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Contact Pressure Study of N95 Filtering Face-piece Respirators Using Finite Element Method

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ABSTRACT

Respirators protect workers from hazardous airborne particles. It is important to evaluate respirator comfort and fit for all workers of diverse anthropometry as contact pressure plays a vital role. This paper presents the procedure and results of studying contact pressure of N95 filtering face-piece respirators (FFR) by using a finite element method. Finite element models of respirators and headforms have been improved based on a previous study. The headform model contains a skin layer, muscle layer, and bone layer. The whole facial area is divided into four parts (two areas for cheeks, one area for upper forehead, and one area for chin). Two N95 FFR models (one is one-size-fits-all and the other FFR has two sizes, i.e., small and medium/large) are used to simulate the interaction between the respirator and the headform. The results show that the respirator with two sizes provides better contact pressure distribution than the one-size-fits-all respirator. It has also been shown that the one-size-fits-all respirator works well for the large, medium, and short/wide headforms, but there are indications of potential leakages for the small and long/narrow headforms. For the respirator with two sizes, the medium/large size respirator works well for the large and long/narrow headforms, while the small size respirator works well for the medium, small, and short/wide headforms. The medium/large size respirator has potential leakages for the medium headform. Furthermore, the N95 FFR with two sizes has a more uniform pressure distribution than the one-size-fits-all respirator. Future studies are needed to validate these observations with human subjects.

Keywords: FEM, N95 filtering face piece respirator, respirator sizing, contact pressure.
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1 INTRODUCTION

As a respiratory protective device, an N95 filtering face-piece respirator (FFR) is designed to provide its wearer with a very snug facial fit and relatively efficient filtration of airborne particles. The respirator filter media is designed to remove very small contaminants from the air as well as blocking large droplets. The N95 designation means that the respirator can filter out at least 95% of the airborne contaminants. Respirator designers aim to ensure a good respirator comfort and fit, reduce development costs, and shorten the time to market. Contact pressure distribution plays an important role in respirator comfort and fit. This work focuses on studying the contact pressure of different N95 FFRs using a finite element (FE) method.

Respirator fit, which refers to how well a respirator seals to the face, is an important design performance characteristic that respirator designers, wearers, and standards developers care about. Fit factor (FF), expressed as the challenge aerosol concentration outside the respirator divided by the challenge aerosol concentration that leaks or penetrates into the respirator during a fit test, is an important criterion of protection performance. However, FF is an overall performance measure that does not provide any information about the location of leaks and therefore provides little feedback to the designer as to how to correct the problem.

Some researchers have focused on the sealing pressure distribution between a respirator and face and the relationship between the sealing pressure and the respirator fit. Cohen [3] described an experimental method for evaluating mask seals by measuring seal pressure distributions. A relationship between FF and sealing pressure distributions for evaluating the sealing performance was developed. Cohen's work suggests that the pressure measurement may be a promising new tool for design and evaluation of protective mask seals, but the relationship of pressure distributions and FF is nonlinear and may not be described quantitatively.

The development of powerful computational tools provides new approaches to study issues of respirator fit. In this computational approach, laser scanners create digital representations of the complex geometries of a human head and a respirator face-piece. Then the three-dimensional image is manipulated and subjected to computational analysis of the interface between the respirator and human face to calculate seal pressure distributions.

Bitterman et al. [1] was the first to use the FE method to calculate the pressure between an oxygen mask and a pilot's face. The sealing part of the mask, which is a hyper-elastic material, deformed when load was applied. Since the model of the pilot's face was simplified as a rigid surface, the face had contact forces without deformation. Piccione et al. [6] modeled the interface between an elastomeric respirator and the human face by applying a FE analysis tool, DYNA3d, which was an explicit 3D code (an old version of LS-DYNA). A solid element model of the human face was created by giving the surface of the scanned human face a thickness. Therefore, both the human face and respirator deformed. Furthermore, a mask fit and discomfort model was developed to evaluate fit, protection and discomfort according to contact location, pressure, shear and friction. Butler et al. [2] used computational tools to solve three respirator related problems. An outward leak of breathing gases into a near-flammable environment was simulated and a flow field inside a half-face-piece respirator was studied. It brought computational fluid dynamics into the simulation of respirator fit. Pieper and Hughes [7] borrowed a Computer-Generated Imagery (CGI) technique to simulate the fit performance of a dust mask with facial movement. Detailed motion capture data of real facial movement was interpreted to produce a FE model (node and element definitions) along with a time history of modal displacements. The FE data were stored as an Abaqus output database and subsequently used as a global model to drive a similar facial sub-model to evaluate the fit and sealing performance of a pouch style face mask design. Yang et al. [10] presented a method to simulate the interaction between a respirator and a headform based on explicit analysis software, LS-DYNA. Both the respirator and headform were modeled as shell elements and were deformable. A dynamic contact process and pressure distribution was observed. The results showed that strap forces play an important role in pressure distribution on the face.

Respirator comfort is another important characteristic. The most fundamental work on respirator comfort was done by Snook [9]. The assumption was that several locations on the face are more sensitive to forces than other locations. Twelve facial locations were selected and subjected to five different forces. Comfort was measured psychophysically. It showed that the force exerted against the face is a factor of discomfort.

In the literature, most studies have a simplified face model of one layer with unified thicknesses. However, based on anatomy, the human head is a complex component which includes skin, muscle, and bone with different thickness on different locations. Furthermore, no one has simulated N95 FFR. In this paper, we study the contact pressure characteristics between N95 FFR and headforms using the finite element software, LS-DYNA. The headform model consists of skin, muscle, and bone layers and the whole facial area is divided into four segments (two segments for cheeks, one segment for upper forehead, and one segment for chin). All four segments have different thicknesses on each layer. There are different categories for N95 FFR, i.e. one-size-fits-all respirators, respirators with two sizes, and respirators with three sizes. However, we only investigate the first two categories in this study. We attempt to answer which category is the best choice in terms of contact pressure performance. Five newly-developed standard headforms developed by the National Institute for Occupational Safety and Health (NIOSH) are used for this study [12]. Based on these improved models, contact pressure of respirators and headforms are obtained for different categories of N95 FFR.

