Evaluating Hearing Protection Comfort Through Computer Modeling

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Abstract: People are less likely to wear hearing protection that is uncomfortable. The overall comfort of the hearing protection is therefore a primary design feature. Methods for evaluating comfort typically include production and use testing of physical prototypes which are expensive and time consuming which reduces the number of design options to test. This work demonstrates the use of computer modeling to predict wearer discomfort by modeling the interaction between ear protection devices and the human ear.

Obtaining an optimal comfort design is challenging because of large variations in human ear shape and complicated material behavior in both ear canal and ear plug. Generating a set of human ear models required the use of large and small scale 3D scanning technologies to create geometries representing both external and internal structures. Multiple material layers were used to approximate the actual layers in the region.

The model simulated the insertion and stress relaxation of the hearing protection devices. Results from these models were compared against discomfort measured in use. The model results show that discomfort is a function of contact pressure and area. Average contact pressure and total contact force were identified as the key metrics that correlate to comfort ratings from the use studies

Keywords: hearing protection, comfort, finite element model, human ear, hyperelastic, discomfort, skin, ear, 3dMD, NextEngine, Geomagic, consumer

1. Background

Methods for predicting how a product will be perceived by a population of users are highly valued tools for product developers as they make design decisions. A common approach is to conduct use tests (Casali, 1987) where a subset of the population uses prototype products and provides feedback on key features. These tests can be expensive to conduct and require functional prototype products. Modeling tools like Abaqus provide opportunities for developers to pre-screening design and material options reducing costs and increasing speed to market.

Hearing protection devices like ear plugs are effective only when designed to have the correct sound attenuating characteristics and worn properly. It is widely believed that comfort is a key factor determining whether people will wear the hearing protection (Casali, 1987). It is therefore critical to design the product to be comfortable if it is to be effective.

Comfort or the lack of comfort (discomfort) is a complex perception being a combination of a wide range of sensations. The amount of applied pressure that corresponds to discomfort depends on location on the body, gender, duration and other parameters (Albin, 2007). Ear plug discomfort is fortunately simpler being primarily a physiological response to the contact pressures between the user and the product (Ballachanda, 1995). The finite element analysis method has been used by others to predict comfort of a wide range of consumer products (Camprubi, 2008, Antunes, 2008). It is reasonable to assume that the finite element method can be used to predict contact pressure within the ear caused by the ear plug and therefore estimate amount of discomfort it causes.

Hearing protection falls into three general categories; plugs, muffs, and bands. Ear muffs surround the ear and contact the head. Ear plugs with bands typically are placed just into the ear canal and are held in place by the force of the band. Ear plugs are typically pressed into the ear canal and are held in place by frictional forces. In many manufacturing environments hearing protection is worn for an entire shift (Casali, 1987). The materials that make up the ear plugs being evaluated in this study were tested and found to have a stress relaxation time on the order of minutes which is very small compared with the length of time these products are worn. We will therefore approach the problem with a pseudo-steady state model.

The hearing aid industry has developed many tools for producing devices that fit the unique geometry of each ear. Several researchers have used these tools to produce detailed three dimensional geometries of the ear canal structure (Stinson, 1989). One technique is used to produce a cast of the ear canal using a silicone material that hardens in place and is removed. These ‘ear impressions’ provide an accurate physical representation of the canal shape. These casts can in turn be scanned using three dimensional scanning equipment to create virtual ear canal geometries. The same technique is not typically used for external ear geometry. Three dimensional scanning technologies make it possible to measure the external ear with enough detail to produce a high quality 3D image. The ear plug designs of interest in this study require the ear geometry of both the external ear (pina) and the ear canal.

2. Objectives

The objective of this effort is to evaluate the potential of using solid mechanics computer modeling as a tool for predicting the comfort of novel ear plug designs. Like most modeling projects modeling the interaction between ear plugs and a human wearer requires assumptions and simplifications. The goal of this work is to evaluate whether the particular set of assumptions and simplifications provide adequate accuracy to be a useable product development tool.

