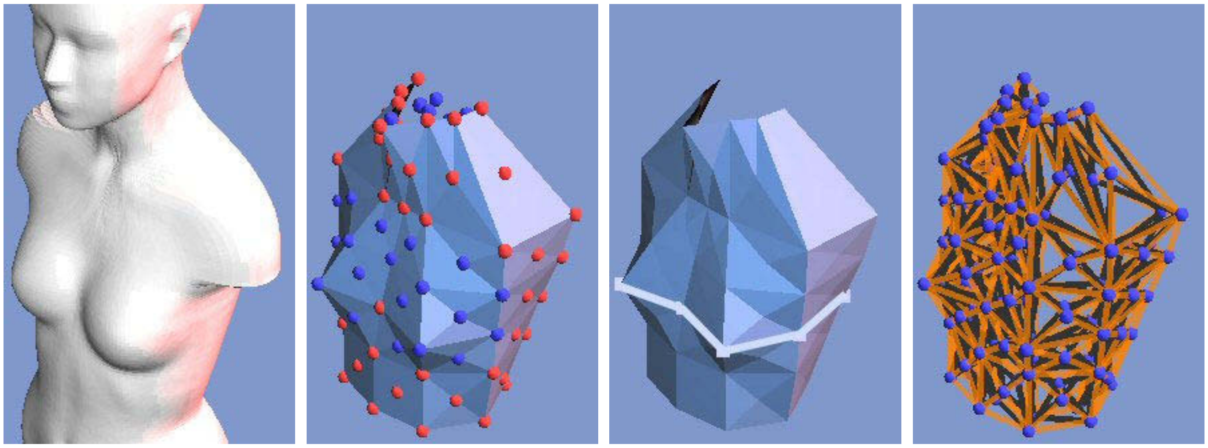

Fig. 1: Models in this research. (a) A body shape, (b) a control mesh with fixed nodes shown in red and free nodes in blue, (c) a constraining line which connects tensegric nodes, and (d) a tensegric model [1].

2. METHOD OVERVIEW

Here, we overview the calculation method to decide the shape of the tensegric model [1,8-10].

2.1 Tensegrity

Tensegrity is a neologism artificial word composed of "tense" and "integrity" used to represent architectural structures proposed by Buckminster Fuller [3]. The tensegrity structure is a combination of tensile parts and prestressed parts and maintains a whole shape by balancing the internal forces (tension and stress) and external forces. Conventionally, there are two types of tensegrity; geodesic dome [3] and prestress structure [4]. However, those outlines are limited to ball-like or bar-like shapes, and are not applicable to arbitrary shapes such as a body shape.

In the past, we have developed a "tensegric model", an improved tensegrity structure as a tight combination of prestress structure units shown in Fig.2. An elementary unit as a minimum set of tensegrity (Fig.2, left) is placed on a triangle with an arbitrary geometry. Initial length of each prestressed part is decided arbitrarily according to the supposed thickness of a soft tissue, and that of each tensile part is decided to keep balance of the entire shape. Next, another elementary unit is placed and merged by the both side (Fig.2, right). As like this way, any number of elementary units can be combined together, then a tensegric model is formed on one side of an arbitrary triangular mesh. Fig.1 (d) shows the tensegric model generated inside of the control mesh of Fig.1 (b).

2.2 Calculation

Its deformation is computed iteratively to maintain the balance of pseudo forces, as shown in Fig.3. When focusing on one prestressed part, its both end nodes are $\mathbf{P}_a$ and $\mathbf{P}_b$. $\mathbf{P}_a$ is connected to the other node $\mathbf{Q}_{a,i}$ (i=1,2, ...) via a tensile part with tension $N_{a,i}$, and similarly $N_{b,j}$ (j=1,2, ...) is a tension between $\mathbf{P}_b$ and $\mathbf{Q}_{b,j}$. $\mathbf{F}_a$ and $\mathbf{F}_b$ are external forces. The balanced position $\mathbf{P}_a$ and $\mathbf{P}_b$ is decided by solving quadric equations; a static force balance, static momentum balance, constant length of prestressed part as h, and tension of tensile part. Usually, some boundary conditions are given to the model. Some nodes are fixed in location. In Fig.1 (b), fixed nodes except for the breasts are colored by red, and other nodes on the surface of the body and nodes inside of the body are free node colored by blue. An external force works on a node to move it to the direction of the force. But, the force magnitude has a dimension of length which move the node when solving the equations, so we call it as "pseudo force".

