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A Development of Tailor-Made Design System for Arm Brace

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ABSTRACT

Since a brace is required to fit to an individual body shape, the tailor-made design is the most effective approach to produce an ideal one. Our research objective is to develop a tailor-made design system for arm brace. In this paper, we propose a shape modeling method for designing an arm brace fits to the user's arm. Our idea is that the tailor-made arm brace can be designed by deforming a standard arm brace as fit to an individual arm. In our system, a user inputs shape models and geometrical constraints of the brace model, and the system outputs the final shape automatically. This system achieves low-cost design of an arm brace with the shape fits to the arm.

Keywords: brace, tailor-made design, reverse engineering, mesh deformation, tensegric modeling, t-FFD.

1. INTRODUCTION

A brace is an assistive device for disabled persons with disorders of the limbs. It is an indispensable tool for their daily life and rehabilitation. In order to get the proper effect, its shape is required to fit to an individual limb.

So in traditional way, it should be produced manually by well-trained prosthetist with official qualification. At first, they take a negative cast of a user's limb by a plaster material. At this time, the limb is wrapped with a plastic film not to become dirty. It takes several minutes until the cast fixes. Since the user is forced to keep the posture during that time, it has a heavy burden for her/him. Secondly, they take a positive cast from the negative cast. Thirdly, a brace is produced by thermoforming using plastic materials. Finally, they finish it by manual process. As a result, the product shape has a surface fits to the limb. However, it takes 1-week at least to finish the all processes, and the mold cannot be reused. So, the production cost is not negligible. Moreover, since the final shape has individual difference, the product quality is non-uniform.

Recently, the digital design methods for garment [2,10,12,14] have been developed, and we can see the dedicated CAD systems. Robson's method [12] was developed for increasing the reality of a virtual human character. In the method, an initial 3D garment is constructed from 2D sketch lines, and the final shape is calculated automatically as wrap a virtual human body by a geometrical transformation. Also, some design methods for brace or prosthetic limb [1,4] already exist. Clin's method [1] was developed for torso brace design. In the method, torso model is represented by personalized finite elements, and the system simulates the shape deformation based on the geometrical constraints given by the brace model. Facoetti's method [4] was developed for socket design of lower limb prosthesis. In the method, an operator can design an optimal socket model according to the guidance based on orthopedic knowledge, and the model is represented free-form surface. However, since the product model is designed from scratch in these methods, it takes the time according to the complexity. So, these methods assume that the model has simple shape which is homeomorphic to disk or cylinder.

Also, personalized arm brace (Fig. 1) is in strong demand. However, since arm has high posture degrees of freedom compared with the other body parts, the brace has multiple feature shapes required for the function, such as hole, joint, end lines and so on. Since the design cost of arm brace by the conventional methods mentioned above is not negligible, those cannot be applied for the tailor-made design.

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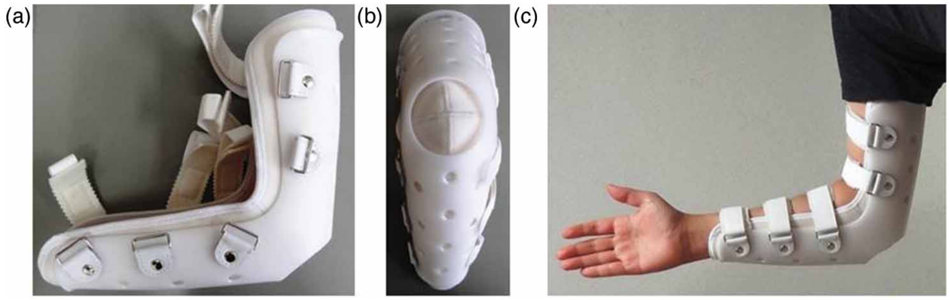

Fig. 1: Arm brace (elbow brace): (a) Side view, (b) Top view, and (c) The equipped state.