A successful tool is one that can accurately predict relative differences in consumer comfort ratings for ear plugs. The first step in evaluating this method will be to create and analyze three different ear plug designs with widely different comfort levels. If the model outputs correlate to the measured user comfort perception then we will conclude that this approach has merit as a design tool. The power of this as a predictive tool will require evaluating this correlation over a wide range of products. Success in this first step will justify the larger effort.

3. Analysis Method

Producing a model of the interaction between ear plugs and a user's ear requires a combination of a number of features. Relevant material models must be created that represent both the ear and the ear plug. The geometry of the human ear with both the external ear and ear canal must be combined with the geometry of the ear plugs in a way that represents the stresses and strains that occur when the ear plug is placed into the ear. The model must then predict the steady state contact forces between the two objects. Finally this data must be analyzed to estimate the contact pressures and interpreted properly to determine the amount of discomfort the user is likely to experience as a result.

3.1 Virtual Human Ear

The virtual human ear is developed to represent a population of potential ear plug wearers. A group of twenty subjects were brought in to provide ear geometry measurements. They were evaluated by audiologists to group them into three categories by size (small, medium, and large). Three of each size were chosen randomly to represent those subpopulations. This set of nine geometries was then combined with the ear material properties to create the 'virtual human ears' used in this study.

3.1.1 Human Ear Material Properties

The human ear is not a homogeneous material. Creating an internal bone structure and combining it with cartilage, fatty tissues, muscle and skin would be difficult and may not contribute to overall accuracy. As an initial evaluation therefore, the material layers have been simplified into two layers; a uniform thickness of skin material overlaying a base substrate. The benefit of this approach is that material properties for human skin are published. Data has been published for in vivo indentation testing of human skin (Tran, 2007) that shows the stress/strain relationship for a specific test configuration. Others have published data on the skin alone (Herman, 2007). A virtual test method was set up to mimic the testing conditions used by Tran. The material properties (Young's modulus) were adjusted in the substrate material until the resulting stress/strain curve was adequately close to the published data. Figure 1 shows the virtual test configuration. Here 'h' represents the penetration depth which starts at zero and proceeds to 2mm. The skin/substrate sample is square at 60mm X 60mm with a thickness 't' that is at least 10X the penetration depth; in this case 20mm. The indenter has a spherical cap on a circular cylinder both with a radius of 6.22mm.

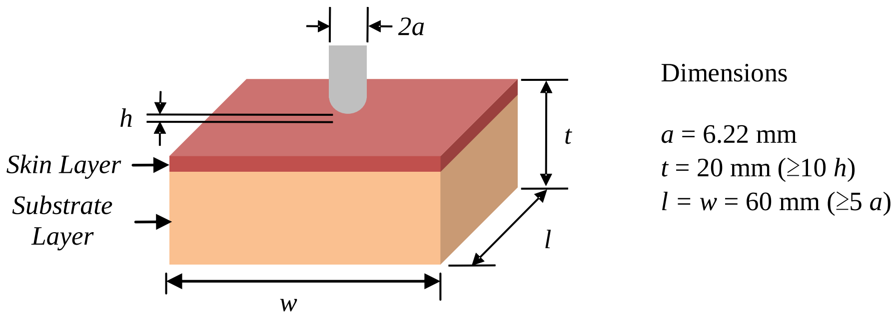

Figure 1. Virtual test configuration designed to mimic the published indentation test method.

The graph in Figure 2 shows that reasonable agreement was reached when the virtual test method had the material properties shown in Table 1. The choice of using a simple elastic solid (Young's modulus) is an assumption based on observations that the ear deformation due to the insertion of the ear plug is relatively small.

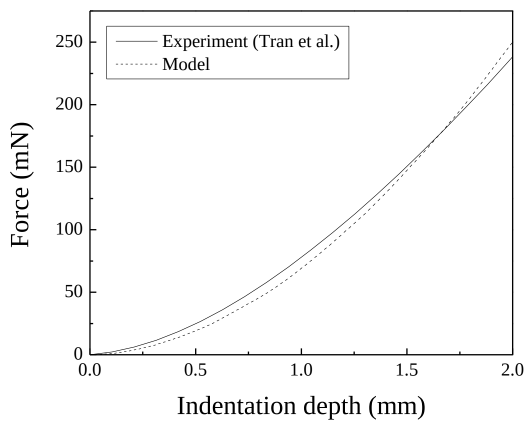

Figure 2. Comparison between the virtual test method and published data.