2 DIGITAL RESPIRATOR AND HEADFORM MODELS

Because both respirators and headforms have complex shape surfaces, the most feasible way to model them is to collect data by a 3D scanner. The original data obtained through scanning are point clouds. It is necessary to transform them into CAD models that can be manipulated in FE analysis.

Fig. 1 shows the procedure of generating digital respirator and headform models. First, the point cloud is obtained by 3D scanning of respirators and headforms. Second, triangular surfaces are transferred to polygon models. Third, a Non-Uniform Rational B-spline (NURBS) surface model is created by applying a reproducible surface over its underlying polygons. Finally, the CAD model is obtained by transformation. Because of the complexity of respirator and headform shapes, deficiencies often occur in CAD models. If these deficiencies cannot be overcome, it may take a few iterations to produce better models.

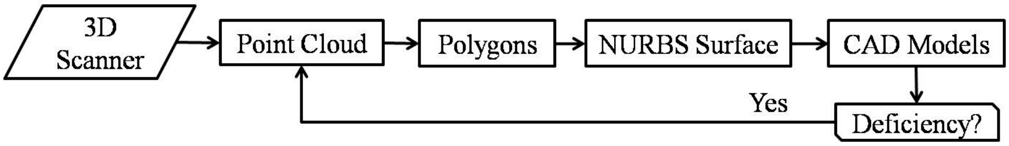


Fig. 1: Procedure of generating digital CAD models.

Point cloud data, which were collected by NIOSH for two N95 FFR models (one FFR comes in one size, i.e., one-size-fits-all and the other FFR model is available in two sizes, i.e., small and medium/large) are shown in Figs. 2, 3, and 4. A reverse engineering technique is used to generate CAD models with manifold closed surfaces. CAD models of the respirators are shown in Figs. 5-7.

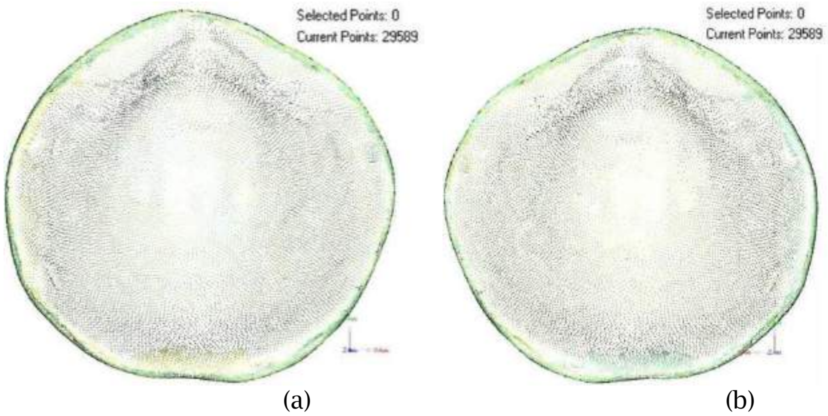
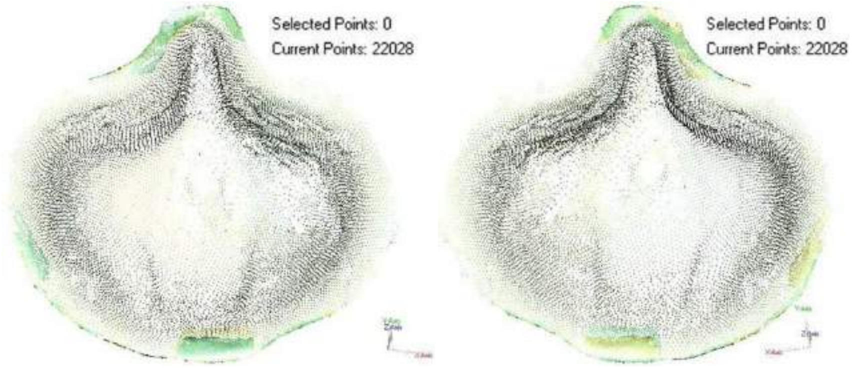


Fig. 2: Point cloud model of one-size-fits-all respirator: (a) front view; (b) back view.

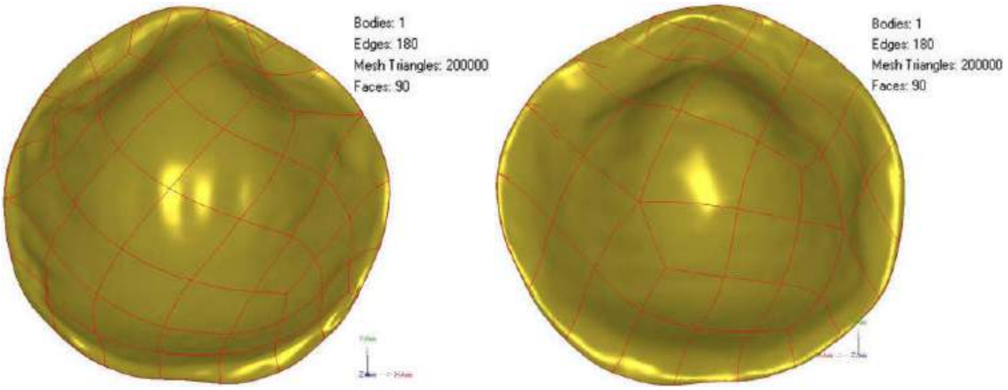
(a) (b)

Fig. 3: Point cloud model of small size respirator: (a) front view; (b) back view.



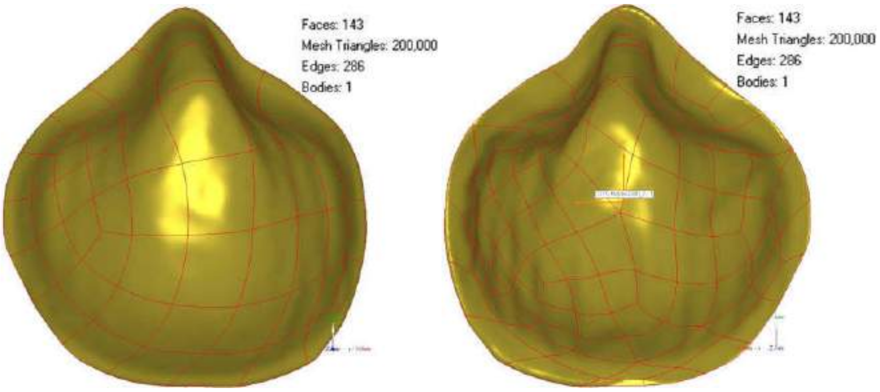
(a) (b)

Fig. 4: Point cloud model of medium/large respirator: (a) front view; (b) back view.