After processing one prestressed part, its position is fixed and another prestressed part is focused for processing. When the whole parts of the model are processed, one computational cycle finishes. This cycle repeats without interruption, and the deforming shape is displayed simultaneously. When the boundary conditions are changed, the model goes to the new status of a static balance. Though the tensegric model shows a dynamic behavior during this calculation, it is totally different from physically based models such as mass-spring systems. The display shows only a calculation process, propagating a local distortion to the entire model. The tensegric model gives a static balance of the model and avoiding unexpected instabilities of dynamic behaviors, if the constraints are not excessively imposed.

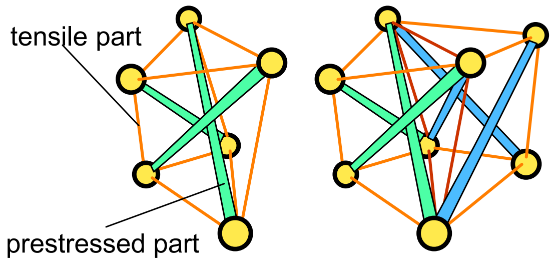

Fig. 2: Elementary unit and a combination of units of tensegric model.

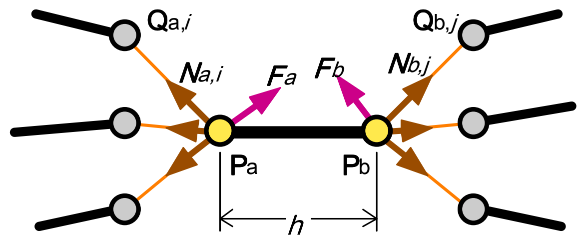

Fig. 3: Pseudo forces in tensegric model.

2.3 Constraints

A body shape is reformed by shaping-undergarments contacting the body, however the collision problem between clothing and skin is not easy to handle [25]. Here, the model of undergarments is simplified as a set of lines, which behave like rubber bands to maintain their length. We call them as "constraining lines". The lines correspond to the nearest nodes on the model's surface. If the line becomes longer than its neutral length, pseudo forces to shorten the line are imposed to the corresponding nodes (Fig.4) and are counted in the balancing calculation. If the user wants to "tighten up" her body, the neutral length is shortened from the initial value.

Because the tensegric model does not have a property to preserve volume of the model but a soft tissue is assumed to be deformable and incompressible, the total volume of the deforming body needs to be constrained as unchanged. We apply pseudo external forces to the outer nodes of the model to maintain the volume of the control mesh during calculation. Suppose Vo is the initial volume and V is the current volume, when $V > Vo$, the volumetric forces direct outward from the center of gravity, and vice versa (Fig.5). Instead of the dense body mesh, the control mesh is used for volume measurement to save computational cost and it is known the volumetric difference between the body and the control mesh is small [1]. Here, volumes of bust and hips are calculated separately.

The volumetric constraint is prioritized to that of constraining lines by setting greater magnitudes to the volumetric forces. However, the user applies an excessively "tightening" constraints by giving too small neutral lengths to the constraining lines, a vibration will occur during the calculation and this sometimes causes instability of the system. Details are discussed in the section **5**.

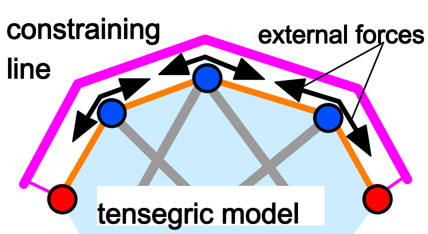

Fig. 4: External forces by constraining lines.

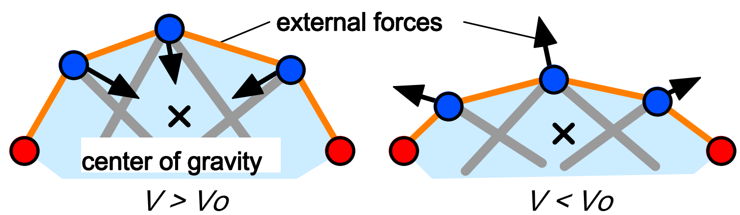

Fig. 5: External forces by constant volume property.