Our research objective is to develop a tailor-made design system for arm brace. In this paper, we propose a shape modeling method for designing a brace model fits to its user's arm. Our idea of a new method is that the tailor-made arm brace can be designed instantly by deforming standard brace as fit to an individual arm. This means that the tailor-made can be achieved by a little effort even if the shape has complex features. It is the most distinctive feature never seen in the conventional methods.

From the next section, we describe the method overview, its details, and demonstrate the experimental results.

2. METHOD OVERVIEW

Here, we overview our proposal method, and describes the details of the calculation algorithm.

2.1. Procedure

In the past, we developed a body shape deformation system which simulates reform effect given by shaping-undergarment [6,7]. In the system, the undergarment model is designed as fit to a body model, and the body model is related geometrically to it. The body model is deformed according to the geometrical constraints of the undergarment model.

In our method, an arm brace model with standard shape ("standard brace model", Fig. 2(a)) is related geometrically to its rough-shape model ("control mesh", Fig. 2(b)) to satisfy the constraints. The standard brace model is a pattern model designed for a standard arm, and means an initial model to obtain a tailor-made brace model. The geometrical constraints are the boundary conditions given for the standard brace model. A shape of the control mesh satisfies them is calculated, and a final shape of the brace model is obtained according to the relation to the control mesh. The models are represented by triangular meshes. The geometrical constraints act on the vertices, and fix them at specified positions through the entire calculations. The "arm model" (Fig. 2(c)) is used for the reference. We assume that these models are already prepared in some way, and we designed by using reverse engineering technique in this study. Generally, the arm brace has some feature shapes locally, and the global shape which satisfies both of the constraints and fits to an individual arm is non-trivial. In the prototype system, a user inputs the models and the geometrical constraints, and the system outputs automatically the tailor-made brace model which satisfies the requirements.

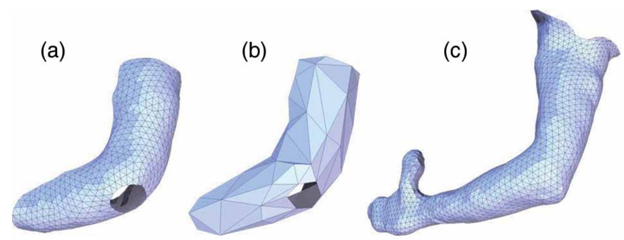

Fig. 2: Input models of our prototype system: (a) Standard brace model, (b) Control mesh, and (c) Arm model.

The deformation algorithm is based on "tensegric modeling" [8] and "t-FFD" [9]. Tensegric modeling is a pseudo physical simulation method for arbitrary meshes. "Tensegric model" is the deformation structure, and is applied to the control mesh in our method. t-FFD is a free-form deformation method for arbitrary meshes, and is used to calculate a final shape of the brace model from the deformed control mesh given by the simulation. The details are described later (Section 2.2 and 2.3). In this method, the deformation process is performed automatically in accordance with following steps.

1. **Establishment of correspondence relation**
   The system makes the geometrical relation of the brace model to the control mesh by mapping algorithm based on t-FFD.
2. **Construction of deformation structure**
   A tensegric model is constructed on the control mesh, and the geometries are constrained to accord with each other.
3. **Tensegric modeling based on geometrical constraints**
   The system calculates the stabilized shape of the tensegric model in the boundary condition

based on the geometrical constraints. Then a deformed control mesh is calculated from the deformed tensegric model.

4. **Restoration**
   A deformed (tailor-made) brace model is given by restoring the geometry from the deformed control mesh and the correspondence relation.

A brace model can be deformed smoothly and globally by conventional t-FFD, but the boundary conditions based on the constraints are not considered in the algorithm. In this study, the geometrical constraints are achieved by implementation of a new mapping algorithm (Section 2.4) to the method. As a result, the final brace model has a smoothly deformed surface which fits to the arm model, and satisfies the constraints.