(a) (b)

Fig. 5: CAD model of one-size-fits-all respirator: (a) front view; (b) back view.



(a) (b)

Fig. 6: CAD model of small size respirator: (a) front view; (b) back view.

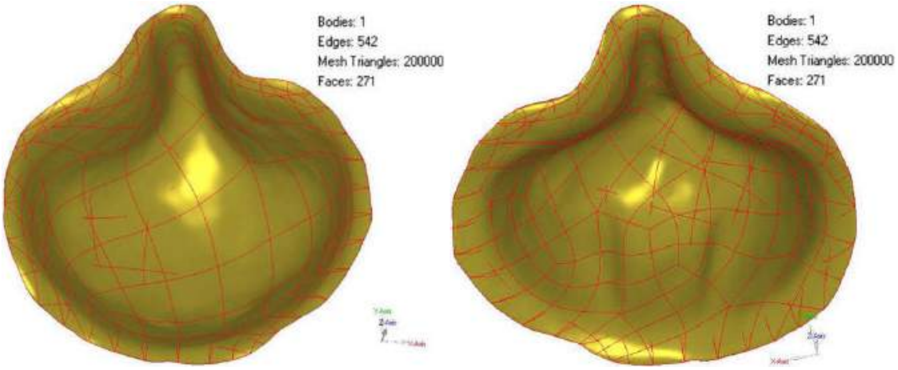


Fig. 7: CAD model of medium/large size respirator: (a) front view; (b) back view.

Five digital 3D headforms used in this study are shown in Fig. 8 (small, medium, large, long/narrow, and short/wide types of heads). These headforms were developed by NIOSH [12].

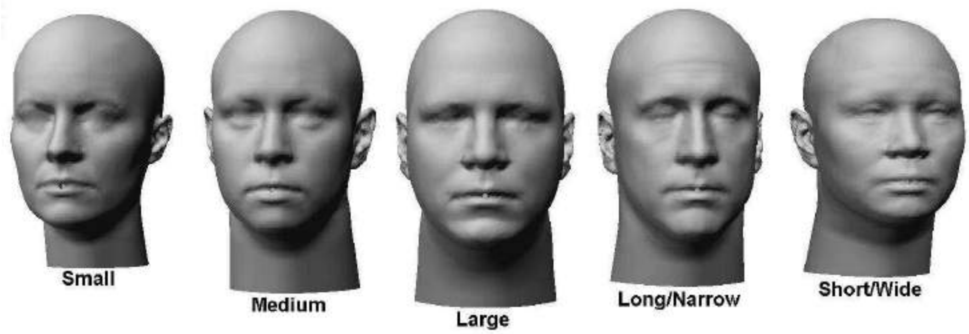


Fig. 8: Five standard digital 3D head forms.

Since the digital headform models from NIOSH are polygon models, they need to be transformed to CAD models using a similar process as that used for the respirator CAD models. Considering that the contact area is mostly on the wearer's face, only front face parts are modeled to improve the computational efficiency (Fig. 9). Each model is made up of about 200 curved sub-surfaces.

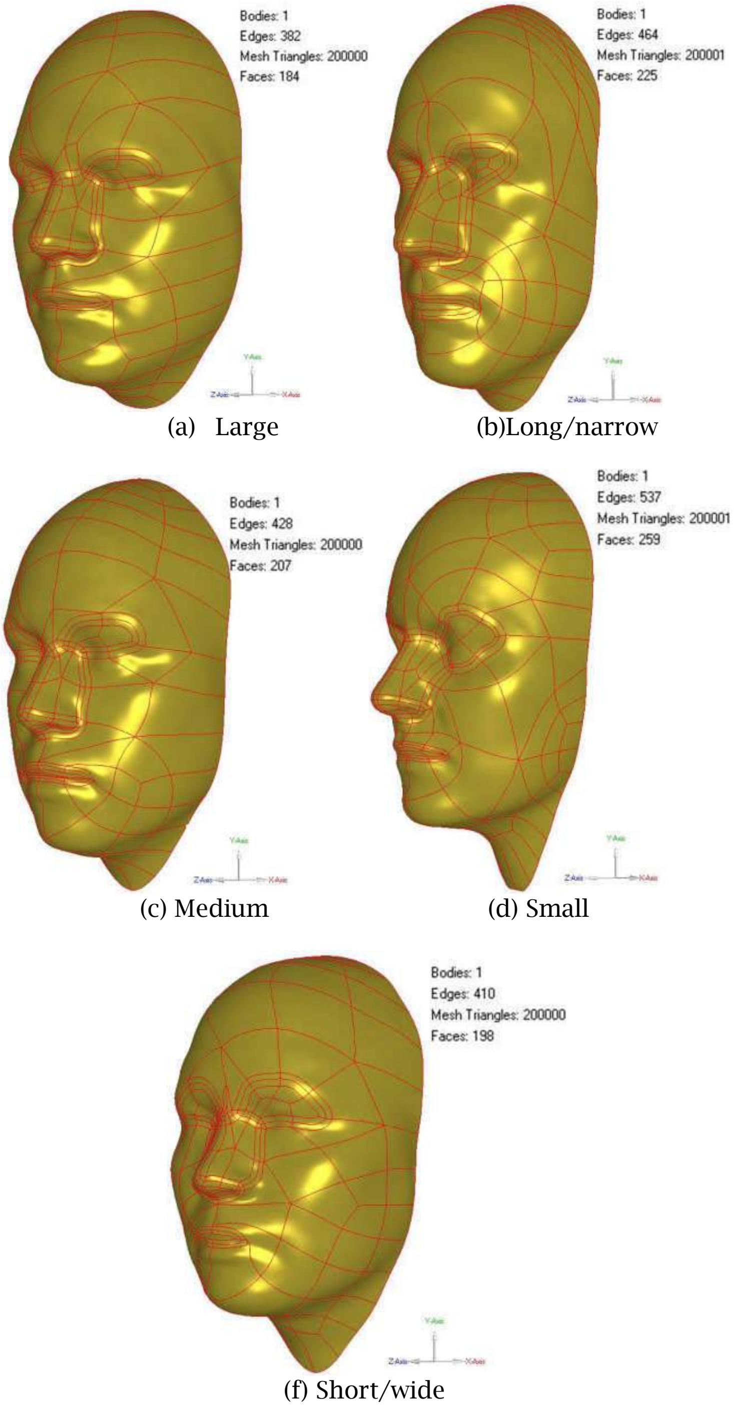


Fig. 9: CAD models of five standard head forms.

