Tensegric-Modeling-Based Soft Tissue Deformation for Shaping-Undergarments

Kazuya G. Kobayashi[1], Taro Ichizawa[2] and Katsutoshi Ootsubo[3]

[1]Toyama Prefectural University, kobayasi@pu-toyama.ac.jp
[2]Toyama Prefectural University, ichi38@cim.pu-toyama.ac.jp
[3]Kinki University, ootsubo@hiro.kindai.ac.jp

ABSTRACT

Soft tissue deformation based on tensegric modeling is proposed. This modeling is especially applicable for human females to reform/alter their body shape using tailor-made undergarments. When a digitized mesh data of customer's body surface is provided, a tensegric model is generated, simulating a physically-based deformation of the body shape. The tensegric model is based on a sparse triangular mesh, which approximates body shape. The constraints on the deformation are the constant volume of the model, and the length of specific lines lying on the model's surface, which correlates directly with the size of the undergarments. After the tensegric model is deformed by those constraints, the deformed body shape is calculated by t-FFD (Free Form Deformation by using Triangular mesh). This process operates in real-time in a standard PC environment, and aids customers appreciate the physical effects of the shaping undergarment.

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

1. INTRODUCTION

Clothes are one of the most fundamental products for daily life, however the information technology has not yet fully extended its productivity to designing and manufacturing of these items. On the other hand, low-cost, mass-produced clothing is widely available due to the globalization of the world economy. Under these circumstances, the textile/apparel industry in advanced countries is urged to develop highly value-added products, and means to do so is tailor-made garments created through information technology. In particular, the market for female undergarments is split between cheap/mass-produced items for the standard body shape, and expensive/tailor-made items created for more individual body shapes. The latter items are called for the purpose of this research, "shaping undergarments". To efficiently produce such items, formerly known as `foundation garments', such as brassieres, girdles, and so on, it would be beneficial to incorporate information technology.

Some ambitious apparel companies are beginning to supply tailor-made undergarments by employing measuring devices at lingerie shops. In such cases, the body shape of a customer is optically scanned to generate a point cloud of the body surface [3]. The point cloud data are transferred to an apparel company, and analyzed to extract the body parameters, such as chest measurement, used for designing the form-fitting undergarments by a human tailor. However, much time passes between the order and its delivery while the customer waits. Moreover, it is not certain whether the customer would be satisfied with the body shape created by wearing the new undergarments. Because the tailor's experience is required to transform the measured body shape into the sizes of the undergarments for the best fit. With the currently available system, the customer cannot confirm the reformed body shape at the time of the order.

Our research objective is to develop a basic system to create a 3D view of the reformed body shape in real-time. This system is intended to be used to present, in real-time, the reforming effect to the customer to stimulate her interest in the product. If the customer is not satisfied by the alteration in her body generated by the shaping undergarments, a clerk will be able to adjust the fitting parameters, to correct the results, and to indicate any over- or under-constricted parts on the displayed body. This process would be repeated until the customer is gratified by the system's predictions. Then, the fitting parameters are sent to the apparel company to design and produce the shaping-undergarment. The requirements for this system are stability, rapid response, and simple usage. The system also should be applicable to manipulate the body's soft tissue, whose volume remains constant yet whose shape is constrained by the undergarments.

2. RELATED RESEARCH

In past, much researches have been performed to simulate human body shapes for models striking different poses and wearing various undergarments. In this paper, we need to process a soft tissue which forms a body silhouette, such as bust and hip. There are mainly two characteristics for deformations: Pursuing exact results or a real-time response. Both characteristics may not be achieved simultaneously.

2.1 Anatomy Based Deformation

The anatomy based model [22],[8],[17] is composed of bone, muscle and skin. After a muscle shape is decided according to the allocation of bones where muscles are combined, skin shape is calculated to smoothly cover the muscles.

The simulation of soft tissue deformation based on FEM (Finite Element Method) [23] is also similar to an anatomy based approach, but is mainly applied to facial expressions.

The robust quasistatic FEM [21] works stably with collision detection. This method takes a layered approach of muscle and outer flesh, requires a skeleton to drive the entire shape.

Without underlying muscles and bones, these methods may not work well to simulate a soft tissue.