2.2. t-FFD

t-FFD uses a triangular mesh model with arbitrary topology to control the deformation. Its deformation steps are shown in Fig. 3. When a designer wishes to deform an original shape (original mesh) ***M′*** (a ping-pong ball) into ***M′*** (an egg) as a white arrow in the figure, it is dissolved into the following three steps shown by the black arrows. In our proposal method, we handle a brace model as an original mesh, and prepare a control mesh with the rough shape.

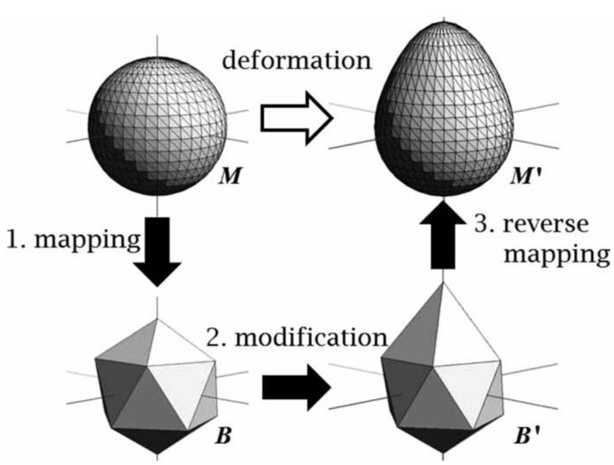

Fig. 3: Procedure of t-FFD.

1. **Mapping**
   A geometrical relationship between the original mesh ***M*** and a control mesh ***B*** is established. A vertex coordinate of ***M*** is affine mapped to several triangles of ***B***, and the "weight" [9] is calculated based on the distance between the vertex and the triangle.
2. **Modification**
   A designer modifies the control mesh ***B*** into ***B′***. The only constraint on this modification is to keep the geometry of ***B*** as non-degenerated.

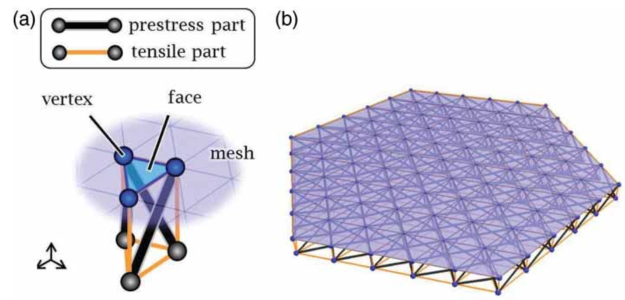

Fig. 4: Tensegric model: (a) Unit structure and (b) Continuous structure.

3. **Reverse mapping**
   A deformed mesh ***M′*** is produced from ***B′*** and ***M*** by resolving the inverse problem of the mapping. A vertex coordinate of ***M′*** is restored by weighted average of the relations. Once the mapping is finished, the modification and this step can be iterated until a designer satisfies.

2.3. Tensegric Model

Tensegric model is a pseudo physical model based a kind of architectural structure "tensegrity" [13]. It is composed of the elements load only pure tension (tensile parts) and pure compression (prestress parts), and achieves self-stabilization by the external forces and the geometrical constraints. It has high geometrical stability instead of physical validity such as FEM. The tensegric modeling is a pseudo physical deformation method by using a tensegric model as deformation structure of triangular mesh, and achieves rubber-like deformation of the mesh stably in interactive speed. In this method, a unit structure (Fig. 4(a)) assigned with a face, and the geometry (vertex coordinate) is controlled by the unit. Unit have homeomorphism against the mesh, the adjacent units share the element parts each other (Fig. 4(b)).

2.4. Hybrid Weighting

In the conventional mapping in t-FFD, a vertex of the original mesh is mapped to the arbitrary triangles of the control mesh by weight based on the Euclidian distance, and we call it "geometry-based weighting". The final coordinate after the deformation is obtained by blending coordinates restored from all the relations. The deformed mesh has smooth surface, but the geometrical constraint to the control mesh cannot be guaranteed, except in the case that a vertex on an original mesh (brace model) accords geometrically with that of the corresponding triangles on the control mesh. We call the condition "accordance condition".

