Contact Area Determination between a N95 Filtering Facepiece Respirator and a Headform

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Abstract. This study investigates two methods to determine the contact area between a N95 filtering facepiece (NFF) respirator and a headform. Five size headforms (large, medium, small, long/narrow and short/wide) wear a NFF respirator (3M 8210) respectively. A biofidelity finite element model of headform is built to simulate its interaction with a NFF respirator. During the simulation, the respirator contacts the headform. Two methods are presented in this paper for determining contact areas: The first one is through the observation of contact pressure distribution. The assumption is that the contact area is the fraction of surface area with positive contact pressure. The second method is through extracting the intersecting area between deformed surfaces of the headform and NFF respirator. Finally, the experiment, which directly measures the dimensions of contact area between prototypes of the headform and the NFF respirator, validates the proposed methods.

Keywords: Headform, respirator, finite element (FE) method, contact area.

1 Introduction

The N95 filtering facepiece (NFF) respirator protects the user by filtering at least 95% of airborne particles out of the breathing air. Respirator contact has been studied for evaluating respirator fit (Lei et al., 2010). Contact areas are generated when a respirator contacts a human face. Hidson (1984) obtained the contact area between a mask and a face by mounting a mask on a standard headform and spraying a chalk dust in the interior zone. The inner boundary of the contact area was drawn by the chalk dust and the outer boundary was drawn by the mask boundary. This method is feasible for the mask, which has a thick contact area, but is not feasible for a respirator, which has a very narrow contact area. Dellweg (et al., 2010) measured contact area between a non-invasive ventilation and an even surface. Color imprints of the mask cushion on scaled paper were taken and the area of the color imprints was recorded by planimetric measurement. In order to use this method, the boundary of the mark has to be nearly in the same plane, while the NFF respirator does not fit this requirement. Friess (2004) used a 3D scanner to calculate the respirator seal area. Subjects' faces were scanned before and after they wore a respirator. The outlines of

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the inner and outer seals of the respirator were marked and recorded. A 3D surface model of the area on the face was created. Still, this method is useful for a respirator has a thick sealing area, but is not suited for a NFF respirator.

This paper focuses on methods to determine contact area between a NFF respirator and a headform. Contact simulations between a NFF respirator and a headform are introduced using high biofidelity FE models (Lei et al., 2010) in Section 2. Two methods to determine contact areas are proposed in Section 3. Experiments are set up for validating the methods in Section 4. Finally, a summery is given.

2 Contact Simulations

Five size headforms (large, medium, small, long/narrow and short/wide) created by the National Institute for Occupational Safety and Health (NIOSH) (Zhuang et al., 2005) are used in this study. An NFF respirator, 3M 8210 (one size), is used. Headforms and the respirator are generated by a 3D scanner (Fig. 1 and 2).

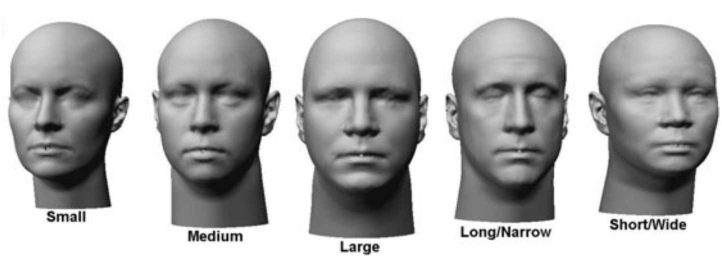


Fig. 1. Five size headform models from NOISH (Zhuang et al., 2005)

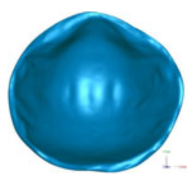
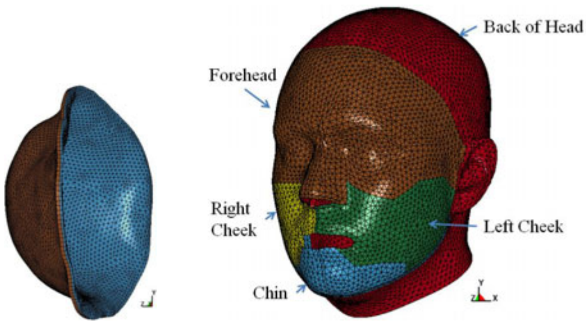