2.2 Deformation with Collision Detection

The banded matrix FEM for soft tissue [1] works in real-time and is used for surgery simulation, such as skin suturing. The nodes of this FE model are classified into four types: Boundary, interior, visible, and contact nodes. Contact nodes are used to specify their displacements by a user's instrument. At that time, it is not appropriate to use the contact nodes as touching points to the shaping undergarments, because the constraint on each node is provided as relative distance to the neighbour node instead of as displacement.

The mass-spring system model [24] simulates physical behavior of an elastic object with viscosity inside the material. This model is composed of a network of mass elements, each of which is connected to the neighbouring elements by springs with damping and frictions. Its dynamic deformation shows natural behaviors and runs in real-time speed by choosing its resolution appropriately. The deforming shape is approximated by a set of elements with a zigzag outline for human body shape, because the element size is uniform and location of each element is decided according to the XYZ lattice. And, it is not clear for imposing volumetric constraints of the shape on mass-spring system.

2.3 Deformation by Transformation

The pose space deformation [12] constitutes an interpolation technique from an original shape to a deformed shape, where both shapes are defined by the skeletal poses. The interactive dynamic deformation [2] and the animating scanned human model [15] employ a transformation between a skeleton and an original shape. These methods require a skeleton to control the deformation and are not applicable for a soft tissue which is not firmly attached to the bones.

The stable real-time deformation model by [14] is composed of a rigid-body FE mesh to solve deformation, and a high-resolution mesh to be displayed. This method is effective to handle a detailed model with a limited computational capacity. However, the high-resolution mesh needs to be embedded in the tetrahedral FE meshes and is transformed by using barycentric coordinates. Because the FE mesh works as a control lattice of FFD [19],[6], the constrained boundary nodes of the FE mesh are kept distant from the high-resolution mesh. If this distance is not adequately small, a body shape, as a high-resolution mesh, may not be properly constrained by any shaping undergarments.

The multi-regression model [4] is based on statistical analysis of measurement data from body shapes, which are collected from tens of women both nude and clothed. This method predicts the effect of the shaping undergarment by extrapolating the measured data. However, it requires many people's cooperation concerning their body shape data. And, these accumulated data may not be applicable for various designs of undergarments.

The above methods mostly satisfy the requirements for the body shape deformation systems; stability and rapid response. However, an additional requirement, simple usage, may not be achieved, because the boundary condition, material characteristics, skeleton, etc., should be defined appropriately to simulate the deformation. The target user of the system are apparel shop clerks, who demonstrate the reforming effect of the tailor-made undergarments, adjust any fitting parameters, and take orders. Because it is important to allow the clerks to wait upon the customers, a knowledge of 3D modeling should not be required of the clerks.

3. TENSEGRIC MODELING

Our proposed system is achieved by employing a tensegric model [16],[11] with t-FFD (Free Form Deformation by using Triangular mesh) [10]. A tensegric model is used as a deformable object and t-FFD is used to generate a deformed body shape.

3.1 Computation of Tensegric Model

Tensegrity is a neologism artificial word composed of "tense" and "integrity" used to represent architectural structures proposed by Buckminster Fuller. 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. The structure is mainly classified into two kinds: The geodesic domes by B.Fuller [5], and the prestress structures by sculptor, K.Snelson [20]. It is thought that various shapes of life forms have a tensegrity structure, such as deformation of cell-shape [7]. More complicated compositions of tensegrity are proposed by networking or accumulating tensegrity units of prestress structures [9],[13], but are not adequate to represent an arbitrary shape which approximates a body shape.

In the past, we have developed a "tensegric model", an improved tensegrity structure as a tight combination of prestress structure units [16]. An elementary unit of a tensegric model is a minimum set of prestress structure, as shown in Figure 1, left. Two elementary units are combined at four tensile parts, as shown in Figure 1, right. As like this way, any number of elementary units can be combined to form a layer. Then, a tensegric model is automatically generated from an arbitrary triangular mesh by putting the bottom triangle of each elementary unit on to each face of the mesh.