3 FINITE ELEMENT MODELS

This section introduces the procedure of generating FE models for both N95 FFRs and headforms. The CAD model of a respirator is a closed surface which has many curved sub-surfaces. After importing the CAD model into LS-DYNA preprocessing software, we obtain a set of solid elements representing this N95 FFR by meshing the volume inside the surface. Fig. 10 shows finite element models of one-size-fits all, small size and medium/large size respirators, with 40874, 24406 and 32062 tetrahedron elements, respectively. We choose to create respirators as solid models instead of as shell models, because solid models represent respirators' shapes more accurately than shell models do.

Since the respirators are made of nonwoven fabric, in this study we use a simple material model: an elastic material with a density of 1.39 g/m^3, a Young's modulus of 27.7M Pa and a Poisson's ratio of 0.37 [8].

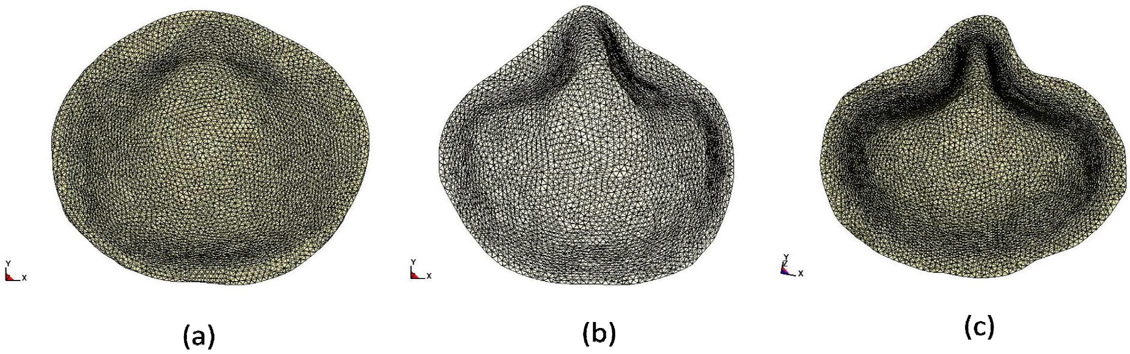


Fig. 10: One-size-fits-all, small size and medium/large size respirators.

After CAD models of headforms are imported into LS-DYNA preprocess software for trimming and dividing, multi-layer headform models can be created by separating the human face and adding different thicknesses to each part. A whole face area has four sub-areas, which are forehead, right cheek, left cheek and chin, as shown in Fig. 11. The forehead part has a skin layer with thickness of 5 mm and a bone layer with 1 mm, while the other parts have a skin layer with thickness of 3 mm, a bone layer with thickness of 1 mm and a muscle layer. Instead of having a constant thickness, the muscle layer has two thicknesses (3 mm and 6 mm), as shown in Fig. 12. Headform models are meshed into 36782 tetrahedron solid elements for finite element analyzing.

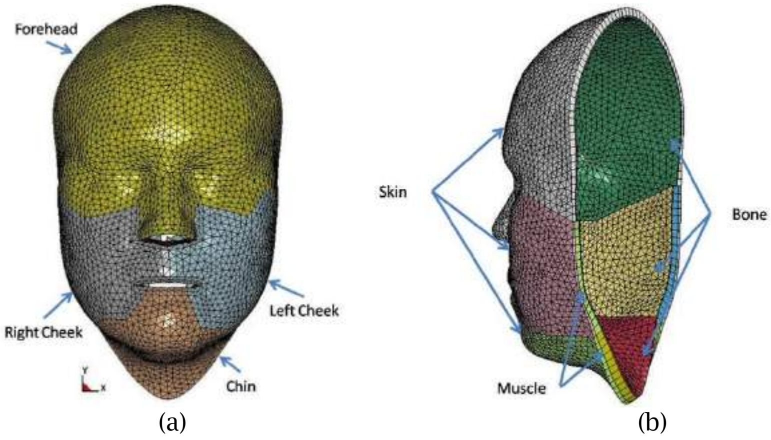


Fig. 11: FE model of medium head (a) Meshed head form; (b) Multi-layer head form.

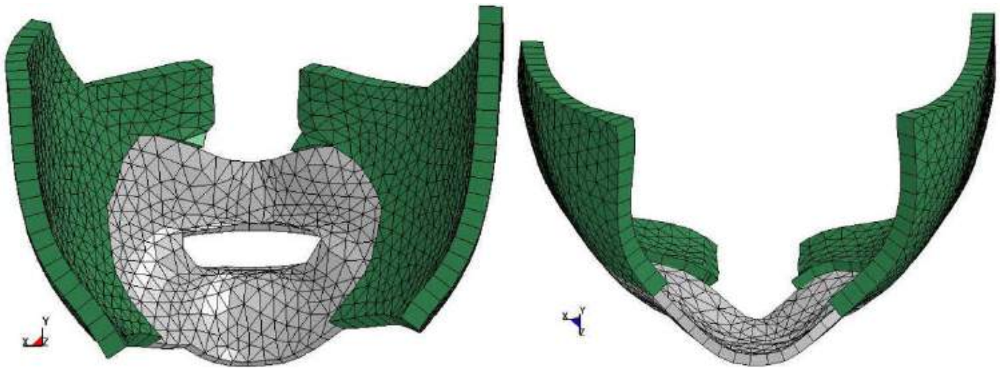


Fig. 12: Muscle layer with two thicknesses (gray color area has a thickness of 3 mm and green color area has a thickness of 6 mm).

In order to build accurate deformable headform models, it is important to have accurate material properties. From Fung [5] and Duck [4], we set up the ELASTIC material properties of layers for headform models in Table 1.