The skin and substrate are both close to incompressible (Herman, 2007). The Poisson's ratio was set near 0.5 to account for that fact. The final choice of material properties for the virtual human ear are shown in Table 1.

Table 1. Material property values for virtual human ear.

Tissue	Young's Modulus	Poisson's Ratio
Skin	5.67 kPa	0.48
Base Substrate	36.62 kPa	0.42

3.1.2 Ear Geometry

The internal structure of the ear was generated using 'ear impressions' made by audiologists. A cast of the ear canal was made for both ears of each subject. The casting process was conducted by audiologists who start by inserting a small foam plug to prevent the putty like casting material from contacting the ear drum. Enough casting material is used to fill the concha and some of the surrounding folds. The resulting cast represents a portion of the outer ear and the ear canal up to approximately 8mm from the ear drum.

Scans of the ear casts were created using the HD 3D scanner by NextEngine Inc. of Santa Monica, California. This equipment moves a plane of laser light across the surface of the object of interest creating a line of monochromatic light that traces out the surface where the plane intersects with the object. The system captures these shapes as the plane of light moves across the object resulting in a representation of the surface of the object facing the system. The system then rotates the object and scans from a new angle. The entire structure can be captured with five or six scans which can be completed in under ten minutes. NextEngine's ScanStudio HD® software is designed to stitch together 3D surface patches from each scan. The resulting 3D geometry represents the entire ear cast. The geometry was stored in a STL (steriolithography) file with average triangle side lengths of 0.66mm.

The external ear geometry was captured using the 3dMDTorso® equipment from 3dMD of Atlanta, Georgia. Using multiple cameras that capture images from different angles simultaneously a three dimensional surface is generated. Scanning and ear casts were completed on both ears for all subjects. The ear scan data was also stored in the STL format. This method produced surface triangles with an average side length of 0.97mm.

The internal ear geometry STL files were combined with the external ear geometry STL files using GeoMagic Studio® produced by GeoMagic of Research Triangle Park, North Carolina. Each of these scanning methods is generally good at producing high quality three dimensional surfaces. It is common for both systems to have inaccuracies or holes in the data. In cases where the holes were large on ear cast files additional scans were made to fill in the holes. In the case of missing data in the external ear files the holes were filled in using hole filling algorithms available in the software. Images were carefully compared with photographs taken. The need for filling holes was generally small. The central image in Figure 3 shows the combined surface showing the size of the portion captured by the ear cast (red), and by the external scan (blue).

The size of the ear casts were chosen so they accurately represent the shape of the concha and some surrounding areas. The external ear scans also were generally good at seeing those same areas. This provided surfaces that existed in both geometry files. GeoMagic Studio® was used to automatically rotate and translate the internal ear to align it with the outside ear surface. A comparison between the photograph and resulting combined 3D geometry is shown in Figure 3. The resulting combination of surfaces was then given sides and a back so that an enclosed volume was created roughly 2cm larger than the extents of the outside edge of the ear. The back of the volume was flat and was set to be approximately 40mm behind the outer surface of the head.

The combined ear geometry file was converted into a NURBS surface using functions available in GeoMagics Studio®. The resulting surface was stored in an IGES file format for importing into Abaqus CAE.

In Abaqus CAE two sections were created based on the imported ear geometry. The skin layer section was created as a membrane type set to 2mm thick and based on the surface of the ear. The substrate layer section was created based on the volume of the ear geometry.