Its deformation is computed iteratively to maintain the balance of pseudo forces, as shown in Figure 2. 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 $\boldsymbol{N}_{a,i}$, and similarly $\boldsymbol{N}_{b,j}$ (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, such as gravitational forces. The balance of these forces is represented by the following equations;

static force balance: $\sum_i \boldsymbol{N}_{a,i} + \boldsymbol{F}_a = \sum_j \boldsymbol{N}_{b,j} + \boldsymbol{F}_b$

static momentum balance: $(\sum_i \boldsymbol{N}_{a,i} + \boldsymbol{F}_a) \,//\, (\mathbf{P}_a - \mathbf{P}_b)$

constant length of prestressed part: $| \mathbf{P}_a - \mathbf{P}_b | = h$

tension of tensile part: $\boldsymbol{N}_{a,i} = k \max(0, | \mathbf{P}_a - \mathbf{Q}_{a,i} | - d_{a,i}) (\mathbf{P}_a - \mathbf{Q}_{a,i}) / | \mathbf{P}_a - \mathbf{Q}_{a,i} |$

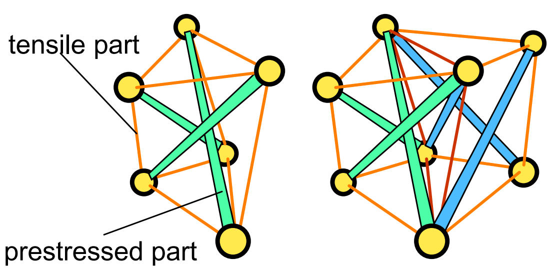


Fig. 1. Elementary unit and a combination of units of tensegric model.

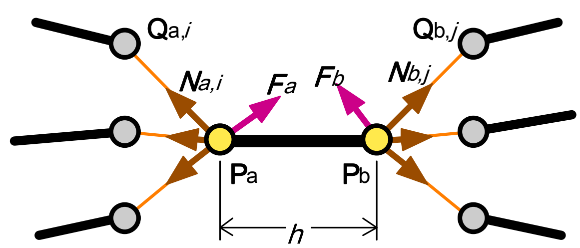


Fig. 2. Pseudo forces in tensegric model.

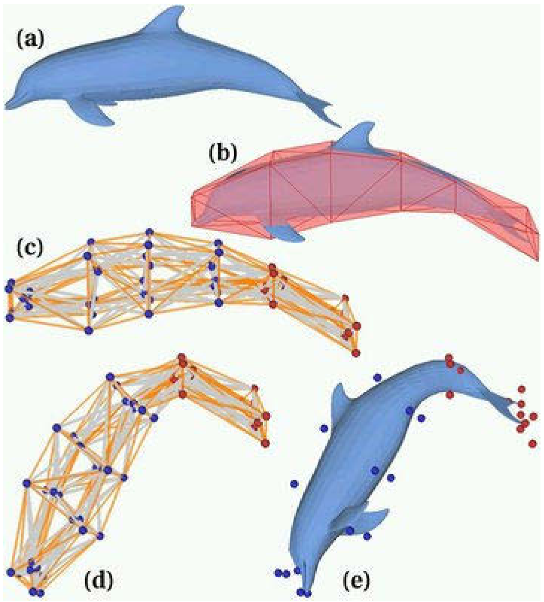


Fig. 3. "Dolphin" example of tensegric modeling.

$N_{b,j}$ is defined vice versa. Where, h is a constant length of prestressed part, k is a spring constant of Hooke's law, $d_{a,i}$ is a natural length of a tensile part $\mathbf{P}_a$-$\mathbf{Q}_{a,i}$, and $\max(x, y)$ is a function to return a greater value. When external forces and other prestressed parts are fixed, these equations become quadric formulae which have two possible solutions; stable or unstable neutral positions of $\mathbf{P}_a$ and $\mathbf{P}_b$. The stable neutral is chosen by taking a solution with smaller value of the total tensions, $|\sum_i N_{a,i}| + |\sum_j N_{b,j}|$.

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 and the display is refreshed, one computational cycle finishes. This cycle repeats without interruption, and the deforming shape is displayed simultaneously to satisfy the above equations and boundary conditions, such as specified fixed nodes, external forces, etc. When those conditions are changed, the model goes to the new status of a static balance. Usually, the deformation magnitude decreases like a damping effect, as the computation cycle is repeated. However, this does not mean a dynamic behavior like mass-spring systems. Because a tensegric model does not assume mass or damping properties, but calculates the local balancing position of a prestressed part and propagates that change to the rest of the model. The tensegric model is different from mass-spring systems about giving a static balance of the model and avoiding unexpected instabilities of dynamic behaviors.

