Study of a Diaper on a Moving Baby using ABAQUS

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Abstract: ABAQUS is used to simulate interactions of an absorbent personal care product (a diaper), with its user and their environment. This problem, being almost completely driven by complex contact between highly deformable and moving bodies, is a challenging proposition. Advanced contact algorithms, non-linear material models and multi-body dynamic analysis capabilities in ABAQUS are used to successfully study the structural interactions of a diaper, a baby and their environment. Aspects of product fit and comfort are often difficult to quantify either by direct measurement or from user feedback. However, by utilizing features of ABAQUS, it is possible to predict physical interactions that occur between the diaper and baby. ABAQUS provides predictions of contact interactions, stress profiles, and strain distributions that are otherwise not measurable. Based on these predictions, one can infer aspects of fit quality and comfort. Detailed predictions of stress, strain and contact within a product also provide a means to evaluate how well that product will be able to perform its intended function. Intimate absorbent personal care products, such as diapers, rely on a combination of containment, redistribution and capture of body waste to provide utility. The function of a diaper is dramatically affected and often driven by structural interactions between itself, its user and the surrounding environment. ABAQUS provides a means to study the response of a complex, multi-component diaper worn by a moving baby.

1. Background

Today's disposable diapers, while often taken for granted, are complex in design, consisting of multiple components and soft, thin materials. High quality fit and comfort are among the design goals for a product developer. Since the wearer of the product is a baby, direct design feedback regarding comfort is practically impossible to obtain. Developers must rely on observations and perceptions when evaluating the comfort and fit of a product on a baby. Additionally, a product designed to absorb body fluids can be significantly affected by local strain within the absorbent material. For these and other reasons, we desire to predict the deformation of, and contact interaction between, a virtual diaper and baby. The complexity of deformable, irregular geometries, non-linear and anisotropic materials in general contact makes this class of problem a challenge for even the most advanced finite element analysis software. Using ABAQUS, we have had success analyzing diaper deformation.

2. Objectives

The objectives of the analysis described in this paper are two fold. First, we wish to calculate the local strains within the absorbent material and other diaper components that result from the necessary deformation to conform to the infant's geometry. Second, we wish to evaluate the contact details (e.g., high stress areas) due to the interaction between baby and diaper.

3. Analysis Method

Due to the nature and complexity of the contact interactions, ABAQUS/Explicit was chosen to conduct the simulation. Simplifications to the product and infant models were necessary in order to make the simulation feasible. An existing product design was chosen as the basis for the product model to allow comparison of the deformed shape with observations as a means of validation.

ABAQUS/CAE was used to build the finite element model used for this simulation. Using CAE terminology, the model includes several parts that are instanced into an assembly. The virtual baby instance is derived from a solid part resembling the topology of an infant's lower torso of a size appropriate for the virtual product. The virtual product is based upon component parts (both shell and solid) as defined by imported product drawings. Both baby and product are defined in an initial, stress free condition.

Product application is accomplished by displacing both the product and the baby. Donning is performed in multiple steps, allowing boundary conditions to be added and removed to manipulate the product onto the body. The goal of the product application is not to duplicate a realistic donning, rather it is to get the product, by the most efficient means possible, onto the torso and allow it to seek a low energy configuration.

Depending on the target of the analysis, the product and torso model can be defined as either a full representation or symmetrically cut half-shape. In general, both human topology and product designs have symmetric right and left halves. However, often either movements or external loadings are asymmetric requiring a full representation treatment.

3.1 Virtual Baby

A virtual baby model depicting an infant's lower torso is defined to represent the shape, movement and deformation behavior of a diaper wearer. This model could potentially be quite complex, but practically should be as simple as possible to be representative of a baby within the context of the analysis. For example, the virtual baby (represented by just the lower torso) might be deformable with articulated hips and legs. In the present case, the virtual baby model consists of a solid part that is strategically partitioned to create a series of interior edges. Some of these edges and their end points are used to define rigid body constraints and connector definitions. A complete lower torso model typically consists of connectors representing the lower spine, right and left hip joints.