Layer	Density (g/m^3)	Young's Modulus (MPa)	Poisson's Ratio
Skin	1.2	0.6	0.45
Muscle	1.6	0.79	0.42
Bone	4.5	1000	0.3

Tab. 1: Mechanical properties of headform layers.

4 FINITE ELEMENT ANALYSIS

After FE models of N95 FFRs and headforms are built, we can simulate the interaction between a N95 FFR and a headform in LS-DYNA. The simulation process is similar to the process of a user donning a N95 FFR. At the initial stage, the N95 FFR and headform models are assembled in such a way that there is an approximately 3mm gap between the N95 FFR and headform model in order to prevent penetration, as shown in Fig. 13. At the next stage, loads and boundary conditions are applied and the N95 FFR is moving toward the headform. At the third stage, the N95 FFR gradually contacts the headform with an increasing number of contact points. At the fourth stage, the N95 FFR is nearly stable on the headform and the pressure distribution on the contact areas can be determined.

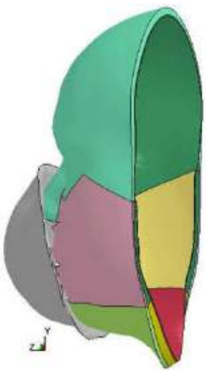


Fig. 13: Respirator & head form pair.

4.1 Loads and Boundary Conditions

This simulation contains three kinds of loads. The first one is the body load from steady gravity in the Y direction. The second is the strap loads applied on four locations, including left/upper, right/upper, left/ lower and right/lower in Fig. 14 where the load values and directions are specified in Table 2. The third is the friction forces whenever the respirator contacts the headform. LS_DYNA's contacting solver is used with input parameters, including a skin friction coefficient. The skin friction coefficient varies in the literature. According to Bitterman[1] and Zhang's work [11], 0.2 is an appropriate value.

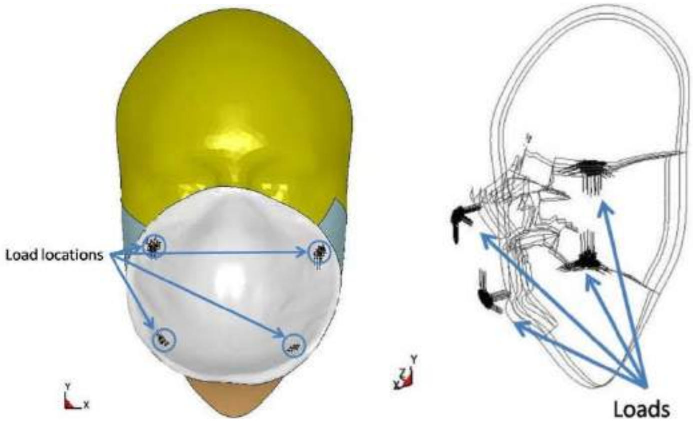


Fig. 14: Locations and directions of loads.

Load location	Force in X direction	Force in Y direction	Force in Z direction
Left/ upper	20N	10N	-40N
Right/ upper	-20N	10N	-40N
Left/ Lower	20N	-10N	-40N
Right/ Lower	-20N	-10N	-40N

Tab. 2: Load directions and values in each location.

We assume that the headform does not move when the N95 FFR is worn. Six degrees of freedom of boundary nodes in headform are constrained. The N95 FFR can move towards the headform with no constraint on the degrees of freedom. Fig. 15 shows boundary conditions of the back surface of the headform model, on which nodes are fixed in six degrees of freedom.

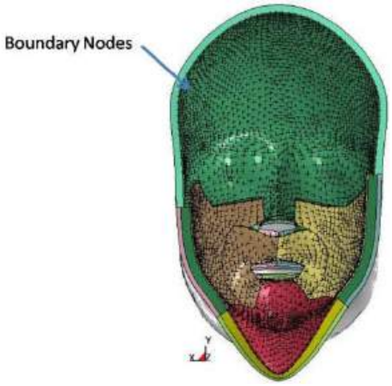


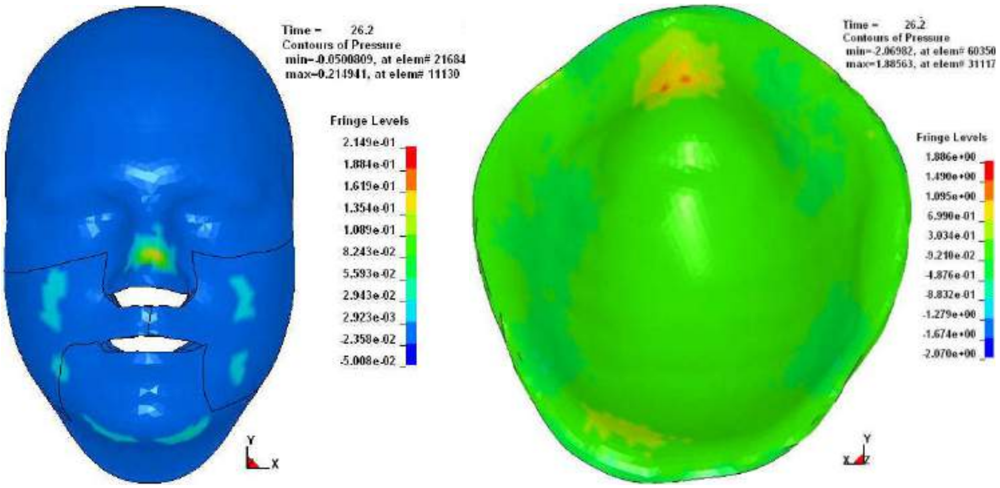
Fig. 15: Boundary nodes on the back of head form.

4.2 One-Size-Fits-All Respirator

The one-size-fits-all respirator, with 125mm width, 130mm length, and 1.5mm thickness, is designed to fit all five standard headforms. Thus, the simulation of its contact with all five headforms is carried out in LS-DYNA. The same mechanical properties, loads and boundary conditions are applied in all five simulations.