3.2 Tensegric Modeling

Because a tensegric model requires additional computational costs, it is generated from an approximated shape with a sparse mesh. We employ a transformation method "t-FFD" [10] to deform a detailed shape according tothe tensegric model.

Figure 3 shows an example of tensegric modeling. The original shape "dolphin" is shown in (a), and its control mesh (pink) is shown in (b) which is created by simplifying the original shape. By the nature of t-FFD, the control mesh does not need to envelope the original mesh, nor to be closed as 2-manifold. A tensegric model is automatically generated from the control mesh, as shown in (c). Here, internal lines (gray) are prestressed parts, and contour and internal lines (ocher) are tensile parts. Then, a user sets constraints on the node points of the tensegric model, that is, the points (red) around the dolphin's tail are fixed and the other points (blue) are freely moved by a downward gravitational force. As a result, the tensegric model is deformed, as shown in (d), to maintain the balance between pseudo forces. Because the outer triangles of the tensegric model are the same as the control mesh, t-FFD deforms the original shape, as shown in (e). Note that this process has been stably accomplished in real-time speed, and the user has only specified the fixing points as constraints, indicating a simple usage.

3.3 Body Shape and Tensegric Model

Figure 4 shows the models used in this research.

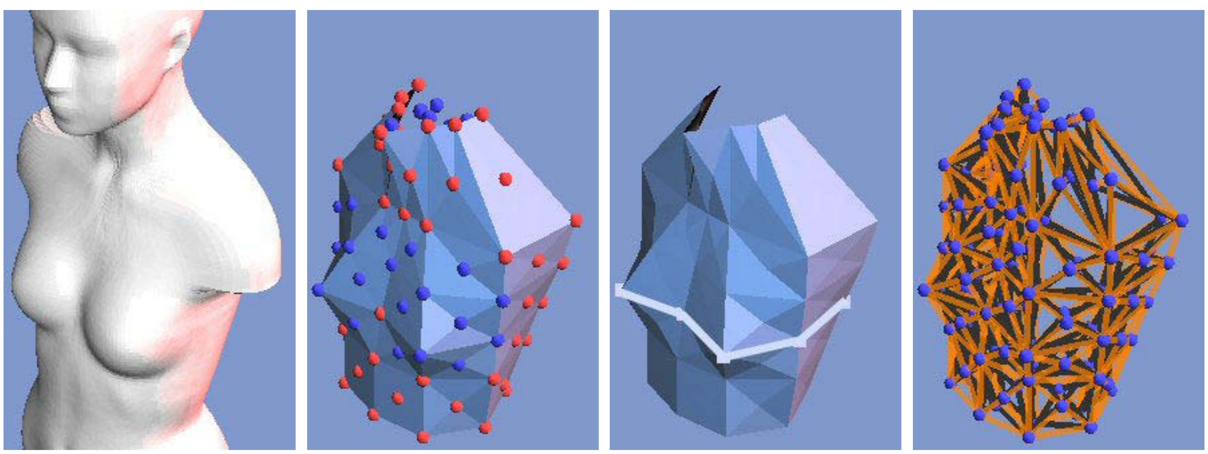
A mannequin is used as the original body shape, which is measured by a 3D scanner and represented by a dense mesh (about 62,000 polygons), as shown in (a). The characteristic parts of the body, such as nipples or under-bust (the area under the bust), are detected, and the parameters of their location and/or size are extracted. Then, the geometry of a template polygon is changed to incorporate those parameters and is used as a control mesh of t-FFD (120 polygons), as shown in (b). Because the control mesh is not required to be a 2-manifold closed shell, it only covers the deformed part and its surroundings. In the figure (b), each node of the control mesh is colorized to show the fixing constraints; the light (red) node is fixed, and the dark (blue) moves freely. The surrounding area is fixed to smoothly connect to the body surface between the deformed part and the unchanged part. A constraint by line length (see 3.5) is imposed to the control mesh indicated as light (white) lines, as shown in (c). A tensegric model is automatically generated from the control mesh, as shown in (d).

3.4 Constraints of Volume

Because a soft tissue is assumed to be deformable and incompressible, the total volume of the deforming body needs to be constrained as unchanged. However, the tensegric modeling does not have a constant volume property. The volume-preserving model [18] handles a combination of Bezier solids by adjusting control points and weights. This technique is limited to the shape models whose volume and derivatives are analytically defined, and is not applicable to the tensegric deformation.

