Technical Paper

# Prediction of Diaper Shape While Worn by Using Finite Element Method
## – Focus on Posture of Open Legs Wearing Tape-Type Baby Disposable Diaper –

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**Abstract**: A method to predict a diaper condition while worn is proposed in this study, based on the pattern paper of a disposable diaper, material properties and body shape. This paper in particular reports the analysis results on the posture of open legs when a tape-type baby diaper is worn by using the explicit finite element method. Upon analysis, geometric mapping of a diaper, dynamic computation regarding strain generated in a diaper resulting from mapping as a geometric boundary condition, and dynamic computation regarding strain of gather rubber as a geometric boundary condition are sequentially conducted to obtain the shape while worn. When the leg gather (hereinafter, "LG") position as well as vacant space distribution was compared with the actual diaper in order to verify appropriateness of analysis results, the error rate was approximately 3.8% at maximum in regards to the LG position ; therefore a certain level of appropriateness was confirmed. On the other hand, the error in analysis results was significant in the vacant space distribution, indicating the need to model the crease formed upon product packaging as observed in the actual diaper. Since it is possible to calculate the shape of a disposable diaper while worn based on the pattern paper and material properties with this method, it is considered to be useful upon investigating the shape of pattern paper in the design phase.

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### 1. Introduction

Disposable diapers ("hereinafter, diapers") have become indispensable for childcare in Japan. According a 2010 survey [1], the conversion rate from cloth diapers to disposable diapers has reached 95%. Furthermore, the production quantity of diapers for infants and young children is trending up despite the downward trend in Japan's birth rate, as a result of prolonged diaper use as well as of increased demand in various Asian countries including China [2].

Diapers are generally comprised of (1) top sheet that contacts with the skin, (2) super absorbent polymer (SAP) that absorbs urine and (3) back sheet to prevent leakage of urine (Fig. 1). It is not an exaggeration to say that in particular, research and development of SAP significantly contributes to the development of diapers. Excellence in water absorption performance, moisture permeability, antimicrobial property, and texture has been achieved with highly-functional polymer, and diapers are indispensable in the scenes of nursing care and childcare at present.

However, troubles relating to diapers are still reported despite the fact that highly-functional materials have been developed. Representative problems include skin irritation such as rash due to wet conditions, side leakage around the crotch and waist, discomfort due to insufficient flexibility of diapers, etc. [3-4]. It is difficult to solve these problems simply by developing highly-functional materials, and it is necessary to develop products by comprehensively understanding physiological characteristics of skin, thermal environment between diaper and skin, morphological characteristics of the waist, etc. However, since there is very narrow space between diaper and skin, there is no study that quantitatively analyzed the inside condition of diapers worn in the past and diapers are often designed in accordance with qualitative data in the scenes of product development. Examples that applied computer simulation to diaper design have been rarely reported, although CAE including computer simulation is the trend of product development in recent years [6-7].

Therefore, the purpose of this study is to predict the inside condition of diapers while worn by using computer

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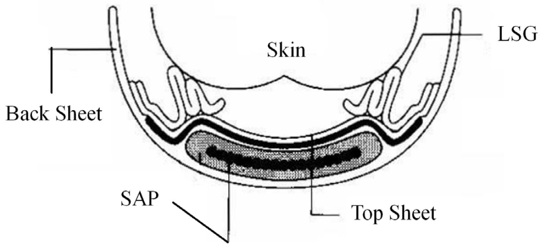



**Fig. 1** Structure of a diaper (cross−section). [5]

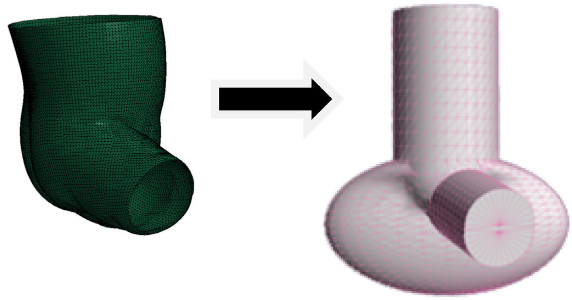


**Fig. 2** Simplified shape of human body model.

simulation, as it is difficult to measure it directly. The shape while worn as well as vacant space distribution in the case of a tape-type baby diaper is estimated particularly in this paper by using the finite element method, in regards to the posture of open legs as the basic posture for babies in the supine position. We will also verify appropriateness of simulation results by using the method to measure vacant space as proposed in our previous paper [8].