Fig. 2. Scanned 3M 8210 respirator model

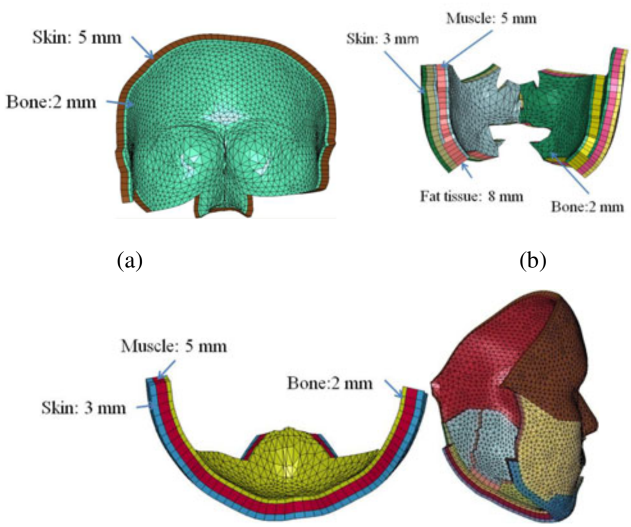
Five size headforms wear the respirator separately. Thus, there are five contact simulations (Lei et al., 2010). Fig. 3(a) shows that the respirator model is comprised of multiple layers and two straps. As shown in Fig. 3(b), the headform model is divided into five parts (two areas for cheeks, one area for the upper forehead, one area for the chin, and one area for the back side of head). It has multiple layers that include a skin layer, muscle layer, fat tissue layer, and bone layer, as shown in Fig. 4.

Two stages are used for the contact simulation. Stage I is to wrap the straps around the back of the headform and pull the respirator away from the face. Fig. 5(a) is the initial state of Stage I and Fig. 5(b) is the ending state of Stage I.



(a) (b)

Fig. 3. FE models of (a) the respirator and (b) the headform



(a) (b)

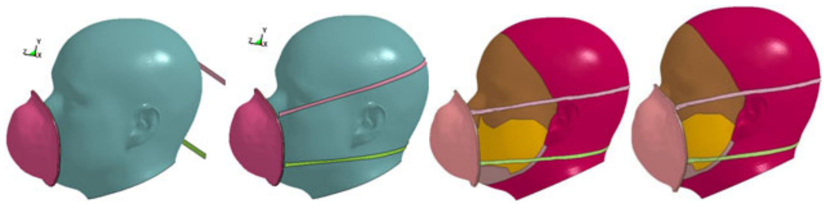
(c) (d)

Fig. 4. Layers in (a) forehead part; (b) left and right cheek parts; (c) chin part; (d) four front face parts together

Stage II is to release the respirator so that the respirator moves towards the face. Deformed geometries and internal stresses are imported into the initial state of Stage II (Fig. 5c). Strap forces and contact interactions are automatically generated between the respirator and headform. Finally, the respirator contacts the human face (Fig. 5d).

3 Determination of Contact Area

This section presents two methods to determine the contact area. The first one is through pressure distributions on the headform surface and the assumption is that contact area is the fraction of surface area with positive pressures. The second one is through extracting the intersecting area between the deformed surfaces of the headform and the respirator.



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

Fig. 5. Stages: (a) Stage I initial state; (b) Stage I ending state**;** (c) Stage II initial state; (d) Stage II ending state

3.1 Contact Area from Pressure Distributions

When two objects contact, the stresses and deformation arise (Johnson, 1985). On a point of contact area, the stress is resolved into a pressure, acting along the common normal of the contact surface, and a shear, acting in the tangent plane of the contact surface. The pressure is highly concentrated on the contact area. Thus, we can assume that the contact area is part of surface area where pressure is positive.