In our method, this problem was solved by implementation of a new weighting algorithm using accordance condition, and we call it "hybrid weighting". It consists of 2-processes; "topology-based weighting" and "gradation processing". The details are described in section 2.4.1 and 2.4.2.

2.4.1. Topology-based weighting

Generally, a brace has some functional feature shapes, and they have to fit to the proper positions on the target arm. In the manual tailor-made, a prosthetist confirms the positions by measuring a real arm, and designs the global shape satisfies the local constraints in geometry. In this method, we achieve the constraints by a new weighting method of mapping in t-FFD, and we call it "topology-based weighting". The algorithm is based on the accordance condition, and is dissolved into following 2-processes; "specification of constraints" and "weight calculation".

- **Specification of constraints**
  A user specifies typical vertex constitute the feature shapes on a brace model: "feature vertex" (FV, Fig. 5(a)), and the system finds the "control vertex" (CV, Fig. 5(b)). CV means corresponding vertex of FV, and has the same geometry. FV is constrained geometrically to accord to CV by this method. Then the system extracts a "feature line" (FL, Fig. 5(a)). It means a continuous "geodesic line" with single stroke on a mesh model, and connects all FVs to each other. In our method, geodesic line means an edge sequence with single stroke on a mesh model, and connects 2-vertices with the shortest distance on the edges. The calculation algorithm is based on "Dijkstra's algorithm" [3].

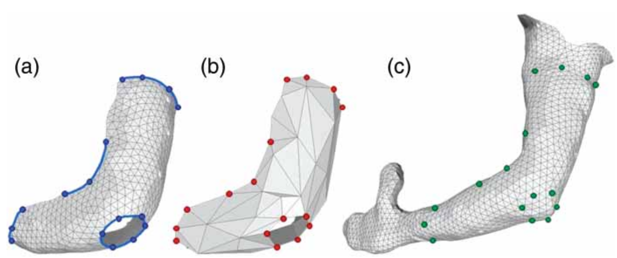

Fig. 5: Constraining objects: (a) FVs (blue points) and FLs (blue lines), (b) CVs (red points), and (c) TPs (green points).

- **Weight calculation**
  In this process, a new mapping weight for t-FFD is calculated based on the mesh topology. The weight of a triangle T_{ij}: W_{ij} related to a vertex position: p of a brace model is given as follows:

$$W_{ij} = \frac{w_{ij}}{\Sigma_i \Sigma_j w_{ij}}, \quad w_{ij} = g_{ij} \cdot t_i \tag{2.1}$$

$$t_i = \begin{cases} 1 - \dfrac{d}{s_i} & \text{(on a FL)} \\ \dfrac{u_i}{\Sigma_i u_i} & \text{(otherwise)} \end{cases}, \quad u_i = 1 - \frac{l_i}{\alpha} \tag{2.2}$$

Here, α is a range of a geometrical constraint, and is decided not to cross-over the other constraint by a user. l_i is a geodesic distance from p to a FV in the range. s_i is a geodesic distance of from q_i to q_{i+1}, and q_i is a FV, and q_{i+1} is a FV neighbors q_i. d is a geodesic distance from p to q_i. g_{ij} is a geometry-based weight of a triangle neighbors a CV related to q_i.

2.4.2. Gradation processing

Gradation processing is blending calculation of geometry-based weights and topology-based weights. As the result, topology-based weight is mapped on the mesh gradationally. The restored position of p: p' is given as follows:

$$p' = (1 - x) \cdot \frac{\Sigma_k V_k p_k{}'}{\Sigma_k V_k} + x \cdot \Sigma_i \Sigma_j W_{ij} p_{ij}{}', \quad x = 1 - \frac{r}{\alpha} \tag{2.3}$$

Here, r is a geodesic distance from p to FLs. $p_{ij}{}'$ is a restored position of p by T_{ij}. V_k is a geometry-based weight of a triangle related to p: T_k, and $p_k{}'$ is a restored position of p by T_k. Fig. 6 shows a color map based on a topology-based weight.