## 2. Model development

### 2.1 Dynamic explicit method

A dynamic explicit finite element method is adopted for simulation, since this paper handles a non-linear problem to have a diaper in the condition of pattern paper to be worn on a human body. The dynamic explicit method has advantages compared with other solution methods (static/dynamic implicit methods and static explicit method), in the sense that it is robust to contact/friction problems with adoption of the penalty method, etc. and the computation cost is also low because there is no need to solve simultaneous equations [9]. LS-DYNA is used as a FEM program in this study, while the explicit method using central difference method is adopted for time integration [10].

### 2.2 Diaper wearing method

The process to have a diaper worn is divided into multiple analyses and a diaper is put on a human body model in stages, in order to predict the diaper shape while worn based on the pattern paper in this study. Analyses are largely comprised of the geometric mapping process of a diaper in the condition of pattern paper into a human body model (hereinafter, "analysis I"), dynamic computation regarding strain generated in a diaper resulting from mapping as a boundary condition (hereinafter, "analysis II"), and dynamic computation regarding displacement of the thread rubber adhered to the gather (hereinafter, "gather rubber") to prevent leakage around the groin as a boundary condition (hereinafter, "analysis III"). Each process is explained in detail as follows.

#### 2.2.1 Mapping into human body model

The diaper model in a planar shape is geometrically converted into a steric shape in the analysis I. This is to reduce computational complexity of dynamic computation after the analysis II, by making the diaper model into a steric shape in advance. In addition, it is important to avoid initial penetration between the diaper model and human body model in dynamic computation for the purpose of smooth analysis. Thus, the shape of the human body model is approximated with a cylinder and ellipsoidal body as indicated in Fig. 2, and the diaper model is mapped into the approximate shape by affine transformation.

#### 2.2.2 Dynamic computation regarding strain resulting from mapping as a boundary condition

The diaper model is deformed into a steric shape that appears to cover the human body model as a result of mapping described in the above. In the analysis II, dynamic computation is performed with the strain generated in the diaper resulting from mapping as the boundary condition. In this case, however, only strain generated in the nonwoven fabric, absorbent, etc. is used as a geometric boundary condition, setting the strain of gather rubber to zero, including leg gather (hereinafter, "LG"), leg side gather (hereinafter, "LSG") and waist gather(hereinafter, "WG"). To calculate strain in the nonwoven fabric/absorbent areas, plain strain (strain tensor) in the relevant triangle element is obtained on the local coordinate system first, and strain tensor on the world coordinate system is calculated by tensor transformation. The procedure for specific calculation is indicated in the following.

The displacement vector of the triangle element after mapping is expressed by the following in the local coordinate system ($\xi$, $\eta$).

$$\mathbf{u}(\xi,\eta)=\begin{bmatrix}u_\xi(\xi,\eta)\\ u_\eta(\xi,\eta)\end{bmatrix} \tag{1}$$

Supposing the condition of plain stress at this time, the strain tensor in the local coordinate system of triangle element is expressed with the following formula [11].

$$\mathbf{E} = \begin{bmatrix} \dfrac{\partial u_\xi}{\partial \xi} & \dfrac{1}{2}\left(\dfrac{\partial u_\xi}{\partial \eta} + \dfrac{\partial u_\eta}{\partial \xi}\right) \\ \dfrac{1}{2}\left(\dfrac{\partial u_\eta}{\partial \xi} + \dfrac{\partial u_\xi}{\partial \eta}\right) & \dfrac{\partial u_\eta}{\partial \eta} \end{bmatrix} \tag{2}$$

When the coordinate transformation matrix from the local coordinate system to world coordinate system is expressed as **A**, the strain tensor of the triangle element in the world coordinate system can be calculated with tensor transformation.

$$\left[E'_{ij}\right] = \mathbf{A}\left[E_{ij}\right]\mathbf{A}^T \tag{3}$$

$E_{ij}$, $E'_{ij}$ represent each component of strain tensor in the local coordinate system and world coordinate system, respectively.