Using contact pressure as the indicator is the easiest way to determine contact area, since LS-DYNA has the post-processing software, named PrePost, that can directly plot the pressure distribution on the headform surface. Figs. 6(a)-(e) give the contours of pressure on the headform surfaces (large medium, small, long/narrow and short/wide). The surface area with a deep blue color indicates zero pressure, while the area with other colors indicates the contact area that has positive pressure values.

3.2 Contact Area from the Intersection of Surfaces

The contact area depends on the geometry of the contact bodies. When the respirator contacts the headform, their surfaces contact each other and the intersection happens. Therefore, the contact area can be determined by extracting the intersecting area between surfaces.

The definition of intersection is that a set of points common to two or more geometric surfaces. In respirator contact area, points belonging to the respirator surface exactly locate on the headform surface without distance. However, the headform and respirator surfaces are discretized into triangle elements and conforming contact among these triangles in 3D space is nearly impossible. Thus, we should expand our definition of intersection to the one that a set of points on the respirator surface is close to the headform surface with a very small offset distance, like 0.1 mm.

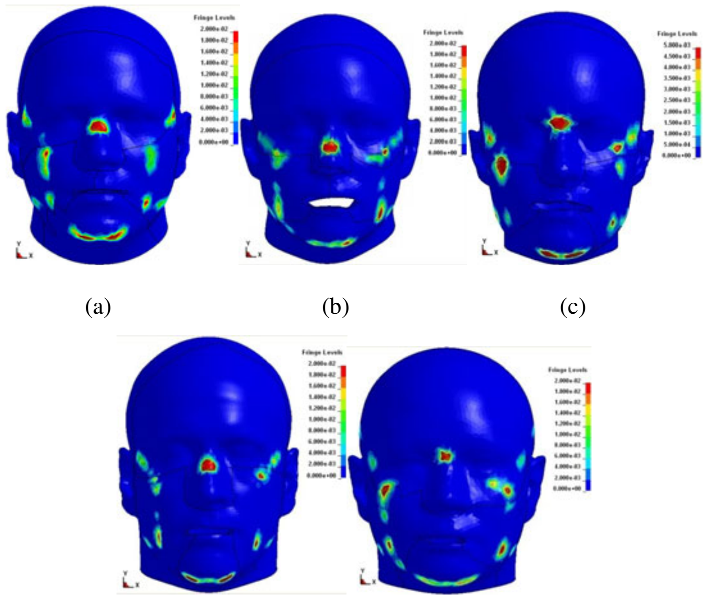


Fig. 6. Pressure distribution: (a) large; (b) medium; (c) small; (d) long/narrow; (e) short/wide

In the final state of Stage II, the shapes and positions of the headform and respirator reach a constant state. The inner surface of the respirator and the outer surface of the headform are extracted and stored as a Keyword file that stores the information of unstructured surfaces consisting of triangles, as shown in Fig. 7. The format of the Keyword file is described in LS-DYNA's Keyword user's manual (Livermore software Technology corporation, 2007). A Matlab program is developed to read the Keyword file. Two sets of data are exported from the Keyword file. One is the set of triangle elements and the other one is the set of nodes which are denoted by global Cartesian coordinates. So, two matrixes are created for restoring the two sets of data and for further operating.

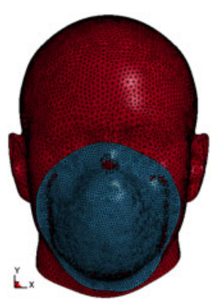


Fig. 7. Respirator and headform surfaces in Keyword format

The next step is to use an algorithm to find the shell elements on contact area. Let us set the respirator surface as the slave segment and the headform surface as the master segment. At the beginning, a search for each slave node on the respirator surface to find its nearest node on the master segment (the headform surface) is done. Consider a slave node, N_s, and a master node, A_m, which is N_s's nearest node on the headform surface. The master element m is one of the elements that contain the node A_m. Fig. 8 shows that the node P_m is the projection of N_s onto the plane that has the element m. The vector $\vec{g}$ begins at the node A_m and ends at the node N_s; the vector $\vec{h}$ begins at the node A_m and ends at the node P_m; the vector $\vec{l}$ begins at the node P_m and ends at the node N_s. The vectors $\vec{c_1}$ and $\vec{c_2}$ begin at the node A_m and end at the node B_m and C_m, respectively.