3. REAL BODY DATA

In the previous work [1], we used a mannequin model to show the effectiveness of our method. However, it is not sufficient to deliver our system into practical field, such as apparel shops, where a body scanning device is equipped. Capturing the mannequin data is advantageous over scanning real human bodies by the following points;

- static pose: not moving during the capture

- repeatable measurement: taking data at any time at any numbers until you satisfy
- no privacy: no need to secure personal data to handle
- good posture: formalized pose with good symmetry and also ideal shape

In order to improve our system, real body data of two female humans are provided by Hokuriku S.T.R. Cooperative (see section **7**). Fig.6 shows the data. Here, we name the model as F1 in the upper row, F2 in the bottom. Both are wearing thin and loose undergarments when the data was captured. The left underarm of F2 seems to have fractures, which is caused by moving her arm during the scanning. The left images of Fig.6 are viewed from front, and the right are from the back. Data of arms and legs are separated and saved as different files by the scanning device *Cousette* [2]. By using cross-sectional views, *Cousette* detects characteristic parts of the body; top shoulder, nipples, under-bust, waist line, hip line, crotch, and so on. These data are used to generate a control mesh by assigning appropriate geometry to each node of the template. The outside images of Fig.6 show control meshes and nodes of the prestress parts of the tensegric models. The tensegric structures are not shown, here. The blue balls (darker ones in monochrome printing) are free unconstrained nodes and locate inside the control mesh and around breasts and hips. The reds (lighter) are fixed nodes. As the characteristics of t-FFD, the original body shape will deform around not only blue nodes, but also their surrounding area. Then, the nodes at the neck and stomach are fixed to avoid irregular deformation.