#### 2.2.3 Dynamic computation regarding displacement of the gather rubber as a boundary condition

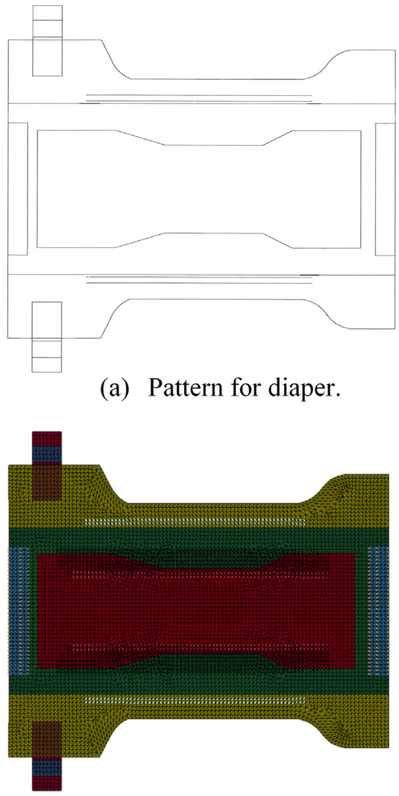
The diaper shape obtained from the analysis II is a condition of putting a diaper without gather rubber on a human body. In the analysis III, therefore, the displacement of gather rubber is given to the calculation results of the analysis II as a boundary condition, to perform dynamic computation in the case of having it worn on a human body model. A gather rubber is normally adhered to the gather sheet in a condition stretched 1.5 to 2.5 times longer than the natural length in order to enhance adhesion to a human body. Therefore, the displacement of gather rubber is set in the same way as the designated scale factors on the drawing in the analysis III as well. Dynamic computation for diaper materials other than the gather rubber is conducted under the condition succeeding the strain/stress obtained from the analysis II.

## 3. Experimental

The shape of a baby diaper while worn is calculated by using the method in the above section. The diaper model and human body model used for analyses as well as the boundary condition, etc. in dynamic computation in the analyses II and III are explained in the following.

### 3.1 Diaper model

The finite element model of a diaper was created with LS-PrePost (ver. 4.0) for LS-DYNA, by using the pattern paper data on tape-type diapers (Moony by Unicharm ; Size S) as indicated in Fig. 3 (a). A diaper is



(a) Pattern for diaper.

(b) FE model for diaper.

**Fig. 3** Diaper model used for analyses.

mainly comprised of an absorbent sheet, top sheet, back sheet, LSG and fastener. For LSG and LG, a rubber yarn that enhances contact with the skin is also adhered to prevent leakage around the groin. Based on the above, elements were also divided for each member as shown in Fig. 3(b) upon model creation. The type of elements included a triangular shell element for members other than the gather rubber as well as a spring element for the gather rubber, which were divided at the element length of 4mm on average. To shorten the calculation time, the diaper and human body are considered as left-right symmetric in this study, and a model with only the left-half of the body was created.

The piecewise linear isotropic plasticity model was adopted to members other than the gather rubber as the material model due to its excellent versatility, and the spring nonlinear elastic model was used for the gather rubber. Properties for each material are indicated in Table 1. For Young's modulus and Poisson's ratio, values were selected in reference to the literature [7], according to the dimension of the pattern paper that matches measurements for each member obtained from dynamic computation regarding strain resulting from mapping as a boundary condition (analysis II). Actual measurements were used in regards to the density and thickness. For the gather rubber, tension test was conducted until a 100mm

Table 1 Mechanical properties of diaper model.

| Member | Nonwoven fabric | Absorber |
|---|---|---|
| Young modulus [MPa] | 0.5 | 1.0 |
| Poisson ratio [-] | 0.2 | 0.3 |
| Density [ton/mm$^3$] | $2.5\times10^{-10}$ | $1.136\times10^{-10}$ |
| Thickness [mm] | 0.3 | 5.7 |

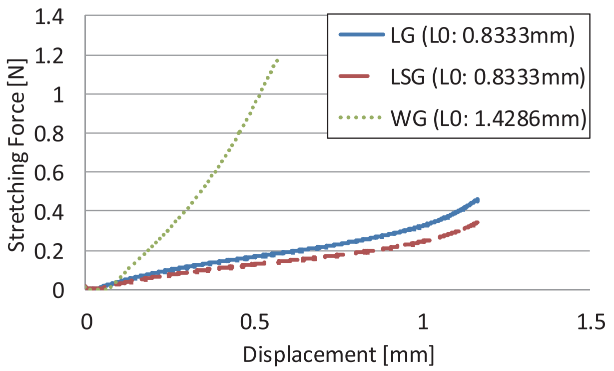



**Fig. 4** Force-Displacement curve of gather lubbers.

test piece extended to 240mm (WG only ; 140mm) at the speed of 100mm/min and the force-displacement curve obtained was used as the material model based on poly-linear approximation. Fig. 4 indicates the force-displacement curve where initial length is converted into element length of each elastic rubber (LG·LSG : 0.8333 mm,WG : 1.4286mm). The gather rubber is made of polyurethane.