We apply a pseudo external force to the tensegric model to maintain the volume of the control mesh during deformation. This volumetric forces are directed outward and act on each node of the tensegric model as external forces, when the current volume is smaller than the initial volume, and vice versa.

Instead of the body shape with a dense mesh, the control mesh is used for volume measurement to save computational cost. In case the control mesh is not provided as a 2-manifold closed shell, the volume is computed as a sum of tetrahedral, whose bottoms constitute triangles of the control mesh and apices are the center of gravity of the mesh vertices. The volumetric difference between the body and the control mesh is small, because the control mesh is created properly fitting to the body shape. Additionally, t-FFD is invariant for scaling transformation of the control mesh [10], so, the volume of the body shape varies almost proportionally to the volume of the control mesh about relatively small deformations. Hence, constraining the control mesh is possibly applicable instead of the body shape.



(a) (b) (c) (d)

Fig. 4. Models in this research: (a) A mannequin body shape, (b) a control mesh, (c) a line to constrain the length, and (d) a tensegric model.

3.5 Constraints of Length of Line on Model's Surface

Reforming of a body by shaping-undergarments is interpreted as the constraints on the tensegric model, as follows.

The undergarments are simplified as a set of lines, which behave like rubber bands to maintain their length. The lines are corresponded to the nearest nodes lying on the tensegric model's surface. If the line's length becomes longer than its initial value, pseudo forces to expand the line are generated and imposed to the nodes on the line as external forces of the tensegric model. Then, the tensegric model changes its shape to a newly balanced status to satisfy the constraints: Volume of the model and length of the lines.

The reason why the control mesh is constrained instead of the body shape is explained as in 3.4.

4. EXAMPLES

According to section 3, we have developed a prototype system to present the body shape reformation. The system is implemented on a personal computer with Windows-XP OS, Mobile Pentium-IV 1.7 GHz CPU, 512 MB memory, and an on-board graphic card.

In this example, a mannequin is used as an original body shape, and a brassier is assumed to be the shaping-undergarment. Because the mannequin's breast part becomes deformed, a control mesh is designed to cover this part, as shown in Figure 4(b). The shaping-brassier is simplified to reform the chest measurement, which passes over the nipples, and constrains the length of the line on the tensegric model, as shown in Figure 4(c).

Figures 5, 6 and 7 illustrate the body shapes from different viewpoints. Each figure on the left is the original shape, while the right figure is the deformed shape. Deformation is achieved to maintain the volume of the control mesh, and to specify the chest measurement as 90% of the original length, meaning that the brassier constricts the breast. As a result, the volume becomes 100.6% of the original, and the chest measurement becomes 97%. The deformed images demonstrate the effect of the undergarment reforming the entire shape of the breast portion.

Figure 8 shows the deformed control mesh, shaded according to the degree of distortion. The lighter parts are highly distorted, while the darker parts remain unchanged. Shading is calculated around each vertex to compare the ratio of the area of the surrounding triangles before and after the deformation. The image demonstrates that the upper middle part of the breast is over-constricted.

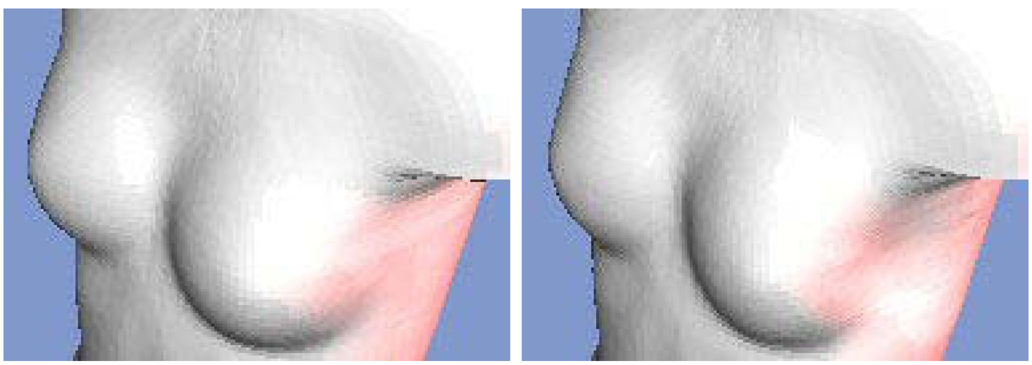


Fig. 5. Oblique views of the body shape: Original (left) and deformed (right).