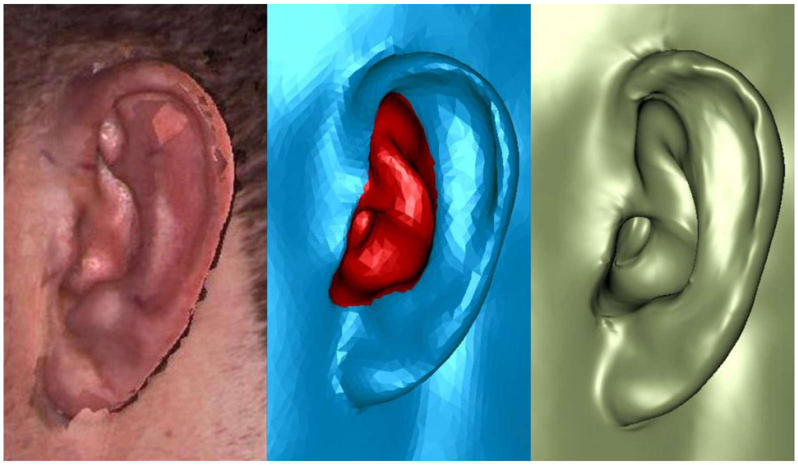

Figure 3. Comparision of photograph (left), the combined STL geometry file (middle) showing the ear cast portion in red, and the NURBS surface created using the combined 3D geometry files (right). There is good shape agreement.

3.2 Virtual Product

3.2.1 Ear Plug Material Models

Three different ear plug designs were tested. Two of the designs were constructed of a soft foam in combination with a hard plastic portion. The third was an elastic solid. The modeling approach was to model just the deformable portion of the ear plug and to treat the hard plastic portions as fixed surfaces. The soft materials for each ear plug were tested by compressing to 20% strain and holding for 20 seconds. Each compression test was run at 0.5, 2.0, and 4.0 mm/second compression rate.

An example of one foam material is shown in Figure 4. The first portion of the plot represents the compression phase where compression force increases with time followed by the hold phase where there is a decrease in compression force as stress relaxation takes place in the material. The data was separated into a uniaxial compression curve that represents the instantaneous stress/strain relationship as shown in the left graph in Figure 5. The hold period data was converted into normalized stress and entered as shear test data in the viscoelastic material behavior. This graph shows the gathered data had good reproducibility with a sample size of three.

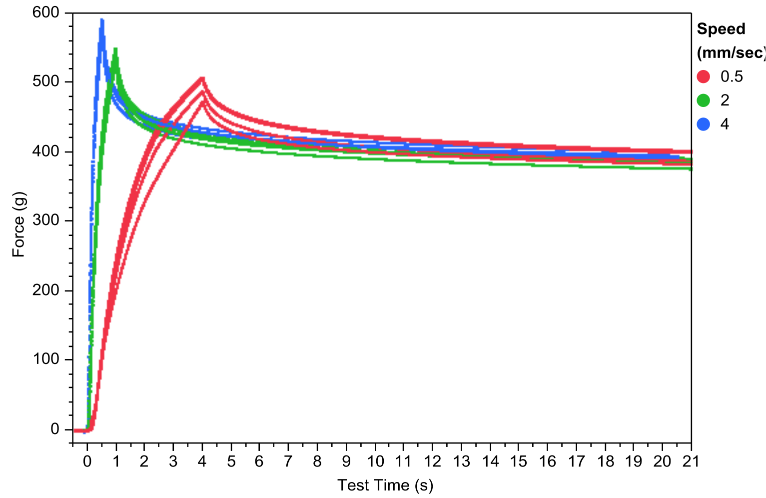

Figure 4. Materials were tested by compressing them to 20% strain and holding for 20 seconds. This material shows significant stress relaxation common to many ear plug foams.