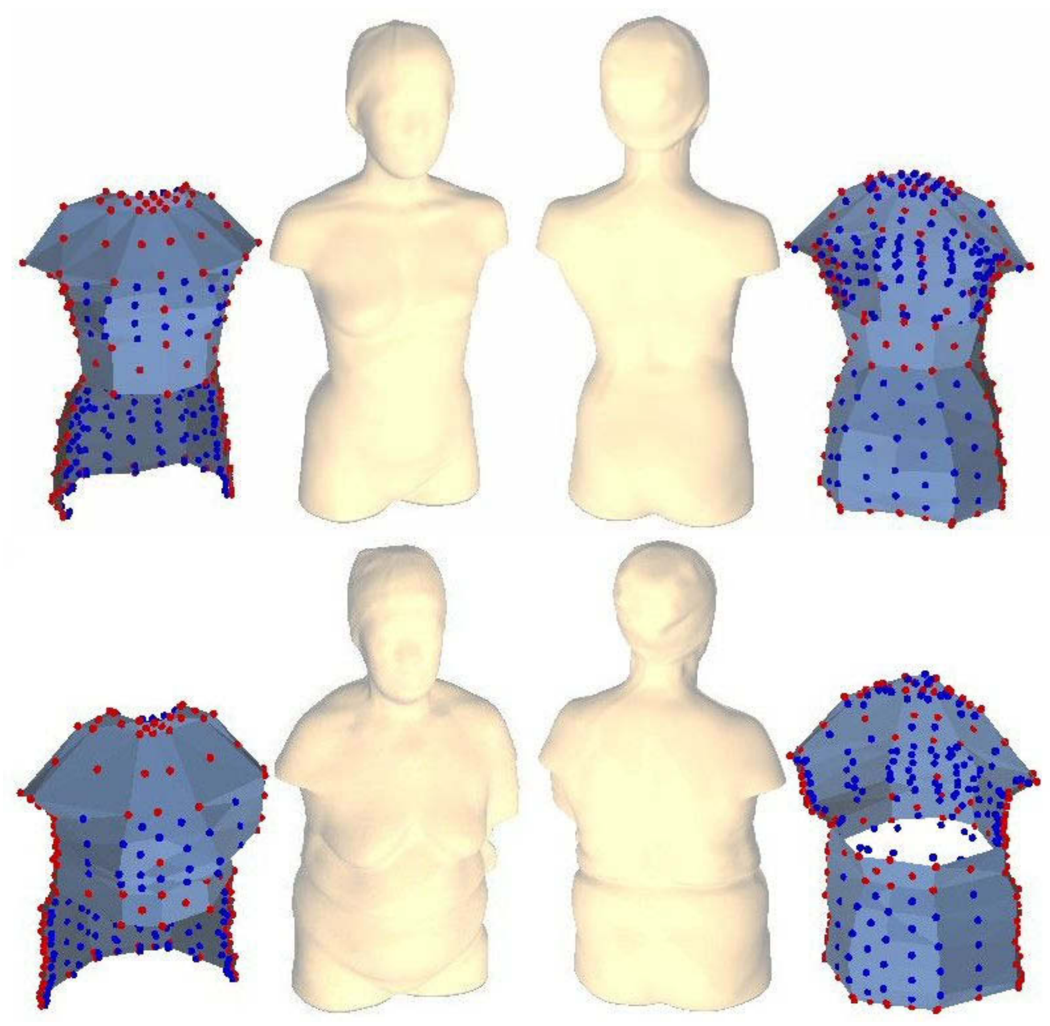

Fig. 6: The body shapes (center) and control meshes (outside) of the model F1 (top) and F2 (bottom). Views are from the front (left) and the back (right).

4. CONSTRAINING LINES

In the previous work [1], constraining lines are of one type for bust only. Here, we adopt three types of constraints for each of bust and hips, shown in Fig.7. The bust constraint type-B1 has the same topology with the previous work. The type-B2 and -B3 intends to pull up the breasts more effectively. The hips constraint type-H3 is like type-B1 to narrow the tissues to pull them up, because volumetric forces are expected to work on unconstrained tissues to make them expand. The type-H2 and -H3 are designed to pull hips up in direct manner. The type-B3 or -H1 intends to gather breasts or hips to the center of the body.

We applied those 6 types of constraining lines to the 2 model data of real human females with the prototype system of soft-tissue deformation, which iterative calculation is improved from the previous system [1] based on the method of section **5**. The deformation results of busts are shown in Fig.8 (the model F1) and Fig.9 (F2), and of hips are in Fig.10. In each case, the line length becomes stable about 120% from its neutral length, and the volumetric error is under 0.0001%.

The bust cases show meaningful results that the nipples of breasts are pulled up with certain heights according to the type of constraints. However, the results of type-B3 seem almost unchanged from the original shapes of both models F1 and F2, and effects to gather breasts are not clearly observed. It is thought, because each segment of the constraining lines completely contacts to the control mesh and it does not connect the nodes away from each other, pseudo forces are averaged by the neighbouring segments and those effect do not appear. To accomplish the intended results, constraint lines are defined to connect the bust tips directly or to connect nodes of upper bust to the nodes around collarbones.

The hip cases show unexpected distortion by the bottom in type-H2 and -H3. The type-H1 seems almost unchanged from the original body, this is thought because of the same reason of type-B3. The type-H3 results show dents below the constraining lines. This is thought, because surrounding tensegric units of the hips do not exist at the groins, or the bases of the legs, deformations of the tensegrity structure at the hip bottom are not propagated properly and remain in extreme way. To accomplish the preferred results of the hips, it is required to provide tensegrity structures at the groins, even if they have fixed nodes on the body surface. They relax the distortions like the fixed control mesh around shoulders do.

5. VIBRATION CONTROL

A prototype system in the previous work [1] operates properly about a mannequin model, if the neutral length of the constraining lines is not set excessively short. Fig.11, left, shows the changes of the nipple's height of each model during iterative calculations with type-B1 constraint, where F0 stands for the mannequin model. Fig.11, right, shows the changes of the volumetric error *(V - V0)/V0* of the control mesh. Thin lines indicate the behavior of the conventional method to apply pseudo forces. Certain vibrations occur at the initial stage of calculation for real human model (see lines of F1-C and F2-C), and volumetric errors remain for conventional method (F1-C, F2-C, F3-C in the right figure). This is thought because of conflicts of pseudo forces [26]. When the first cycle of the iteration begins, the pseudo forces caused by the constraining lines are rather big, because the model shape is not yet fitted to the constraint.