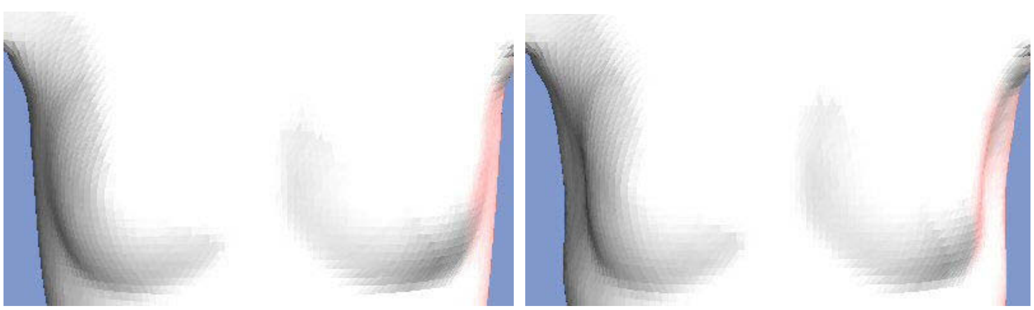


Fig. 6. Front views of the body shape: Original (left) and deformed (right).

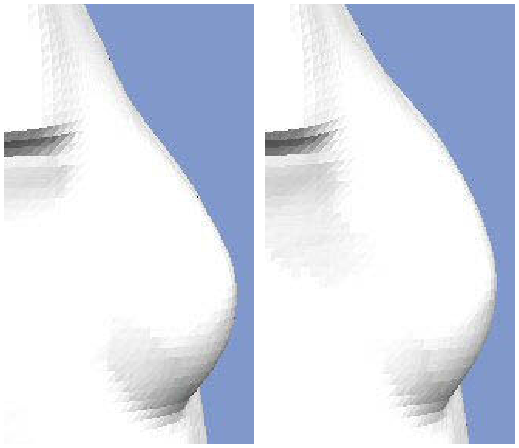


Fig. 7. Side views of the body shape:
Original (left) and deformed (right).

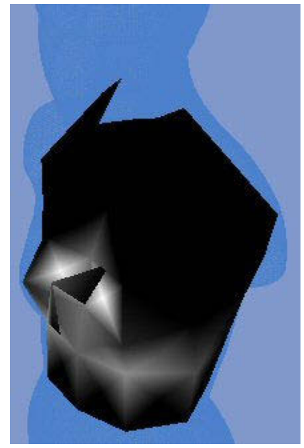


Fig. 8. Image of the deformed control mesh,
shaded according to the degree of distortion.

5. CONCLUSIONS

We proposed a soft tissue deformation method for shaping-undergarments, based on the tensegric modeling. This method was intended to support the tailor-made process of the undergarments at apparel shops: Scanning the customer's body shape, simulating the reforming results, and indicating any over/under-constricted body parts. We have developed a prototype system to demonstrate this process. It ran in real-time and demonstrated the reforming results.

In this paper, the body shape is not applied to the real humans, due to the limit of personal data usage. In practice, the body shape data may contain artifacts caused by improper scanning and so on. The system will abort when inappropriate data is processed. In order to manage such undesirable cases, it is necessary to enhance the system through additional experience with real body data.

6. ACKNOWLEDGMENTS

The body shape data of the mannequin was provided by courtesy of Mr. Makoto Kanatani of Hokuriku S.T.R. Cooperative, Nanto, Toyama, Japan, under the auspices of a cooperative research project between Toyama Prefectural University and Hokuriku S.T.R.

7. REFERENCES

[1] Berkley, J., Weghorst, S., Gladstone, H., Raugi, G., Berg, D. and Ganter, M., Banded Matrix Approach to Finite Element Modeling for Soft Tissue Simulation, Virtual Reality: Research, Development and Application, Vol.4, 1999, pp 203-212.

[2] Capell, S., Green, S., Curless, B., Duchamp, T. and Popovic, Z., Interactive Skeleton-Driven Dynamic Deformation, Procs. of SIGGRAPH, 2002, pp 586-593.