3.1.1 Geometry

Babies come in many shapes and sizes and while there are sources of adult surface anthropometry [1], an accurate three dimensional description of a real baby is nearly impossible to find. As a starting point, we used a 3D laser scan of an infant mannequin as the basis for our baby model geometry. The quality of the torso geometry is therefore dependent on the accuracy of the mannequin. The child geometry began as a point cloud which was subsequently used to define a water tight network of surface patches, and then converted to a solid model. In this study, we reduced the size of the problem by considering a half-shape model (symmetry about the mid-Sagittal plane is assumed).

3.1.2 Articulation/Movement

The solid model representation of the child is imported into CAE and partitioned (cells, faces and edges) in a strategic manner to provide interior edges which take the role of skeletal features. These skeletal features (bones) are implemented using rigid body constraints with one of the joint connector nodes as its reference point. Body movements are prescribed by either driving the joint connector(s) or by driving the bone's reference node directly. For this study, the baby is further simplified by only articulating the leg (at the hip) leaving the spine and pelvis rigid (e.g., no spinal motion considered). The leg movement is simplified as rotations within two body planes (Sagittal and Coronal). Figure 1 shows the skeletal structure, connector location and deformed shapes obtained using this method to articulate the torso.

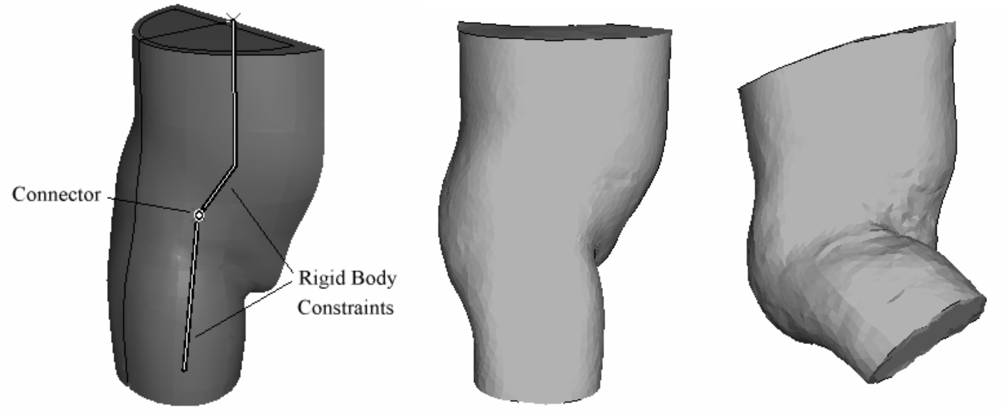

Figure 1. Articulated half baby torso model definition and deformed shapes.

3.1.3 Material Properties

A detailed model of the baby's interior, with muscle, fat, tendons and bones is well beyond the scope and intent of this analysis. As with torso shape, there is variation in the internal detail from baby to baby. And as with torso shape, there is very limited data available in the literature to guide the selection of a representative material model or modulus.

The soft tissue in this application is simply described with a hyperelastic material model. Parameters for the hyperelastic material were set through an evaluation of available data on infants and adults. Refinements could be used to describe a more complex distribution of material properties in the torso, without the expense of defining full interior geometric detail. While the torso model with a single material model has limitations, it is useful for inducing realistic and representative deformation behavior in the diaper and body.

3.2 Virtual Product

There are three aspects to consider with respect to product model definition, namely geometry, materials and construction. The goals of the analysis dictate the details of each. A modern disposable diaper typically consists of several multi-material components, and is constructed in a way that both is conductive to manufacture and provides a performance benefit. Diaper materials include various polymer and non-woven materials. These materials often display both non-linear and anisotropic behavior in addition to being thin with little bending stiffness.

3.2.1 Product Geometry

Simplifications are appropriate when considering a product model. Some product components may be ignored if they do not take a significant role in the interactions being studied. For a given product construction, some components may be combined with others and treated as composites (e.g., composite shells). Complex geometries may be simplified, if appropriate, to achieve a higher quality analysis mesh, depending on the role the geometric features play in the simulation. Each simplification should be considered carefully to insure that it will not negatively affect the results of the analysis. However, without some level of simplification, the analysis may not be practical.