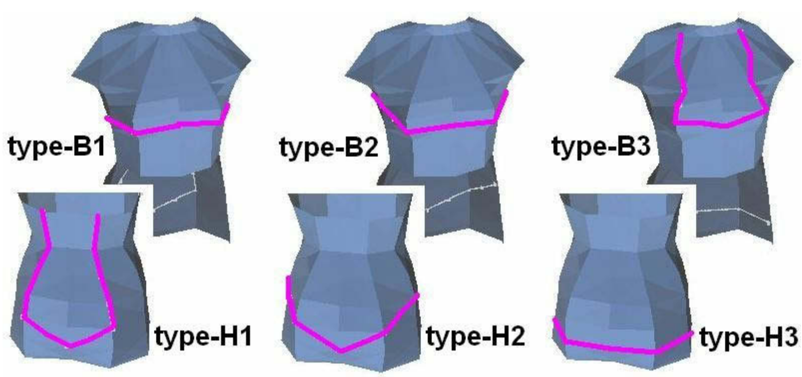

Fig. 7: The constraining lines of different types. Bust from the front view (upper) and hips from back (bottom).

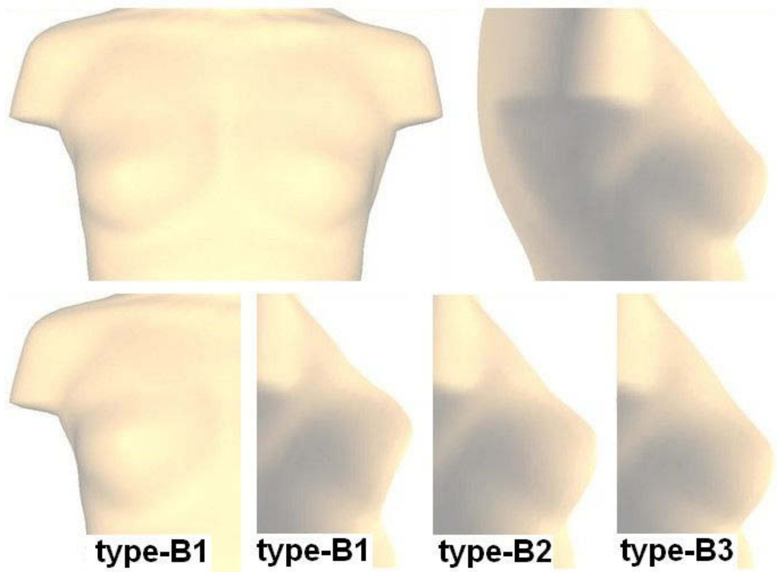

Fig. 8: The bust of the model F1. Original shape (top) and simulated shapes by different constraints (bottom).

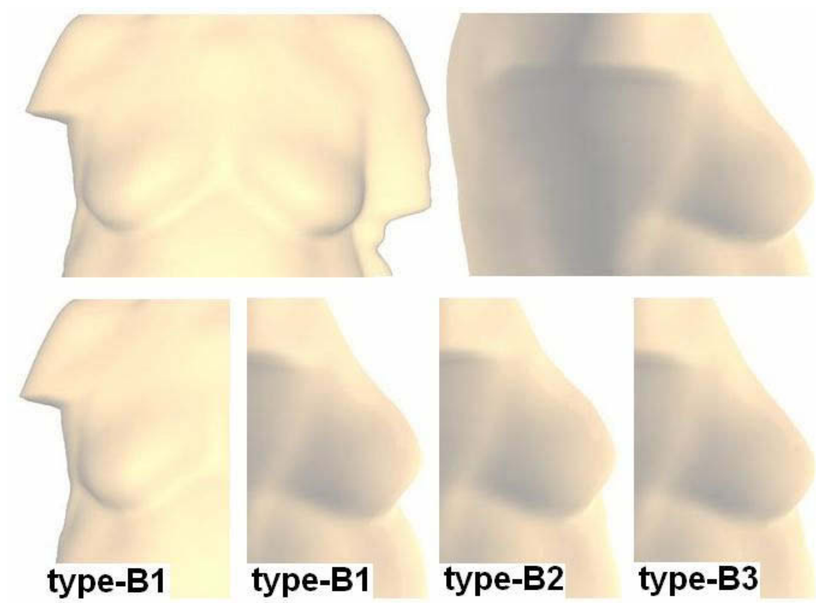

Fig. 9: The bust of the model F2. Original shape (top) and simulated shapes by different constraints (bottom).