### 3.2 Human body model

The finite element model of a human body was created in accordance with the surface shape of a baby doll with a posture of open legs obtained from a three-dimensional measurement (Fig. 5). The triangular shell element was used as the element type for the model, and the rigid model that expresses a rigid body was adopted as a material model on the assumption that deformation of a human body by wearing a diaper is small. A human body is also considered as left-right symmetric similar to the diaper model, and the human body model with only left-half body was prepared.

### 3.3 Boundary condition

The boundary condition for dynamic computation conducted in the analyses II and III is specifically explained in this section. First, strain from mapping described in 2.2.2 above as the geometric condition is defined in each element in the analysis II (Fig. 6). As a constraint condition, a symmetry condition is defined on the cross-section of the diaper model, and a constraint equation of formula (4) is additionally defined between

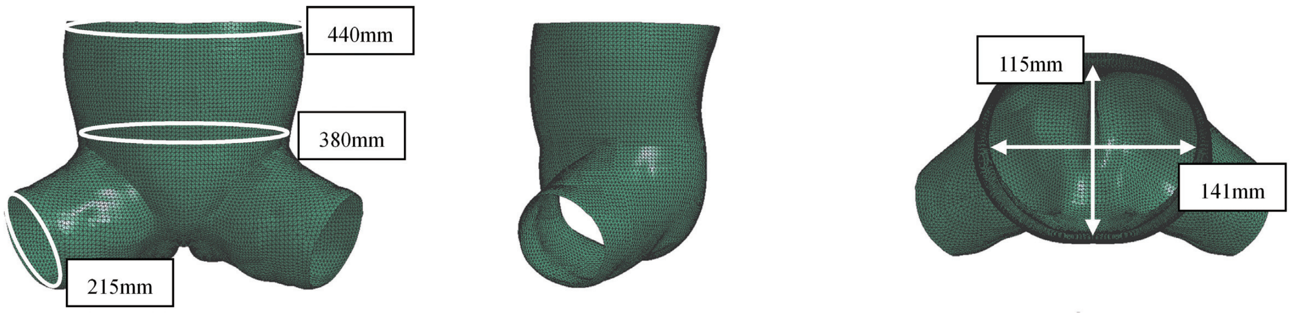



**Fig. 5** Human body model used for analyses.

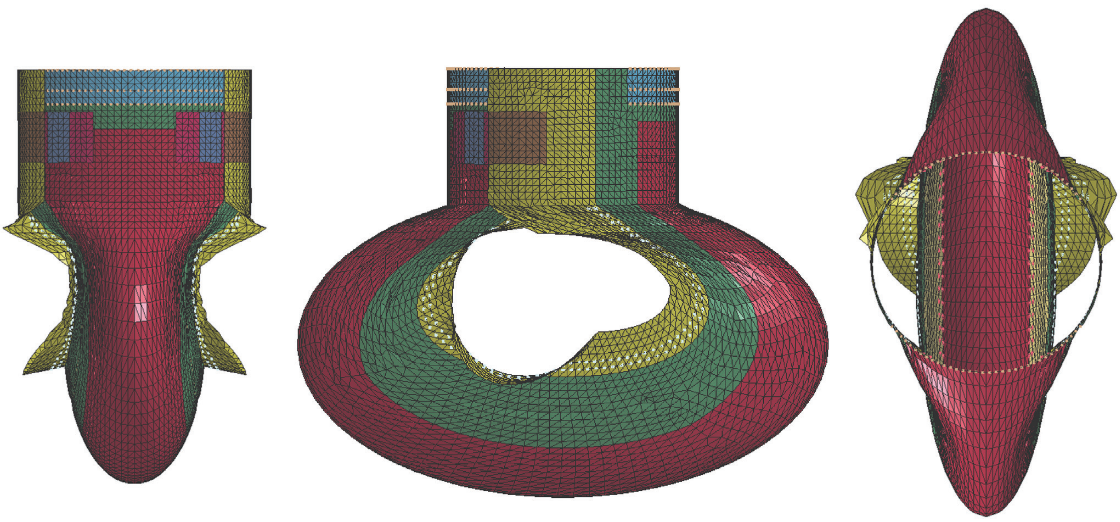


**Fig. 6** Mapping shape of pattern paper used for the analysis II.

**Fig. 7** Result of analysis II.

relevant nodal points to express fixation with a fastener.