Product component geometries are typically defined by two-dimensional topologies (being either 2D planar sections or simple 3D extrusions). These geometries are easily defined by or imported into ABAQUS/CAE. Thin product components are often defined as membranes, shells or composite shells. Thicker components (e.g., absorbent pad) may be defined as shells, continuum shells or solids depending on their shape and the results that are sought. In the study reported here, the absorbent material was defined as solid since we are interested in accurately predicting the degree of compression the pad undergoes. The thicknesses of the 2D regions were specified based on the corresponding components (caliper) thickness (consistent with the thickness used to define the stress-strain behavior of the material). Figure 2 shows examples of a product drawing appropriate for import into CAE and a 3D product model as built within CAE.

3.2.2 Product Materials

Many of the materials used in the diaper product are anisotropic and are characterized by nonlinear stress-strain behavior. Additionally, the components tend to be of relatively low stiffness (compared to other structural materials) and are often very thin. For example, the outercover or outside, away-from-the-body layer on a diaper generally measures tens of centimeters in width and length, but is only millimeters thick and has a characteristic modulus given in kPa. The behavior and topology of the components combine to make their representation within a finite element model challenging. Fortunately, with some simplifying assumptions, we can usually adequately describe these materials using built in ABAQUS material models. In cases where the provided models are inadequate, we have the option to define a custom stress-strain behavior using a user defined model (VUMAT). The appropriate level of simplification of the material stress-strain behavior depends on the goals of the analysis and the strain ranges that are expected within the simulation.

3.2.3 Product Construction

Product construction can range from as simple as comprising a single component (i.e., part) to being very complex where multiple components (parts) are assembled into a functioning product. Product constructions can be approximated using several techniques including tying, using contact or joining product pieces. Again, with respect to construction, simplifying assumptions are generally required to make the model feasible. For example, many of diaper components are attached to each other using spray adhesive. It would be prohibitive to attempt to simulate such an attachment in detail. In this case, we would consider tying regions of the components together using constraints.

To mimic product fit characteristics like gasketing, pre-tensioned elastic features are often used. While ABAQUS does allow the prescription of initial stress, the tensioning of these elastic components may also be achieved by simulating thermal contraction. When components are treated separately, contact constraints must be set up between the individual components and the body and between the components themselves (note, general contact capability has been a significant benefit with respect to handling contact between components). Again the goals of the analysis will determine the level of contact detail that must be included in the model.

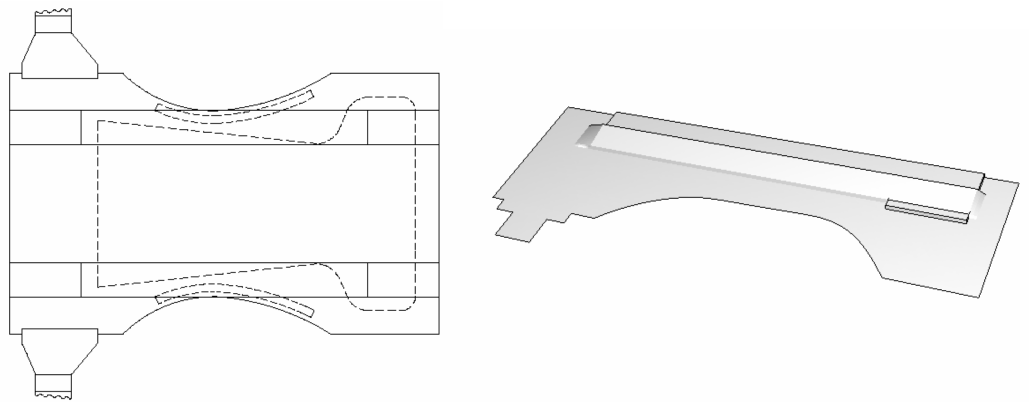

Figure 2. Example 2D product drawing and a 3D product representative model.

3.3 Interaction

The response of the diaper is driven by the contact interaction with the baby. Contact plays the major role in establishing the influence of the body on the product and vice versa. The environment can also affect the deformation of both product and body. For example, gravity tends to make the product sag on the body. We could consider the affect of other environmental factors such as bedding, clothes, high chair, car seat or the like. For simplicity, in this analysis we consider only the environmental effect of gravity by prescribing a gravity (body) force.

The product and body are deformed (using loads and boundary conditions) in a controlled manner to achieve the donning of the product onto the body. Figure 3 shows several stages in this donning process. Notice that the initial condition of the product and body has no physical analogy (i.e., the product initially passes through the body, see figure 3, state 1). Based on the goals of this analysis, we are not interested in the physical accuracy of the donning process, rather, we are interested in getting the product onto the body by the most efficient means that we can.