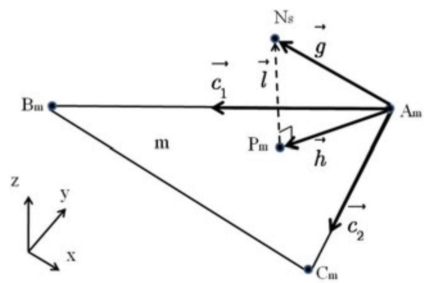


Fig. 8. Projection of a slave node N_s onto the plane that has the master element m

$$\vec{l} = (\vec{g} \bullet \vec{n})\vec{n} \tag{1}$$

$$\vec{h} = \vec{g} - \vec{l} \tag{2}$$

For element m

$$\vec{n} = \frac{\vec{c_1} \times \vec{c_2}}{\left|\vec{c_1} \times \vec{c_2}\right|} \tag{3}$$

If the slave node N_s contacts the master element m, two conditions should be satisfied. First, the node P_m should lie in the triangle element m. The following tests can be used:

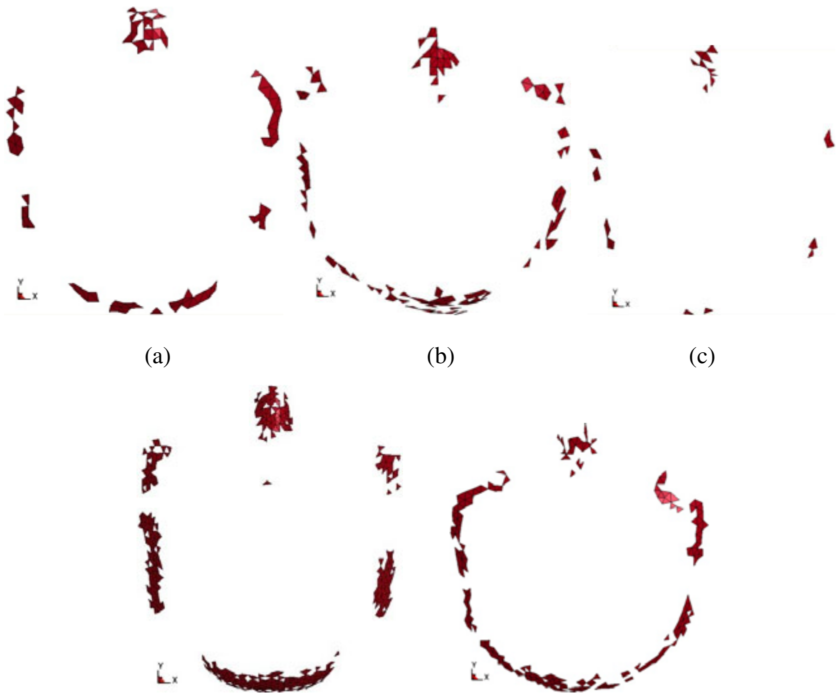
$$\begin{aligned} (\vec{c_1} \times \vec{h}) \bullet (\vec{c_1} \times \vec{c_2}) > 0 \\ (\vec{c_1} \times \vec{h}) \bullet (\vec{h} \times \vec{c_2}) > 0 \end{aligned} \tag{4}$$

Second, the direction of $\vec{l}$ should be opposite to the direction of $\vec{n}$ or the magnitude of $\vec{l}$ should be within a very small tolerance (0.01 mm). According to Equation (1), this condition can be expressed mathematically as following:

$$\vec{g} \bullet \vec{n} < 0.01mm \tag{5}$$

When $\vec{g} \bullet \vec{n} < 0mm$, the slave node N_s penetrates the master element m.