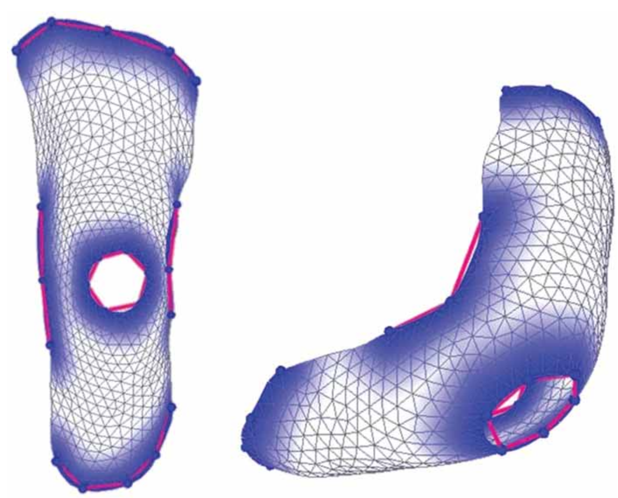

Fig. 6: Color map based on a topology-based weight: (Left) Top view and (Right) Diagonal view. Pink lines connect CVs each other.

In our method, a geometrical constraint for fitting a feature shape of the standard brace model to the arm model is achieved by a geometrical accordance constraints of FVs to "target points" (TPs, Fig. 5(c)). TPs are configured as functionally proper points which FVs should satisfy finally, and is specified on the arm model by a designer. Since FVs accord with CVs by this algorithm, FVs accord to TPs by accordance of CPs to them. Then the final shape is calculated automatically based on the constraint. Fig. 7 shows an example of deformation with geometrical constraints. As shown in this figure, the brace model is deformed smoothly maintaining the accordance of FVs to CVs by using this algorithm.

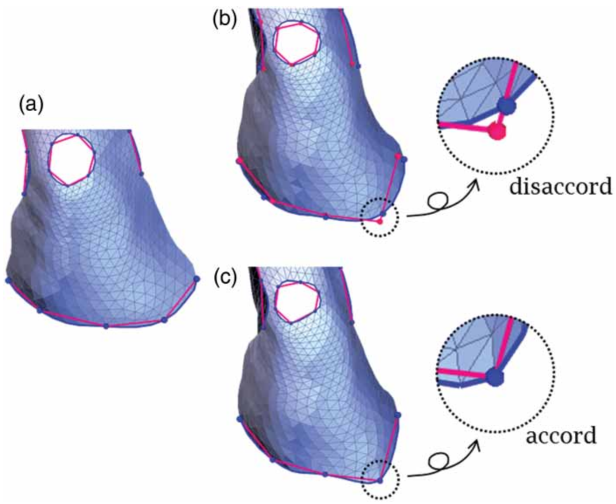

Fig. 7: Deformation with geometrical constraints: (a) Initial shape, (b) Deformed shape (based on the conventional weighting), and (c) Deformed shape (based on the gradational weighting).

3. PREPARATION OF MODELS

Our method assumes that the input models are prepared in some way. In this study, we prepared input models by using reverse engineering system. The system consists of a 3D scan system based on range sensors (Kinect [5]) and a free-ware system for range data processing (Rapidform XOM [11]). The accuracy is about 0.5 mm at 1.0 m, and the scanned data is enough to use as original data of the input models. At first, 4-set range data of a real arm (Fig. 8) were measured by the former system.

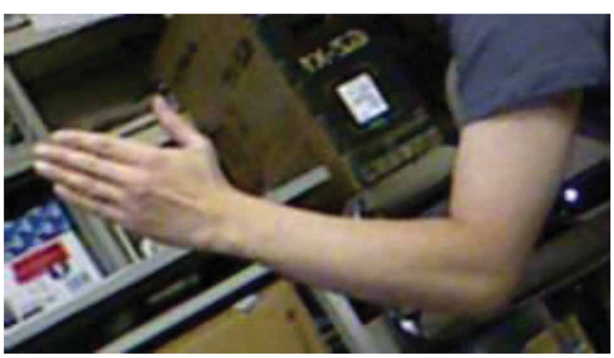

Fig. 8: A real arm used for experimentation.