To don the product, the legs are opened (rotated in the Coronal plane) to eliminate the over closure of the product and body. A contact constraint is then established between product and body (figure 3, state 2) and the product is deformed around the torso. Once the product is pulled to the appropriate height, the sides of the product are wrapped around the torso (figure 3, state 3). Finally, the back of the product is wrapped around the front, the fastener is engaged (contact with no separation) and all loads and boundary conditions are removed from the product (figure 3, state 4).

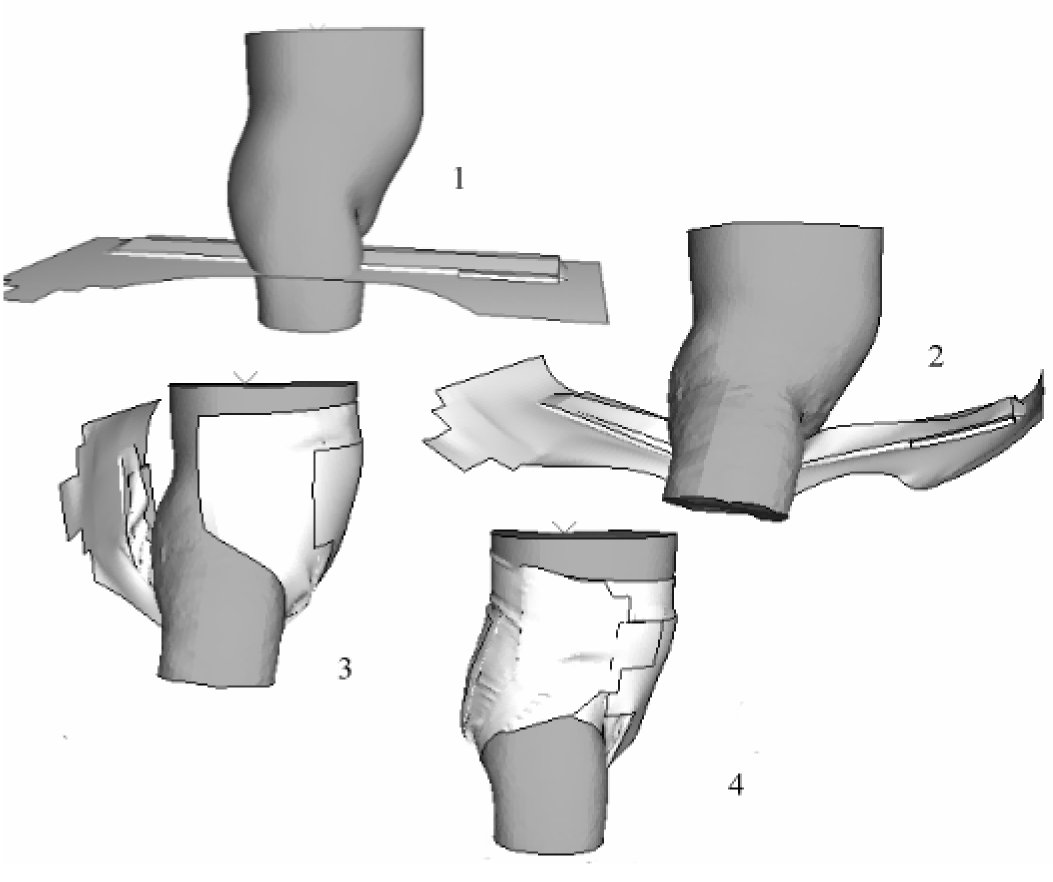

Figure 3. Product and body interactions during product donning.

The product is held in place solely due to contact constraints between itself and with the body. Once the diaper is in place, the body is put through a series of movements causing the product to seek a low energy state approximating the fit of the product design on a child.

3.4 Model Layout

In our problem, we know the geometry of the undeformed (e.g., stress free) diaper; however, we are interested in the state of the product as it is being worn by the baby. Therefore, we must simulate the "assembly" of the diaper/baby system in order to study the result. We accomplish the donning of the product using multiple analysis steps. We spend nearly 70% of our analysis time to don the product and only the final state of the analysis is of most interest with respect to our objectives. Table 1 summarizes the analysis sequence.