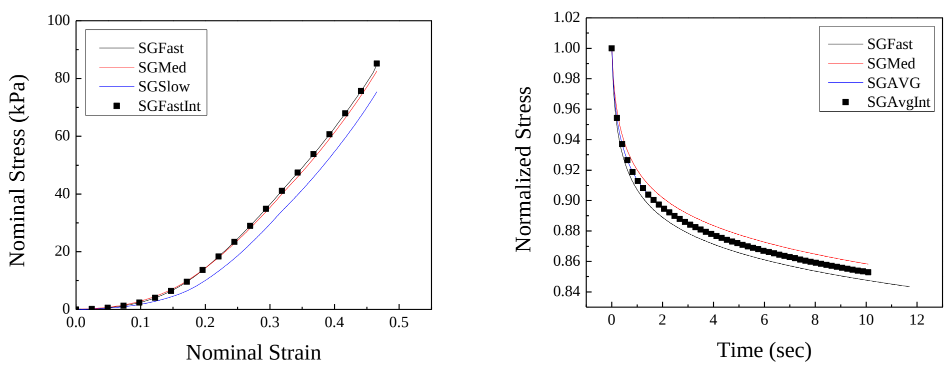

Figure 5. Compression data was converted into two data sets. The left graph shows the stress/strain curve representing the instantaneous uniaxial test data. The data on the right is normalized stress versus time showing the stress relaxation.

3.2.2 Ear Plug Geometry

The geometry of the ear plugs were taken directly from 3D CAD drawings of the ear plugs when available. Competitive products for which CAD drawings were unavailable were measured using a combination of 3D scanning and physical measurements. Individual ear plugs varied and the combination of methods was used to develop geometry files that represented the average ear plug shape. The NextEngine scanner provided a method for measuring soft surfaces without contacting them making it a preferred method for soft materials with opaque surfaces. The NextEngine method is less accurate for surfaces of open cell foams where penetration and subsequent diffusion of the laser light reduces measurement accuracy. The completed 3D CAD files were stored in IGES file format for import into Abaqus CAE.

3.3 Model Construction

The goal of the model is to provide some output that correlates with ear plug discomfort. Based on the literature (Albin, 2007)(Ballachanda, 1995) , contact pressure should play a key role. The model was therefore created to characterize the deformation of the ear canal and ear plug when the ear plug was placed fully into the ear.   The assumption was made that by ensuring that both penetration depth and penetration angle were accurately reproduced in the model the resulting ear plug / ear deformation would also be reproduced and consequently the physical details of the contact.

Measurements of the penetration depth and penetration angle were taken using images captured by the 3DMD equipment. In addition to gathering ear impressions and external ear geometry measurements each subject also wore each of the three ear plugs and had 3D scans taken using the 3DMD device. Care was taken to make sure hair was held back so that as much of the ear was captured as possible. A successful scan would contain measurements of the outer surface of the ear plug and a substantial portion of the external ear. The relative location of the ear plug to the remainder of the ear provided an accurate measure of the penetration depth and insertion angle of the ear plug. Time was taken to ensure the scan quality was adequate. In some cases additional scans were necessary. One ear plug was designed to be inserted quite far into the ear canal. The external portion of the ear plug was a small cylinder that was too small to consistently view with the scanning equipment. In this case small foam squares were affixed to the external end of the ear plug providing a large enough surface to measure depth and angle. An image of the ear plug in place within the ear geometry is shown in figure 6.