$$\Delta h - \Delta l = 0 \quad (4)$$

In the analysis III, displacement of the gather rubber is defined as a geometric condition as shown in Table 2, and strain/stress obtained in the analysis II is also succeeded. The constraint condition is the same as the analysis II. Since the shape of wearing in a static posture with open legs is obtained in this study, all degrees of freedom in the human body model were constrained throughout all analyses.

Restart analysis function was used in this study to conduct the above analyses with LS-DYNA (ver.971). Firstly, the analysis II is conducted as a normal analysis. Secondly, the analysis III is then performed as restart analysis. At this time, analysis results obtained from the analysis II are specified as the "dump file". This leads to balance between the internal force of the diaper in a condition where deformation from mapping is relaxed to some extent and the external force such as contact resistance force, etc., and the analysis III is conducted under this condition.

**Table 2** Scale factor of gather lubber for analysis III.

| | LG | LSG | WG |
|---|---|---|---|
| Scale factor [-] | 2.4 | 2.4 | 1.4 |

## 4. Results and discussion

The diaper shape while worn as obtained in the above analyses as well as vacant space distribution is indicated in this section. Results of comparison with the actual vacant space distribution are also described in order to verify the appropriateness of analysis results. It is not easy to measure the diaper shape while actually being worn by a baby as well as vacant space distribution for verification ; therefore a torso was used in place of a baby.

### 4.1 Shape while worn

Fig. 8 indicates the diaper shape while worn as obtained from the analyses as well as the cross-sectional shape on the median plane. The diaper is tightly attached to the human body due to the rubber tension around LG and WG where elastic materials are used such as rubber, etc. We can also confirm how the shape fills the space between the thigh and LG due to the rubber tension in the case of LSG.

To verify the appropriateness of the shape while worn obtained from the analyses, the location of LG rubber was compared with the actual as it is particularly important for diaper design. Fig. 9 is showing only the LG rubber in the analysis results, with the △ marks on the doll surface representing the actual locations of outside LG rubbers fitted, among pairs of LG rubbers.

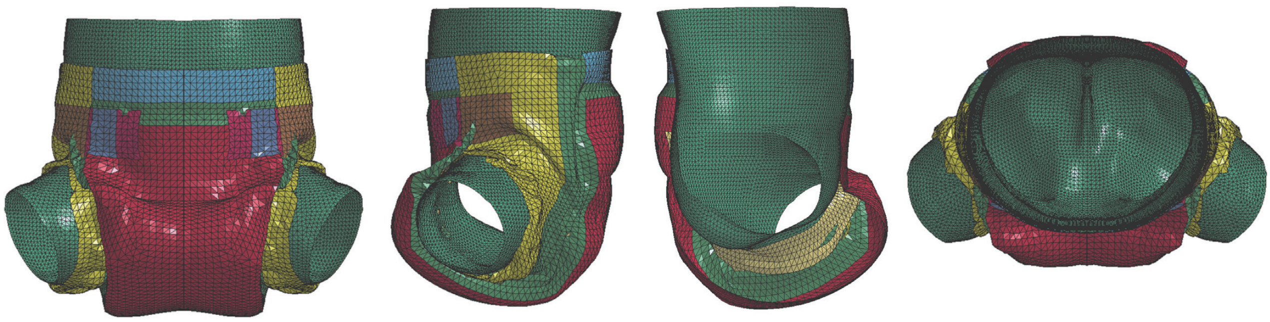


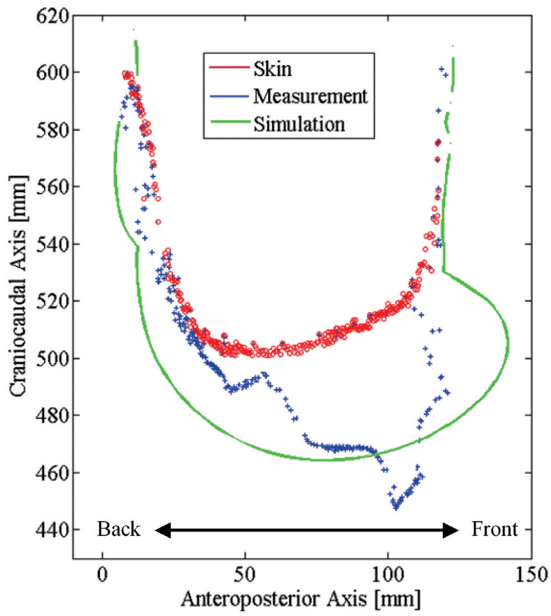
**Fig. 8** Result of analysis III.