Step	Action
1	Open legs
2	Establish contact, move torso down, raise product
3	Wrap front of product around torso
4	Wrap back of product around torso
5	Engage fastener
6	Sit/stand motion cycle 1
7	Sit/stand motion cycle 2

Table 1. Analysis sequence summary.

Our multi-step strategy allows boundary conditions to be applied and removed to conveniently move product and body according to a coordinated and systematic process. Such a strategy is especially important due to the nature of our thin, flexible components to prevent excessive rotation or distortion errors. Mass scaling is often used to expedite the analysis. Boundary conditions and degree of mass scaling must be tuned to avoid numerically unstable conditions that cause the analysis to abort (typically due to excessive rotation/distortion).

3.5 Key Assumptions

As mentioned previously, simplifying assumptions are necessary to make this problem feasible. Fully detailed analysis of either the product or body would be both extremely difficult while providing marginal value at very high cost. The following list highlights the key assumptions:

- Problem assumes half symmetry (about the mid-Sagittal plane)

- Body is treated as a solid comprised of a single material
- Anatomic details (e.g., genitalia) are suppressed
- Skeletal structure is represented by simple, rigid geometry (detailed bone topology is largely ignored)
- Body movement is simplified as simple rotations of the leg (at the hip)
- Some product components are ignored or combined with others and modeled as composite shells
- Product component attachments are simplified to increase model robustness
- Stress relaxation is ignored

4. Verification

A key concern with this simulation is our ability to verify the results, especially since a key motivation for performing the simulation is the limited ability to obtain the results we seek by other means. Qualitative agreement between simulation and experiment does provide a basic verification.

We use two qualitative comparisons to judge the validity of our simulation results. First, the predicted deformed shapes of the product and body are compared to observations made by experienced product designers. Experienced product developers have reported that in most cases, the deformed product shape from the simulation agrees well with their observations on real babies. Second, we perform spot checks comparing contact pressure predictions with discrete measurements. Figure 4 illustrates a comparison of predicted contact pressure values versus those measured in corresponding locations with a similar product on a physical mannequin. These results agree well qualitatively and are similar quantitatively as well.