[3] Cousette, Hokuriku S.T.R. Cooporative, http://www.str.or.jp/e/apparel/cousette.html

[4] Choi, D.-E., Nakamura, K. and Kurokawa, T., Simulation of Brassiere-Wearing Figures using Multi-Regression Models and Its Evaluation, Journal of Textile Machinery Society Japan, Vol. 58, No.6, 2005, pp 35-42, *(in Japanese)*.

[5] The Buckminster Fuller Institute, http://www.bfi.org/

[6] Hsu, W. M. and Hughes, J. F., Direct Manipulation of Free-Form Deformations, Proc. of SIGGRAPH, 1992, pp 177-184.

[7] Ingbur, D. E., The Architecture of Life, *Scientific American*, Vol. 278, No.1, 1998.

[8] Kaehler, K., Haber, J. and Seidel, H.-P., Geometry-based Muscle Modeling for Facial Animation, Proc. of Graphics Interface, 2001, pp 37-46.

[9] Kitrick, C. J., Tensegrity Module Structure and Method of Interconnecting the Modules, United States Patent, No. 4 207 715, 1980.

[10] Kobayashi, K. G. and Ootsubo, K., t-FFD: Free Form Deformation by using Triangular Mesh, Proc. of 8th ACM Symposium on Solid Modeling and Applications, 2003, pp 226-234.
[11] Kobayashi, K. G., Ichizawa, T., Nakano, K. and Ootsubo, K., Tensegric Mobile Controlled by Pseudo Forces, Proc. of 13th Annual Conference of ACM Multimedia, 2005, pp 930-936.
[12] Lewis, J. P., Cordner, M. and Fong, N., Pose Space Deformation: A Unified Approach to Shape Interpolation and Skeleton-Driven Deformation, Proc. of SIGGRAPH, 2000, pp 165-172.
[13] Liapi, K. A., A Visualization Method for the Morphological Exploration of Tensegrity Structures, 5th International Conference on Information Visualization, 2001, pp 25-27.
[14] Mueller, M., Dorsey, J., McMillan, L., Jagnow, R. and Cutler, B., Stable Real-Time Deformation, Procs. of ACM SIGGRAPH Symposium on Computer Animation, 2002.
[15] Oliveira, J., Zhang, D., Spanlang, B. and Buxton, B., Animating Scanned Human Models, *Journal of WSCG*, Vol. 11, No. 1, 2003.
[16] Ootsubo, K. and Kobayashi, K. G., Tensegric Modeling for Arbitrary Mesh Models, Digital Engineering Workshop - 5th Japan-Korea CAD/CAM Workshop, 2005, pp 168-171.
[17] Pratscher, M., Coleman, P., Laszlo, J. and Singh, K., Outside-In Anatomy Based Character Rigging, Eurographics/ACM SIGGRAPH Conference on Computer Animation, 2005, pp 329-338.
[18] Rappoport, A., Sheffer, A. and Bercovier, M., Volume-Preserving Free-Form Solids, 3rd Symposium on Solid Modeling & Applications, 1995, pp 361-372.
[19] Sederberg T. W. and Parry, S. R., Free-Form Deformation of Solid Geometric Models, Proc. of SIGGRAPH, 1986, pp 21-30.
[20] Snelson, K., http://www.kennethsnelson.net/
[21] Teran, J., Sifakis, E., Irving, G., and Fedkiw, R., Robust Quasistatic Finite Elements and Flesh Simulation, Eurographics/ACM SIGGRAPH Conference on Computer Animation, 2005, pp 181-190.
[22] Wu, Y., Kalra, P., and Thalmann, N. M., Physically-based Wrinkle Simulation and Skin Rendering, Eurographics Workshop on Computer Animation and Simmulation, 1997, pp 69-79.
[23] Zachow, E.Gladiline, E., Hege, H.-C. and Deuflhard, P., Finite-Element Simulation of Soft Tissue Deformation, Computer Assisted Radiology and Surgery (CARS), Elsevier Science B.V., 2000, pp 23-28.
[24] Jansson, J. and Vergeest, J. S. M., A Discrete Mechanics Model for Deformable Bodies, *Computer-Aided Design*, Vol. 34, 2002, pp 913-928.