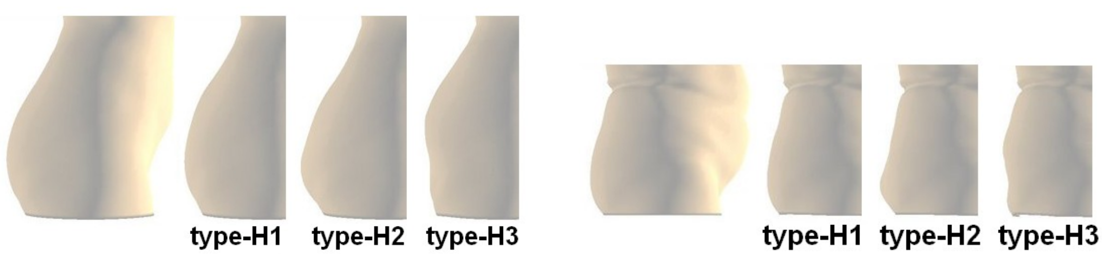

Fig. 10: The side view of hips of the model F0 and F1. Original shape and simulated shapes by different constraints.

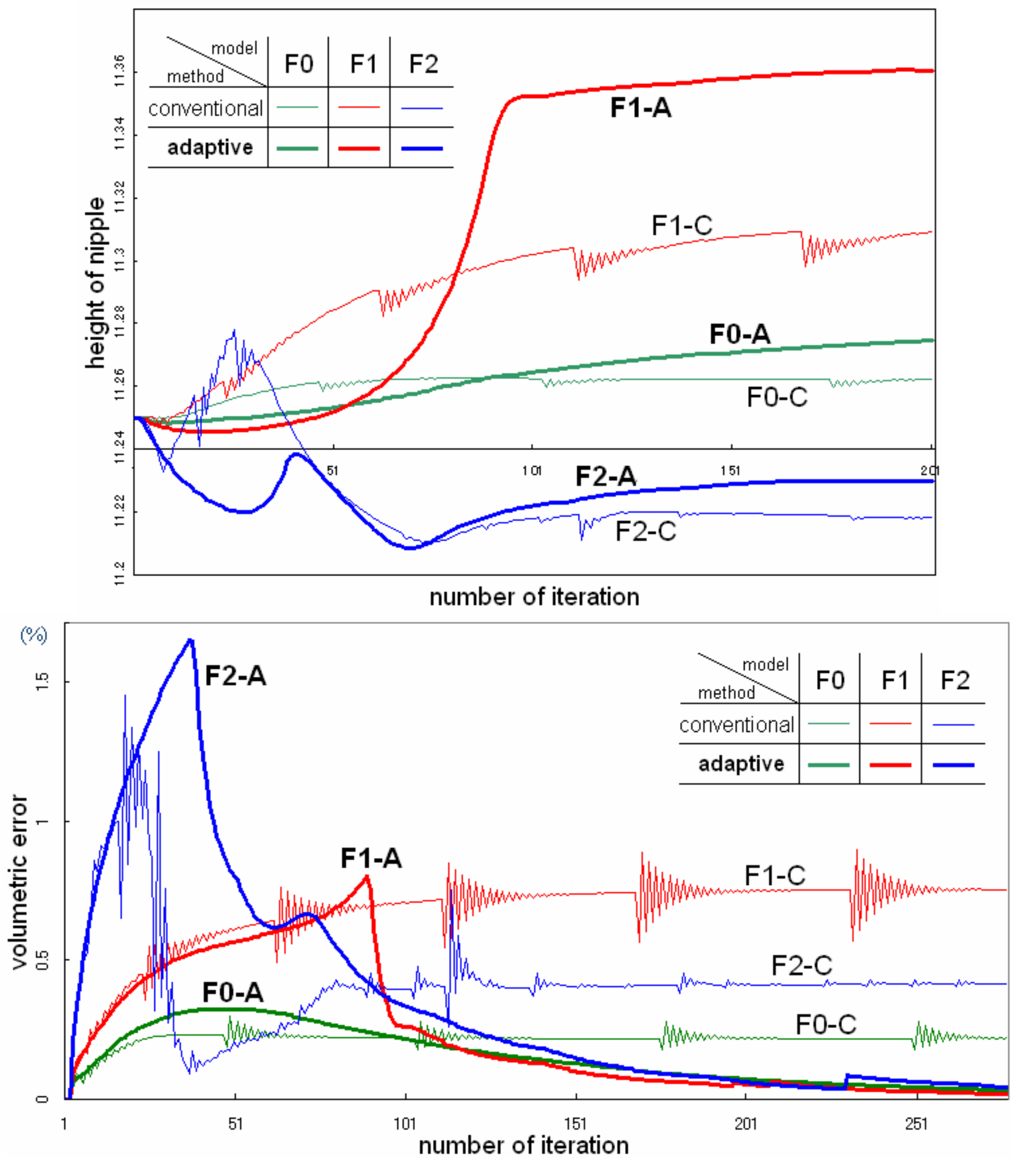

Fig. 11: Changes of nipple's height (top) and volumetric error of bust part (bottom) during iterative calculations.

Then the model is shrunk excessively at the end of the cycle, and in the next cycle the volumetric forces become rather big to expand the shape to correct the volume. Then, in the next cycle, constraining forces get bigger, vice versa. As this way, two different types of pseudo forces alternate their magnitude for each cycle and causes vibration. To avoid this instability, magnitude of the volumetric force is fixed smaller comparing to that of the constraining lines in the conventional method, then the volumetric errors remain.

Here, we introduce an adaptive method for applying pseudo forces [26]. That is, the volumetric forces are suppressed when the constraining line forces have greater magnitude. In Fig.11, thick lines indicate the behavior of this adaptive method. Vibrations are not seen in the figures (F0-A, F1-A, F2-A), and volumetric errors become closer to zero in the right figure. However, some turbulences occur at the initial stage of calculation, such as F2-A in both figures, this is caused by suppression of volumetric forces at the beginning of calculation. In total, the adaptive method works fine to deform the model stably.

Fig. 12: Comparison of bust silhouettes of the model F1. Real body wearing undergarments (left, dark) and simulated shape by type-B2 constraint (right, bright).

6. CORRELATION

We apply the tensegric modeling to show the reforming results by undergarments in interactive speed with easy usage. Because the tensegric model works on pseudo forces and do not handle material properties, such as Young's modulus or Poisson's ratio, its deformation result is not strictly correct as a real object. However, if the deformation result is correlated with the real object, the following parameters to construct the tensegric model could be adjusted to perform more realistic deformations: (1) magnitude of pseudo forces; (2) density of control mesh; (3) thickness of each elementary unit or length of each prestress part *h* in Fig. 3; and (4) types of constraining lines.