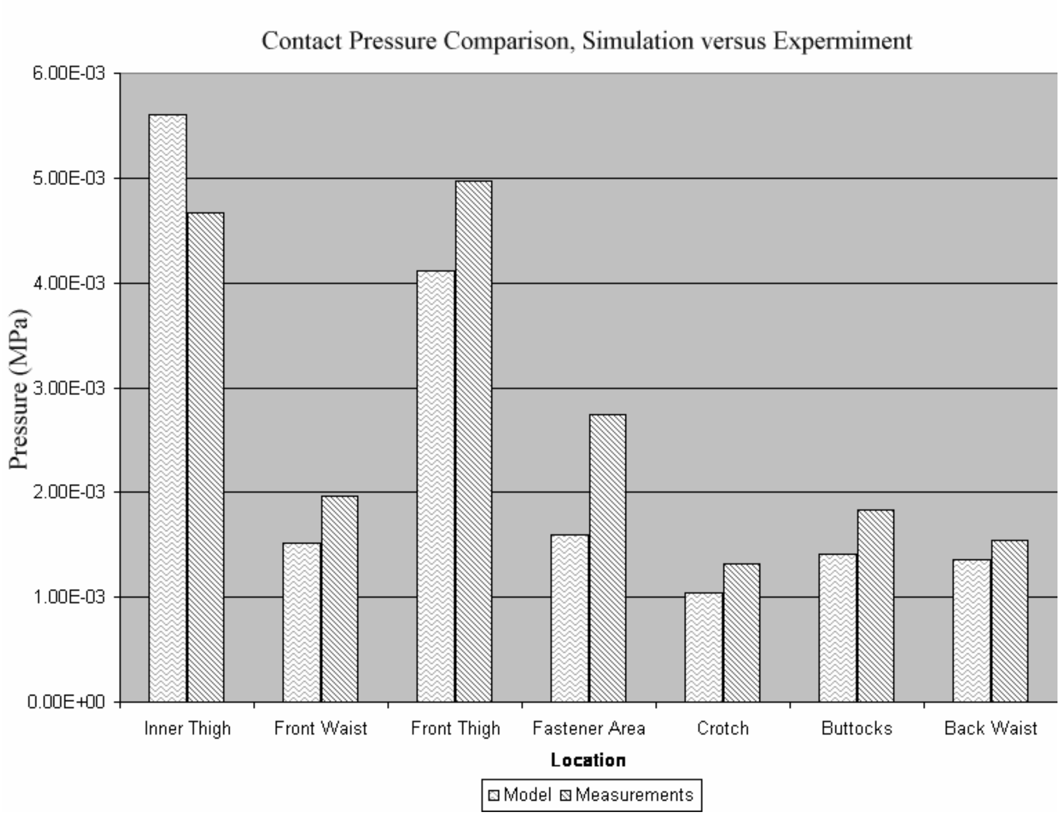

Figure 4. Comparison of simulation results versus experimental contact pressure measurements

5. Sampling of Results

A large finite element model can provide a multiplicity of results. It can be challenging to choose how best to summarize and communicate these results, especially to a non-technical audience. Fortunately, modern data visualization techniques provide human friendly means to communicate complex results, even to the non expert. Several visualizations highlight the outcomes of this analysis.

Perhaps the simplest outcome, but still a very instructive result, is the location of the diaper on the torso. For example, State 4 in Figure 3 shows the diaper placement after donning. The position at this time can be compared to position after several sit/stand motion cycles (such as steps 7&8 of Table 1). Distances and locations of diaper features, like the corners of the front waistband, relative to a point on the body, like the top front node on the torso symmetry plane, can be tracked as a quantitative measure of diaper placement. The basic ABAQUS coordinate and displacement variables provide a useful metric of the way in which the geometry of the diaper conforms to the shape of the torso.

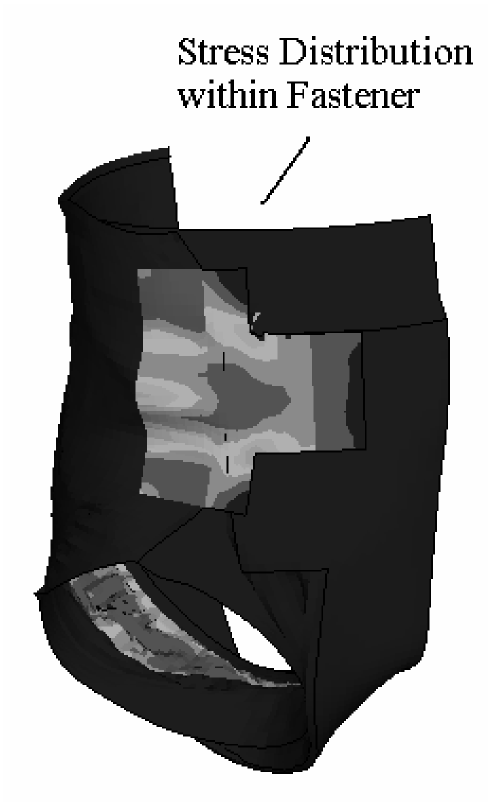

Figure 5. Stress distribution within the diaper fastener and inside view of the containment flap (baby not shown)

Figure 5 shows a contour plot of Von Mises stress within the diaper at the end of the analysis. In this visualization, we can see both the deformed shape of the diaper (with the baby removed from the view) and see the resulting stress distribution within the product components. The stress profile is obviously affected by the material properties used for the components, and so provides a means to track the interplay of component materials in the dynamic of the whole diaper.

One of our objectives was to study the contact interaction between the product and the body. Figure 6 shows a contour plot of contact pressure on the baby's body resulting from the diaper being worn. While the levels in the grayscale version of the contour plot are more difficult to distinguish than in a color plot, we can see regions of relatively higher and lower contact pressure. For example, we see higher contact pressure (lighter region) predicted in the front of the baby's belly Because of assumptions made for both the product and torso model, more caution must be used in interpreting a derived quantity like contact pressure, compared to a simpler feature like node position. As with many conventional ABAQUS simulations, the power of the model comes not from a single extracted result, but from the consistent pattern of behavior exhibited on several levels. The appearance of consistent patterns is of particular value for an interaction dominated by contact, as in this diaper-baby case.