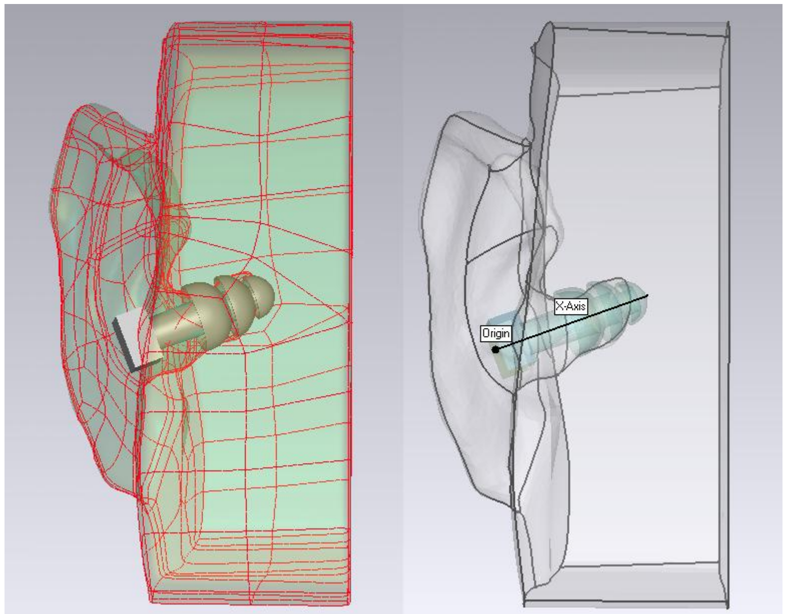

Figure 6. Ear geometry NURBS surface shown as transparent with red outlines. An example ear plug showing angle of insertion and penetration depth. The external block was added to provide a larger surface to visualize the ear plug in place in the ear. Right side image shows location of origin and orientation of x-axis.

The insertion depth and insertion angle were different for each subject and each ear plug. The 3D ear geometry NURBS surface was aligned so that its x-axis was parallel to the insertion axis. In addition the origin was translated so that the origin represented the final resting position of the ear plug. See figure …Thus when the ear plug is placed at an appropriate distance on the negative X-axis, moving the ear plug in the positive X direction until it reaches the origin is equivalent to inserting the ear plug at the correct insertion angle to the correct penetration depth.

Several sections of the geometry were defined to simplify setting the boundary conditions. The section defined by the back side of the ear plug file was set to ‘fixed’. The surfaces on the ear plugs that were in contact with rigid materials were set as non-deformable and were set to move parallel with the X-axis during the insertion step. The outside surfaces of the soft ear plug materials were paired with the outside surface of the ear geometry as contact pairs.

The model was separated into three consecutive steps. The first step preconditions the ear plug and the ear. Many ear plug materials require the wearer to roll them between fingers and thumb to reduce the cross sectional area to make it easier to insert them to the proper depth. Both ear plug designs with soft foam were preconditioned by applying a small displacement normal to the outer surface of the plug. The plug made of the elastic solid had a roughly conical shape and did not require any preconditioning. Additionally during this step the tragus of the ear was pulled forward a small amount to increase the size of the canal opening. This step was 500 milliseconds in duration.

The second step of the model released the foam material and moved the ear plug along the X-axis until it reached its resting position. In general this was done by moving directly along the X-axis. In some cases the ear plug was initially off axis during a portion of the insertion phase in order to improve the way the product fit into the canal opening. However, in all cases the last portion of the insertion was conducted by moving the plug parallel with the x-axis. This step was initiated after the first step completed and is itself completed in 500 milliseconds.

The third step in the model releases the tragus and allows the contact forces to approach equilibrium. This step also starts at the completion of the previous step and is 500 milliseconds in duration.

The friction between the ear plug and the ear was in all cases assumed to be zero. The magnitude of the friction between ear plugs and ear/ear canal was not available to include in this work. The importance of gathering friction data and including it in future models will depend on how inaccurate the present model approach is found to be.

4. Output Data Analysis

4.1 Summary of model results

Discomfort is complex and varies by person, gender, position, exposure time, etc. Albin states that capillary collapse occurs at about 4kPa (Albin, 2007) which some view as an upper limit for comfortable contact pressure. A wide range of comfortable contact pressure exists in literature (Makabe, 1993), (Morris, 1981), (Denton, 1971), (Li, 2001). This wide range makes it difficult to choose an absolute value for pressure that corresponds to discomfort in the ear. It is reasonable to conclude that contact pressure or some related metric is the most appropriate predictor of discomfort. Several potential metrics for discomfort were considered.

<u>Average Contact Pressure</u>: This approach calculates the mean contact pressure for all locations where the contact force is greater than zero. As stated earlier contact pressure is recognized as a being a key driver of discomfort.

<u>Average Contact Force</u>: This approach calculates the numeric mean of all non-zero contact forces. Contact force was included in the analysis because it is tied to contact pressure but is independent of contact area which can be challenging to predict accurately.