Fig. 16 shows pressure distributions on the one-size-fits-all respirator and five headforms in the stable contact stage. The pressure on the sealing part of the respirator is unequally distributed, and it appears in different patterns on different headforms. From the aspect of respirator fit, we assume that the ideal pressure distribution on a human face or the respirator should be a homogeneous contact surface in the shape of a "donut". In other words, any discontinuity of pressure distribution implies that there are possible leakages when users wear the N95 FFR. Also, pressure distributions on large, medium, and short/wide headforms are observed to be nearly homogeneous, although they are not completely homogeneous. However, pressure distributions on the long/narrow headform (Fig. 16b) and the small headform (Fig. 16d) are the worst cases. Therefore, this one-size-fits-all model may not be a good choice for long/narrow and small heads.

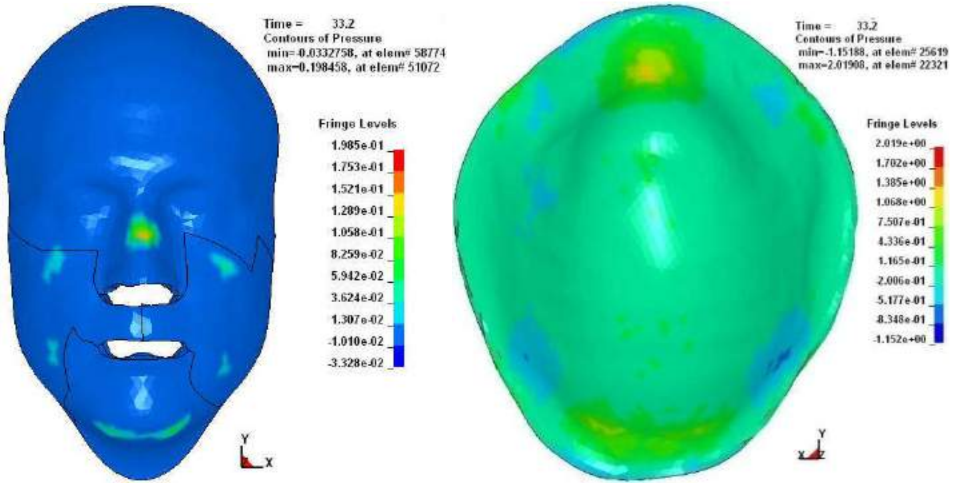
From the point view of respirator comfort, the nose-bridge area suffers the maximum pressure, which is consistent with Snook's [9] findings that the frontal process of the maxilla is more sensitive to force than other locations on the face, although he investigated a different class of respirators. Thus, some special designs should be considered for the N95 FFR in order to reduce the pressure on the nose-bridge area. For example, the one-size-fits-all respirator has a soft pad on the inside surface where the respirator contacts the nose-bridge area.



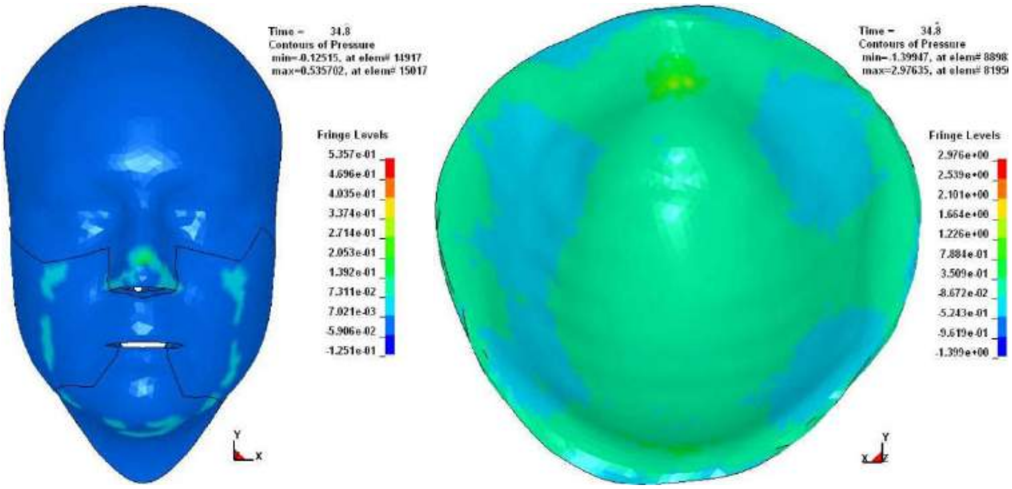
(a) Large head form.

4.3 Two-Size Respirators

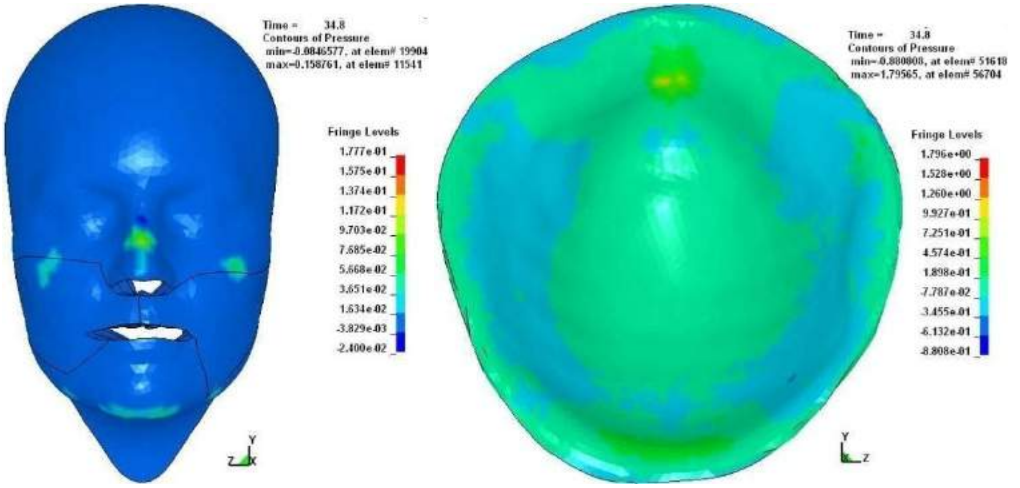
N95 FFRs that come in two sizes are developed to fit a wider array of individuals. The medium/large size respirator used in this study, with 120mm width, 126mm length and 2mm thickness, may be a better choice for large, long/narrow and medium heads. The small size respirator, with 120mm width, 115mm length and 2mm thickness, may be better for small, short/wide head and medium heads. The simulation process is similar to the one-size-fits-all respirator, and the respirator fit criterion is the same. Fig. 17 shows that the medium/large size respirator works well for large and long/narrow headforms. However, potential leakages occur for the medium head-form using the medium/large size respirator. The small size respirator is the best for the medium head-form (Fig. 17d). For small and short/wide head-forms, the small size respirator has similar pressure distribution patterns. In general, N95 FFR studied here with two-sizes has more homogeneous pressure distributions than one-size-fits-all respirators.