Using the criteria described above, we can obtain the contact nodes on the respirator surface and the contact elements on the headform. The contact area consists of these contact elements. Fig. 9(a)-(e) show the contact areas which are from the surface intersections.



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

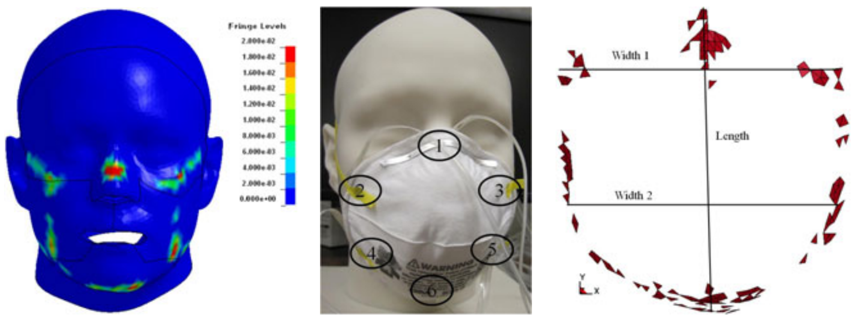
Fig. 9. Contact areas: (a) large; (b) medium; (c) small; (d) long/narrow; (e) short/wide

4 Validation

This section conducts experiments to validate the contact areas from the computation. Because the contact area is covered by the respirator and any movement of the respirator will affect the respirator contact, it is very hard to obtain the contact area from the experiment. However, the experiment can be used to validate our second method of determining the contact area through surface intersecting.

The experiments are based on the characteristics of the pressure distribution and contact area. Fig. 10(a) gives the pressure distribution on the headform surface. Pressures are gathered in six key areas of the headform surface. The six key areas are numbered as followed: (1) nasal bridge, (2) top of right cheek, (3) top of left cheek,

(4) bottom of right cheek, (5) bottom of left cheek, and (6) chin, as shown in Fig. 10(b). Since contact area is related to the pressure distribution, Fig. 10(c) shows that the contact area is also grouped in these six key areas. Thus, we can define three dimensions that depict the contact area. Width 1 is the linear distance of the key area (2) and (3), Width 2 is the linear distance of the key area (4) and (5) and Length is the linear distance of the key area (1) and (6). These three dimensions, Width 1, Width 2 and Length, can be measured in the computational post-processing and the experiment, and be compared for the validation.



(a) (b) (c)

Fig. 10. (a) Pressure distribution; (b) Six key area; (c) Contact area with dimensions

An experiment for validating the results from simulations is set up. Prototypes of five size headforms, produced by American Precision Prototyping, LLC with Polypro-Like Accura 25 material, are used. The surfaces of the prototypes are non-deformable and detailed facial features and sizes are maintained as the same as the NIOSH models (Zhuang et al., 2008). The Tactilus free form sensor system, manufactured by Sensor Products Inc., is incorporated into the experiments. Separate sensors with thin and tactile surface are available for conducting measurements on surfaces with complex geometries like a human face. The user can place sensors at desired locations. The hub collects the pressure data and sends the data to the computer by a cable. The Tactilus software collects and stores the results. A vernier caliper is also used to measure the linear distance.

The respirator is worn by the headform prototypes. Because the NFF respirator is closed to the headform, it is hard to locate their contact area purely by human eyes. So, pressure sensors are adopted for locating the boundary of the contact area. In each respirator-headform combination, the vernier caliper measures the three dimensions of the contact area (Width 1, Width 2, and Length).

Table 1 presents the dimensions of the contact areas in computational results and experimental results. Fig. 11, in which the horizontal axis is the dimensions of contact area from experiments and the vertical axis is the dimensions of contact area from simulations, provides linear regression analysis on computational and experimental results. The R^2 value of 0.9105 indicates that our simulation results are well validated by the experiments.