**Fig. 9** Comparison of analysis result and measurement (LG position).

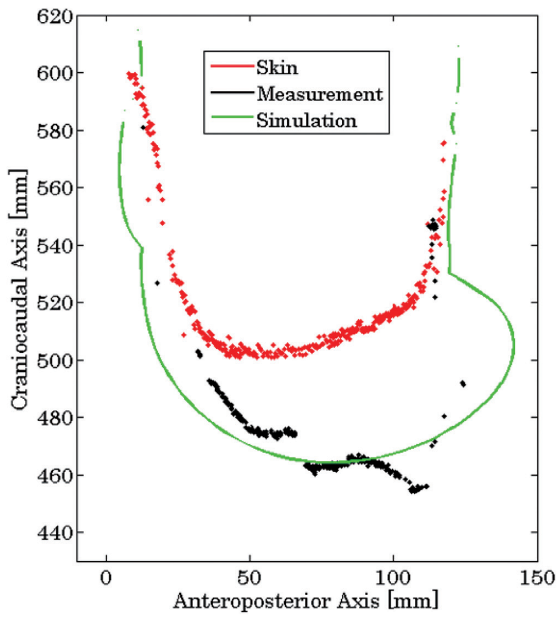
When the distance between △ marks and the nodal points of outside LG rubbers closest to each △ mark was measured, fitting on the front of the femoral area was approximately 1.8mm inside of the actual positions of fitted LG. Fitting at the bottom of and on the back of the femoral area was approximately 6.1mm and 8.0mm outside of the actual positions on average, respectively. These errors are not negligible ; however analysis results indicated a certain level of appropriateness since the error rate to the diaper width (208mm) is approximately 3.8% at maximum.

### 4.2 Vacant space distribution

Vacant space distribution on the median plane obtained from the analyses was compared with the actual vacant space distribution obtained from the vacant space measurement [7], and the results are shown in Fig. 10 (a). For reference, Figure 10 (b) shows vacant space distribution in the case that creases formed on an absorption sheet at the time of product packaging are removed with an iron. It was confirmed from the figure that the vacant space is distributed in a curved shape from the abdominal area to the hip in the analysis results, while it is actually distributed in the shape of V mainly in the lower abdomen. Approximately 60mm maximum of vacant space observed in the actual diaper is due to the crease created in the diaper at the time of product packaging. Simulation result is relatively similar to measurement result when creases are removed (Figure 10 (b)) ; therefore the existence of this crease is considered as a major factor in the difference caused between analysis results and actual vacant space distribution. Deformation behavior considerably varies between the crease area and other areas even for the same material in the case of the actual diaper, indicating the need to improve accuracy of simulation by measuring mechanical properties and modeling the crease area.




(a) Ordinary diaper




(b) Crease-Removed Diaper

**Fig. 10** Comparison of vacant space for median plane between simulation and measurement.

## 5. Conclusion

A method to predict diaper shape while worn was investigated by creating a finite element model from the pattern paper of a diaper, mechanical properties, and body shape of a baby, and sequentially performing mapping and dynamic computation. It was confirmed as a result that the analyses were valid to some extent, in accordance with verification, etc. with the LG position as an index. Since it is possible to calculate the diaper shape while worn from a pattern paper with the method proposed in this study, it seems to be useful when the shape of pattern paper, physical properties of materials, etc. are chosen in the actual diaper design. Although analyses were conducted for a specific body shape and posture in this paper, mapping processing is essentially possible with any body shape or posture ; therefore it is considered to be applicable to prediction of the diaper shape while worn in the case of different body shapes and postures.

However, the vacant space distribution did not always match the actual diaper condition while worn as influenced by crease, etc., indicating the need for further improvement. The diaper wearing procedure adopted in these analyses was very different from the actual procedure, and this may be leading to the gap with the actual condition ; therefore we plan to review the diaper wearing procedure in the future analyses.

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