Then we united the data sets, and constructed a triangular mesh model as an arm model by the latter system. Next, we designed a standard brace model in the same way from an outer cover (Fig. 9) of a real arm brace for the arm. Moreover, the control mesh was modeled by mesh reduction of the standard brace model. Since CV is required to accord geometrically with the corresponding FV, FV was sustained as CV after the reduction process.

Fig. 9: An outer cover used for experimentation.

4. EXAMPLES

In this study, we developed a prototype system based on our proposal method, and performed an experimentation of a tailor-made elbow brace design in order to confirm the usefulness of our method. In the experiment, the effect range in t-FFD, The unit's height parameter in tensegric model, and constraining range were given as 2.5, 0.5, and 3.0.

Fig. 10 shows an experimental result given by the system. As shown in this figure, the brace model was deformed smoothly to fit to the arm model compared with the initial model.

Fig. 11 shows a color map based on the maximum shape deviation between an arm model and a deformed brace model, and the range is set as ±15 mm. Purple color regions in the figure means inner surface of the brace model. Tab. 1 shows absolute values of the maximum shape deviation. As shown in these results, the maximum shape deviation was improved after the deformation. But the maximum value remained at 13.5 mm, so we think it should be improved to within 2.0 mm from a practical standpoint. From the above results, we confirmed that the tailor-made brace model which fits to an arbitrary arm can be obtained by our system.

In this experiment, the design process was finished in few minutes, and all the calculations have

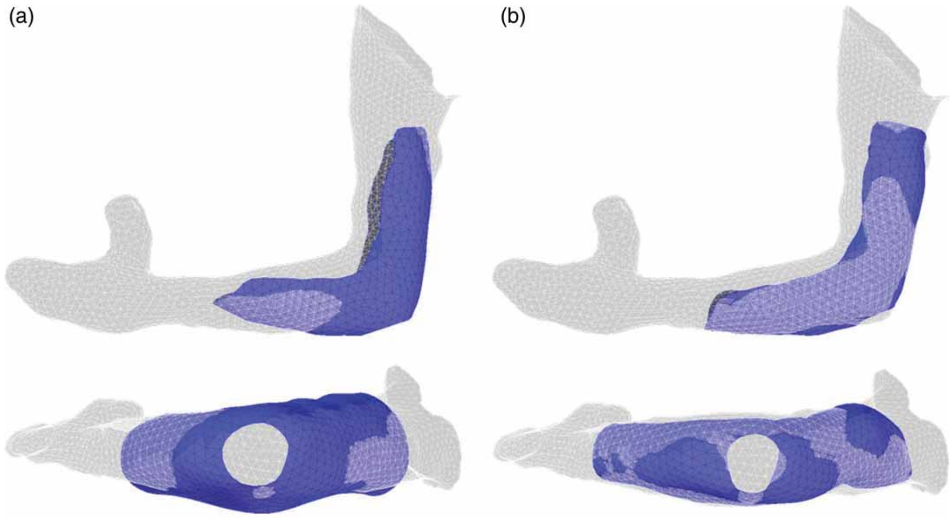

Fig. 10: An experimental result: (a) Initial shape, (b) Deformed shape, (Top) Side view, and (Bottom) Top view. Light gray mesh is an arm model, and blue mesh is a brace model.