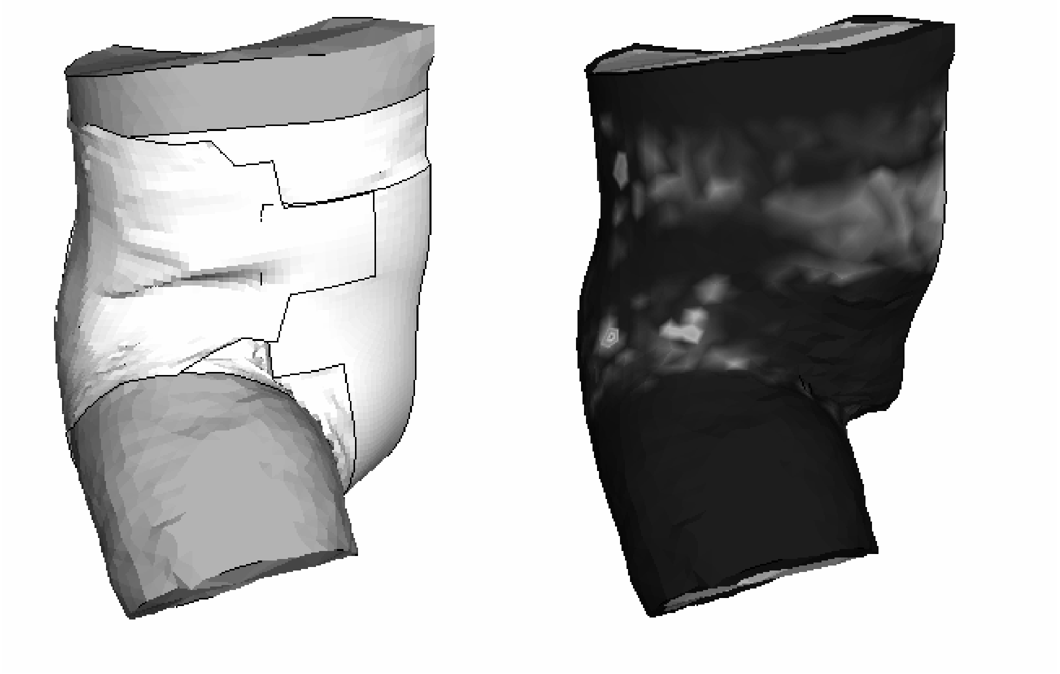

Figure 6. Deformed product/body and resulting contact pressure distribution on body surface.

Figure 7 indicates the gap that is predicted between the product and the body. Note that certain aspects of separation between product and body are known to be important to product function. The finite-element model allows a much more detailed and accessible visualization of gapping than is possible in any other approach. In collaboration with the analyst, the product designer can often determine the impact of such a gap on product performance.