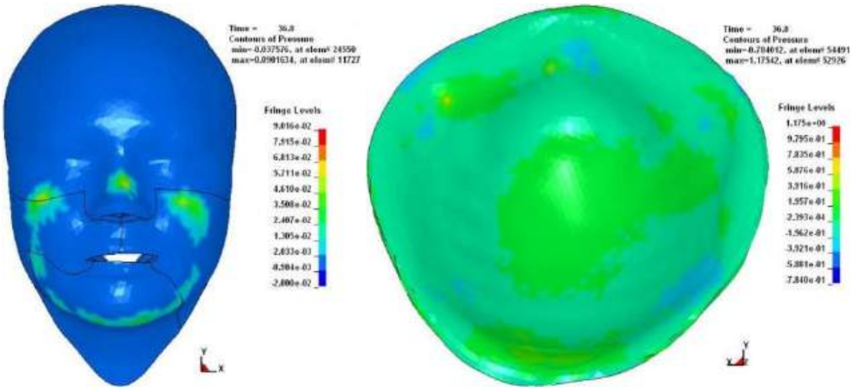
(b) Long/narrow head-form.



(c) Medium head-form.

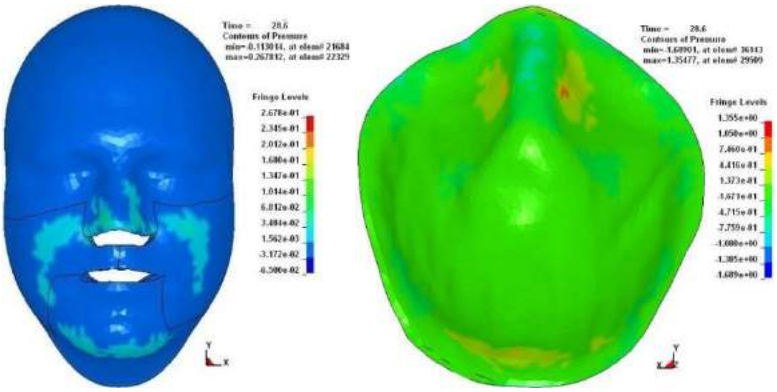


(d) Small head form.

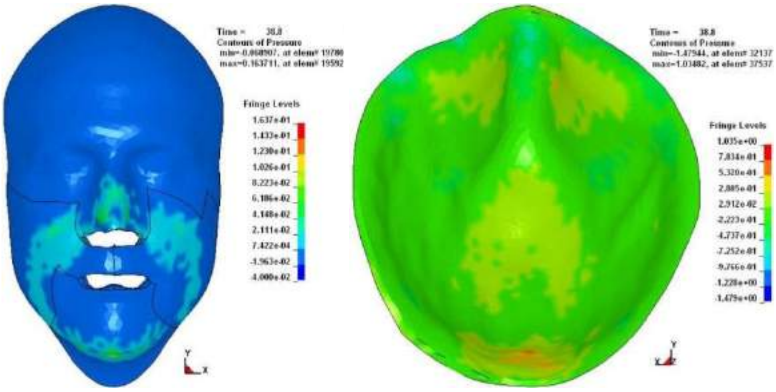


(e) Short/wide head form.

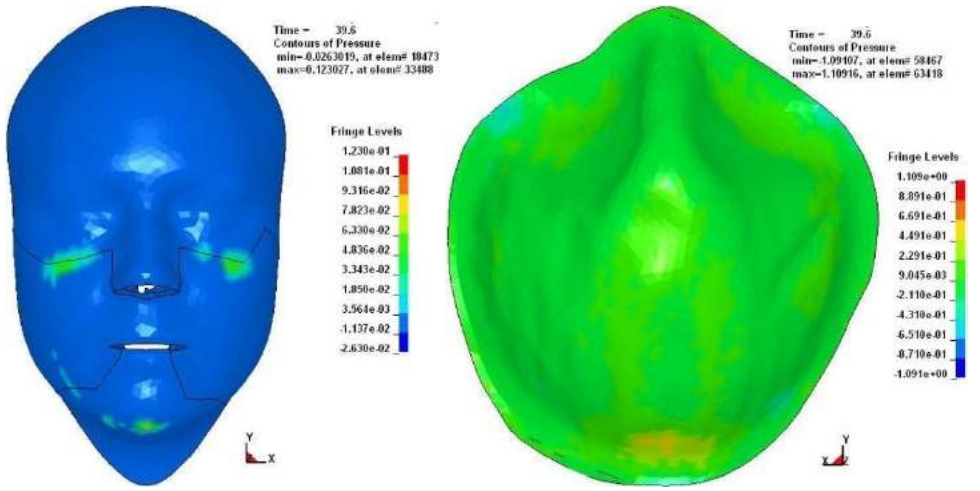
Fig. 16: Pressure distributions of the one-size-fits-all respirator with (a) Large; (b) Large/ Narrow; (c) Medium; (d) Small; (e) Small/ wide head-forms.



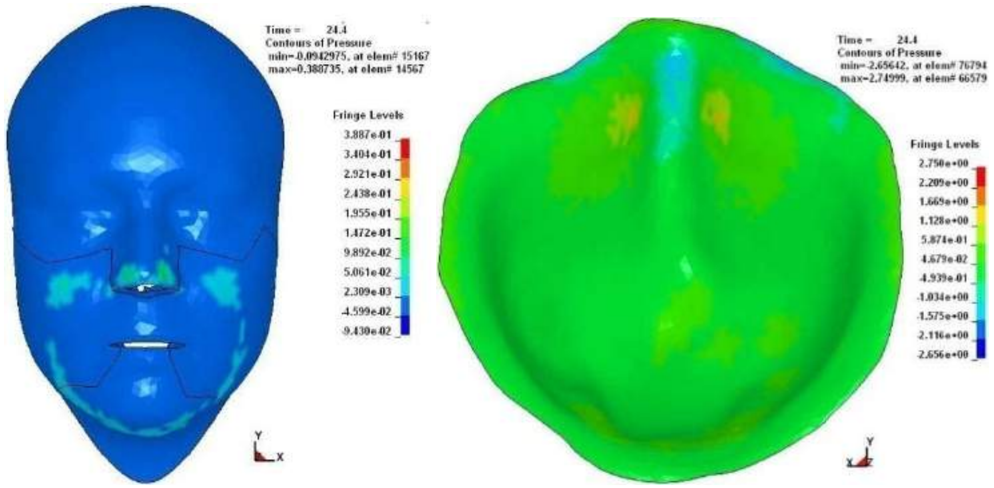
(a) Large head-form & medium/large size respirator.