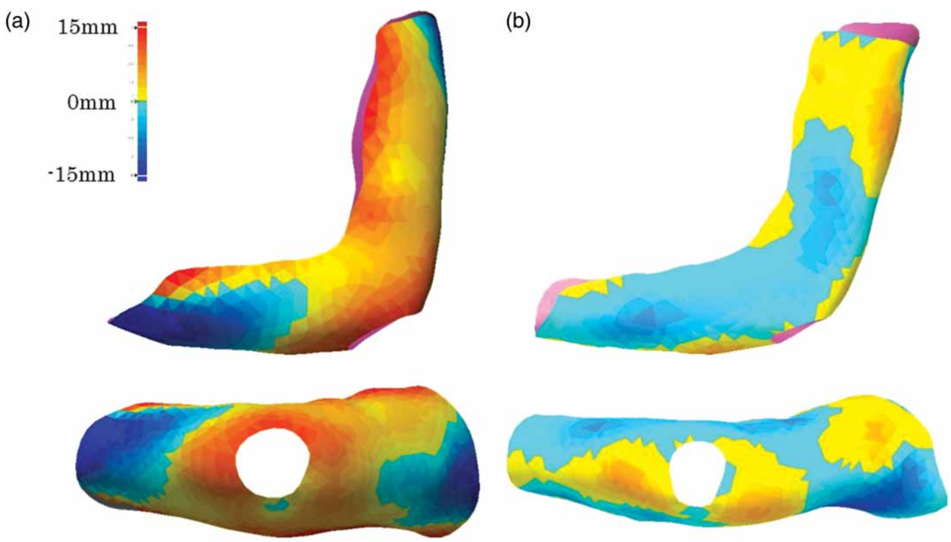

Fig. 11: Color map based on the maximum shape deviation: (a) Initial shape, (b) Deformed shape, (Top) Side view, and (Bottom) Top view.

	Initial shape	Deformed shape
Max [mm]	2.70×10	1.35×10
Ave. [mm]	2.04	1.17

Tab. 1: Absolute values of the maximum shape deviation.

interactive speed by using a commercial PC with standard specification.

In addition, we produced a prototype of the deformed brace model by stereo-lithography. The shape model was created by shelling of the deformed brace model, and the thickness was given as 3 mm to outer direction. Fig. 12 shows the equipped state of the prototype. As shown in this figure, the prototype fits to the arm, and has a functionally proper shape.

5. CONCLUSIONS

Our research objective is a development of a tailor-made brace design system. In this paper, we propose a shape modeling method for designing an arm brace fits to the user's arm. The experimental results based on our prototype system indicated that the final shape of the arm brace can be designed to fits to an arm more than the standard shape. So we have confirmed that our system is useful for design of tailor-made arm brace. Since the personalized brace is designed by simple visual operations to the standard model, a user can get easily an optimal tailor-made arm brace.

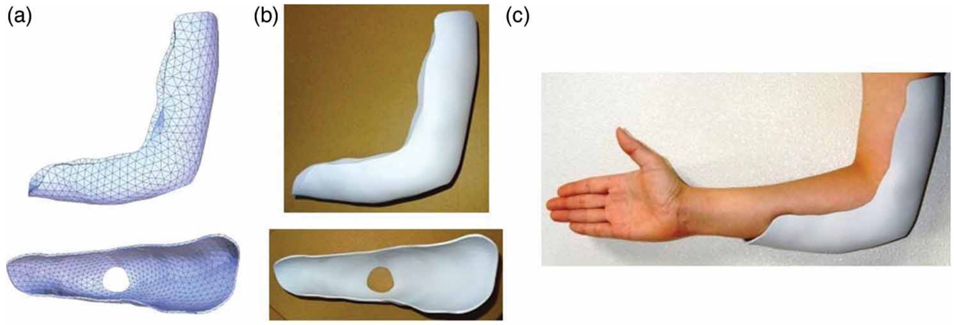

Fig. 12: Prototype models: (a) Shelled model of a deformed brace model, (b) Prototype, (Top) Side view, (Bottom) Bottom view, and (c) The equipped state.

The system can achieve low cost manufacturing and high & uniform quality of the product compared with the old fashion.

In our future works, we will try improvement of the fitness of the final brace model and implementation of a skeletal deformation module of arm to our system. Since the latter extension achieves a design of brace model fits to an arm model with desired posture from that with arbitrary posture, we think it can reduce patient's load in the arm measurement.

ACKNOWLEDGEMENTS

This research was performed under the auspice of a Gifu research and development foundation.

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