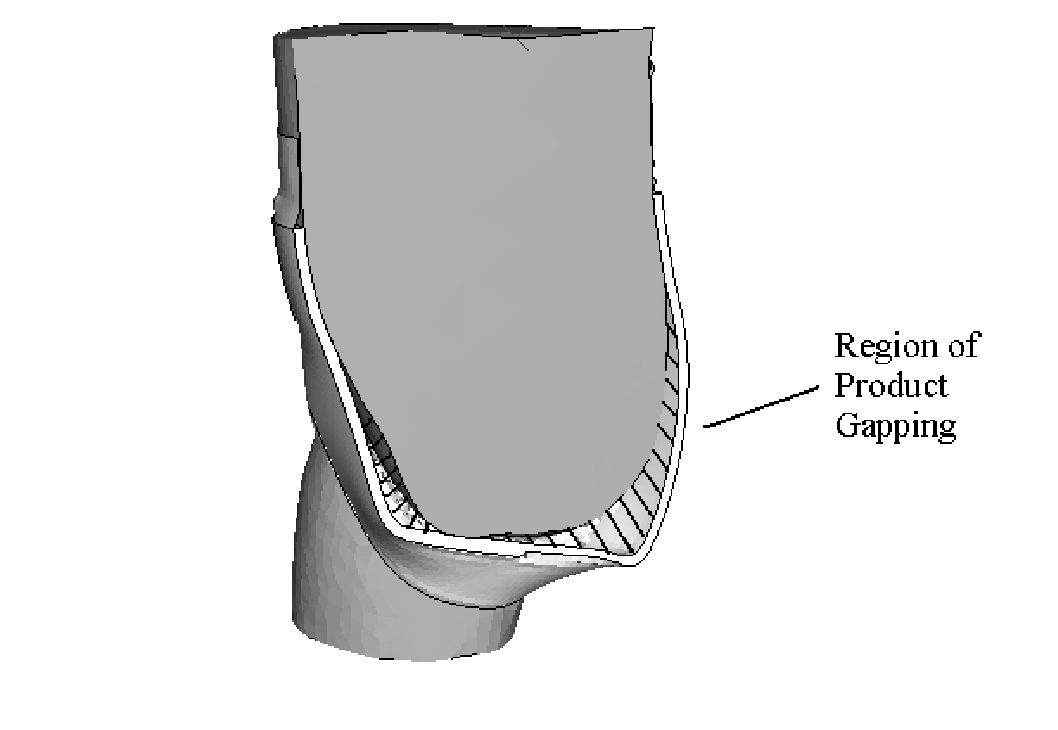

Figure 7. View of model symmetry plane showing a gap between the baby and the diaper absorbent.

6. Conclusions

This example has shown that simulating the interaction between a virtual baby and a virtual diaper is both feasible and useful. While the process is challenging, even with key simplifying assumptions, we have successfully represented how both product and baby deform in movement. While validation is an ongoing process with its own set of challenges, credibility for the model also comes from the consistent pattern of behavior exhibited on several levels. As product developer becomes more familiar with the results and interpretations of the finite-element simulation, and as the analyst refines the simulation to more adeptly explore and expand the insights of the product developer, the fit of a virtual diaper on a virtual baby will take its place next to consumer studies with physical prototypes.

Advanced features of ABAQUS provide fundamental capabilities to facilitate such a virtual analysis. These advanced functionalities, along with the enhanced capabilities of ABAQUS/CAE and its scripting interface, open the doors for many new and unusual classes of analysis that would have been prohibitive only a few years ago. Virtual product simulation is a new tool that can help product developers design better products and solve design problems faster.

7. Challenges for the Analyst

A few words to describe some of the challenges surrounding this analysis are appropriate. Several of these challenges apply to many fields and others are unique to the personal care industry. The common challenges include:

- Defining the appropriate simulation analogue – most problems are quite complex when we consider all of the factors that affect them. An absolutely critical skill required of a good analyst is the ability to distill a complex physical problem to its simplest form while retaining the essence of the problem to be solved. Even though hardware and software capabilities are always improving, the ability to strategically simplify is always an asset.
- Checking that the results make sense – it is easy to forget that just because a simulation arrives at a solution, there is no guarantee that the solution is correct. The solution should be scrutinized and when possible, validated by physical testing. The analyst should have some idea of what to expect and approximate magnitudes of desired results.
- Extracting key results from the simulation – The multitude of strains and stresses for each component, and of derived variables tracking interactions among components, can be overwhelming in many simulations, even for distilled problems. The analyst must be able to pull from the multitude the smaller set that captures and shows the dominant features of concern.

Challenges for the personal care industry:

- We are relative newcomers to the structural analysis arena – while structural analysis is of great interest and can provide useful results and insights, we have not been the historical focus of many development activities. Consequently, while the discipline has thoroughly addressed the needs of more traditional structural analysis, the challenges offered by soft, anisotropic, non-linear and thin materials in complex contact have only recently been addressed. This means that sometimes we have to make the best out of what is available and fill in gaps where necessary.
- Full information on materials is not readily available - databases of mechanical properties are readily available for a wide range of metals and plastics. This allows reasonable material models of these conventional materials to be generated and utilized for many industrial simulations. The materials of the personal care industry tend to be much more proprietary and evolutionary, so material modes must be tailored and re-adjusted to the product at hand.

- Structural analysis models physics, not physiology – while a finite element model may be able to predict the level of contact pressure between a product and a body, it can not tell us if the product is comfortable to wear. Therefore, if our goal is to please a customer, we must gain some understanding of how results from a structural analysis relate to a customers propensity to buy our product.

8. References

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2. "Method of designing a product worn on a body in a virtual environment", United States Patent 6,810,300, Woltman , et al., October 26, 2004

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9. Acknowledgement

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