Table 1. The results of contact area dimensions (Units: mm)

Dimension / Headform	Experiments			Simulations		
	Width 1	Width 2	Length	Width 1	Width 2	Length
Large	108.69	100.03	123.14	108.34	98.90	122.15
Medium	108.84	104.72	120.60	104.16	102.91	115.35
Small	104.83	97.89	107.34	106.41	92.26	108.26
Long/narrow	101.80	94.36	122.61	99.99	89.19	122.09
short/wide	113.94	108.71	110.26	112.90	103.81	114.94

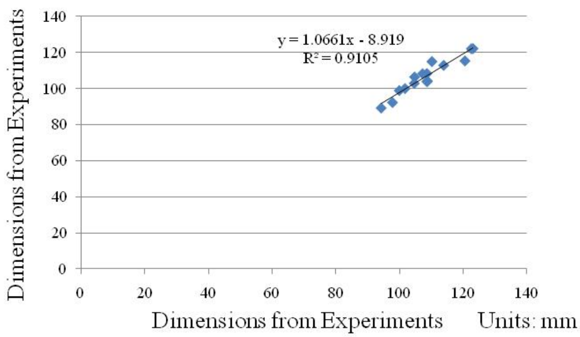


Fig. 11. Correlation of experimental and computational results

5 Conclusion

This paper discusses methods to determine contact area between a NFF respirator and a headform. Five size headforms (large, medium, small, long/narrow and short/wide) wear a NFF (3M 8210) respectively. Two methods were developed for determining the contact areas between a respirator and headform. The first one is through plotting the pressure distribution and the second one is through Matlab programming that extracts the geometry intersection. The first method is easy and fast, but the second one can give more accurate results. Finally, the computational results are validated by experiments.

The contact area between the respirator and headform is very useful for respirator designers and standard makers. It can be used to exam the respirator fit. The discontinuous curve of contact area indicates potential respirator leak locations. The contact area can also be used to design a new half facepiece respirator. By overlapping the contact areas from five respirator-headform combinations, we obtain the workspace of respirator sealing, as shown in Fig. 12.

Future work includes more simulations to obtain contact areas from other respirator brands. In addition, the relationships between the contact area and headform dimensions and between the contact area and respirator designs should be investigated.

Fig. 12. The workspace of respirator sealing

References

1. Dellweg, D., Hochrainer, D., Klauke, M., Kerl, J., Eiger, G., Kohler, D.: Determinants of Skin Contact Pressure Formation During Non-invasive Ventilation. Journal of Biomechanics 43, 652–657 (2010)
2. Friess, M.: Analysis of 3d Data for the Improvement of Respirator Seals-Final Report (2004)
3. Hidson, D.J.: Compotator-aided Design of a Respirator Facepiece Model. Defense Research Establishment Ottawa, Report, Ottawa (1984)
4. Johnson, K.L.: Contact Mechanics. Cambridge University Press, Cambridge (1985)
5. Lei, Z., Yang, J.: Toward High Fidelity Respirator and Headform Models. In: 1st International Conference on Applied Digital Human Modeling, Miami, Florida, July 17-20 (2010)
6. Lei, Z., Yang, J., Zhuang, Z.: Contact Pressure of N95 Filtering Face-Piece Respirators Using Finite Element Method. Computer Aided Design and Applications 7(6), 847–861 (2010)
7. Livermore software Technology Corporation, LS-DYNA Keyword User's Manual. Version 971, LSTC, vol. I (May 2007)
8. Zhuang, Z., Bradtmiller, B.: Head-and-Face Anthropometric Survey of U.S. Respirator Users. Journal of Occupational and Environmental Hygiene 2, 567–576 (2005)
9. Zhuang, Z., Viscusi, D.: A New Approach to Developing Digital 3-D Headforms. In: SAE Digital Human Modeling for Engineering and Design, Pittsburgh, PA, USA (2008)