Fig. 12 shows a comparison between a real body wearing brassieres (left, dark) and a deformed model (right, bright). The left posture is aligned to fit to the model F1 with the type-B2 constraint. The both silhouettes seem similar, and this shows a possible coincidence of deformation between the tensegric model and the real body.

In the previous work [1] and in this paper, we represent a soft tissue of human body as the tensegric model by fixing some tensegric nodes on the body surface area where no deformation is expected such as back or sides of the body, shown as red balls in Fig.1(b). This restriction is introduced to prevent instable behavior or unnatural results of the practical system used in apparel shops, when they display the reforming effects to their customers. For further use of the tensegric model, it is necessary to simulate the change of body posture such as twisting or leaning. This may be achieved by changing the above restriction, that is to constrain the inside tensegric nodes which move with imaginary "bones" to control the posture. Here, the thickness of a soft tissue differs according to the part of the body, e.g. the breast part becomes thicker than the back, and it is simply interpreted as thickness of each elementary unit.

7. CONCLUSIONS

Our proposal on a soft tissue deformation based on the tensegric modeling for shaping-undergarments was extended for practical use. The bodies of real female humans were scanned and our method was applied to them. And, 3 types of constraining lines were introduced for the both part of bust and hips. This showed effective reforming results of deformation. However, the real body data caused problems during iterative calculations, such as vibrations and remaining volumetric errors, then we developed an adaptive method to apply pseudo forces and reduced the problems. The deforming result and the scanned date of body wearing undergarments were compared as similar and the tensegric model for soft tissue deformation was correlated with the real body data. On the other hand, some of the deformation results were found unnatural at bust and hips. In the bust cases, breasts were constricted to raise them but not to gather. This could be solved by the constraining lines connecting the nodes apart from each other. In the hips cases, hips were deformed but excessively distorted at the bottom. This could be solved to use the body data of the legs to generate tensegrity units around the deformation area.

8. ACKNOWLEDGMENTS

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