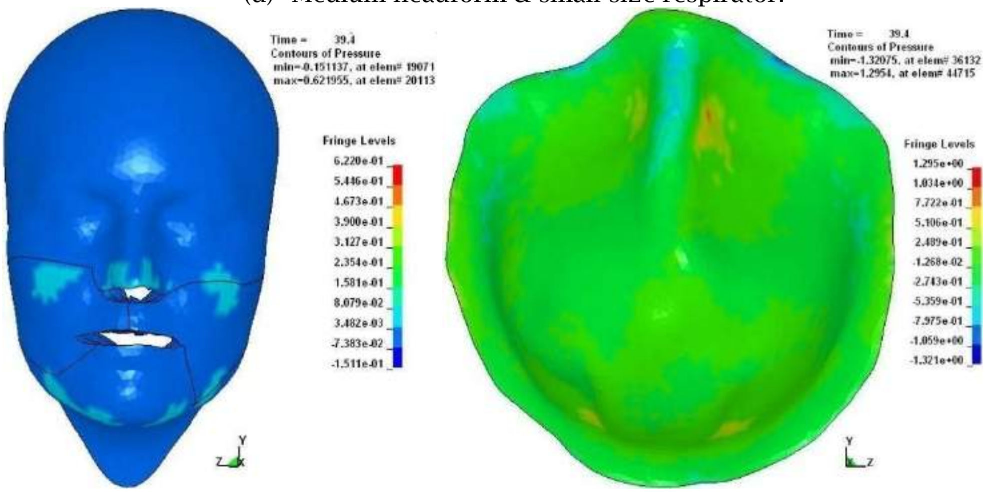
(b) Long/narrow headform & medium/large size respirator.



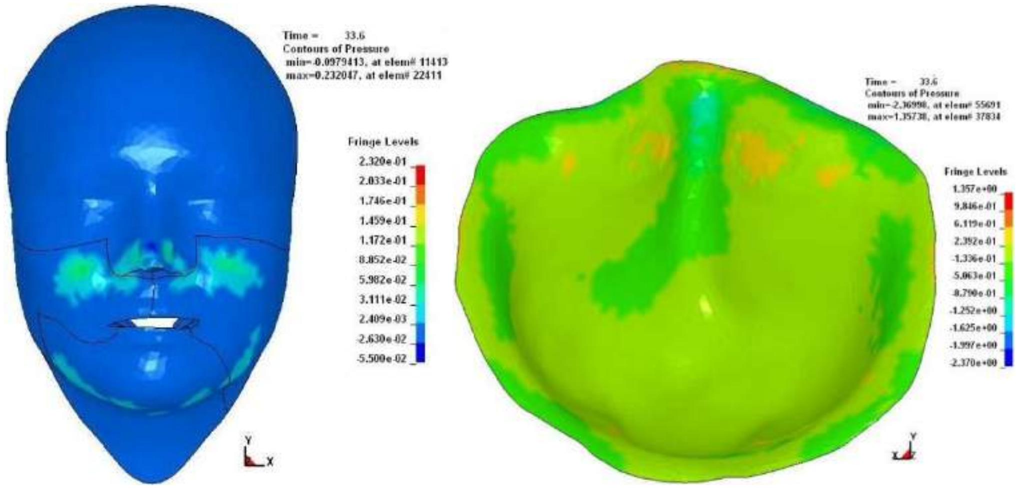
(c) Medium headform & medium/large size respirator.



(d) Medium headform & small size respirator.



(e) Small headform & small size respirator.



(f) Short/wide headform & small size respirator.

Fig. 17: Pressure distributions of the medium/large size respirator with (a) Large; (b) Long/narrow; and (c) Medium head froms; the small size respirator with (d) Medium; (e) Small; and (f) Short/wide headforms.

5 DISCUSSION

Compared to our previous models of respirators and headforms [10], this work has made significant improvements in terms of model fidelity. The human face has a complicated structure and has several layers with different thicknesses. The N95 FFR models are made of solid elements instead of shell elements.

The limitations are as follows: the models still need more accurate material properties, such as different layers of the human face; the N95 FFR needs to be modeled as several layers according to its multilayer structure. In this work, we have not considered the straps in the model. Additional respirator models are needed to generalize these findings. Therefore, our future work will include the following aspects:

1) Searching for more precise material properties for these models;
2) Modeling the N95 FFR as several layers;
3) Including straps in the simulation to consider the head shape effect on the strap tensions.

6 CONCLUSIONS

A simulation model was developed for a contact pressure study of N95 FFRs using FE method. The simulation models were generated from 3D digital models of FFRs and headforms. In this study, we first used a one-size-fits-all N95 FFR to contact all five headforms and then used another N95 FFR available in two sizes to contact different headforms. The loads and boundary conditions were the same for all cases for comparison of the contact pressure distribution characteristics. It was shown that the one-size-fits-all N95 FFR works well for large, medium, and short/wide headforms. However, there are indications of potential leakages for small and long/narrow headforms. For the N95 FFR with two sizes, the medium/large size works well for the large and long/narrow headforms, while the small size works well for the medium, small, and short/wide headforms. The medium/large size has potential leakages for medium headforms. Furthermore, the N95 FFR with two sizes has a more uniform pressure distribution than the one-size-fits-all respirator. Future studies are needed to validate these observations with human subjects.

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The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health. Mention of commercial product or trade name does not constitute endorsement by the National Institute for Occupational Safety and Health and Texas Tech University.

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