<u>Critical Contact Area:</u> This approach calculates the total surface area of contact for all contact pressures greater than 25kPa. This approach was based on our hypothesis that high contact pressure was uncomfortable, and was more uncomfortable if a large area of the body was at that high pressure.

In all three cases the hypothesis is that discomfort perception is directly proportional to the calculated metric.

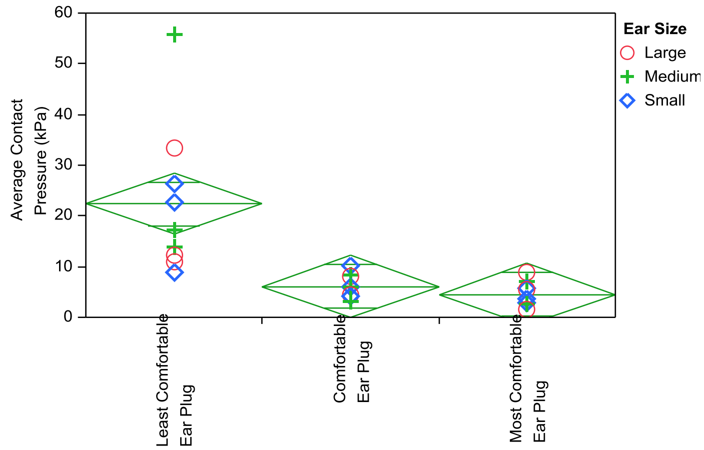

Figure 7. Average Contact Pressure for all three ear plugs from least to most comfortable showing a negative correlation between discomfort and average contact pressure.

All three of the ear plugs were measured in use tests where subjects were asked to rate ear plug comfort. The comfort studies were conducted on separate populations at separate times and were not drawn from the same population of people used to generate the ear geometry data. This eliminated the need to conduct a special study where subject variability was controlled. The assumption was made that subject to subject variability was small compared with differences between products. The fact that comfort ratings were not measured in the same study on the same subjects prevented absolute measurements of comfort ratings. The approach was chosen therefore to simplify ear plug comfort rating into an ordinal variable; most comfortable, middle, and least comfortable. A successful predictive model then would be capable of ranking the products in the same order.

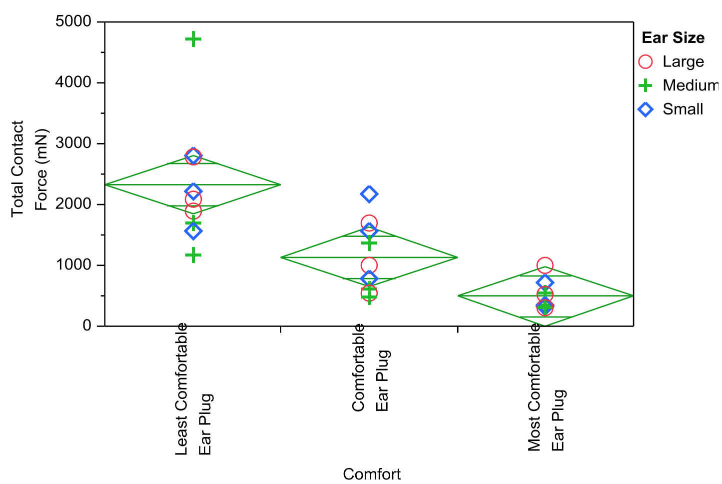

Figure 8. Total contact force for all three ear plugs from least comfortable to most comfortable. A strong negative correlation exists between total contact force and ear plug discomfort.

The average contact pressure and the average contact force both show the desired correlation as shown in Figures 7 and 8. Others have found similar correlations between contact pressure and discomfort, (Morris, 1981), (Denton, 1971). Average contact force also had a strong correlation with discomfort. This is in part due to the fact that pressure is calculated as the force per unit area and the contact areas didn't differ significantly between products as shown in figure 9.

Interestingly the size of the subject's ear canals as determined by the audiologists did not impact the total contact area in any discernable way. The differences between small, medium, and large ear canals didn't have an impact on any of the measured output parameters; total contact force, average contact pressure, or total contact area.

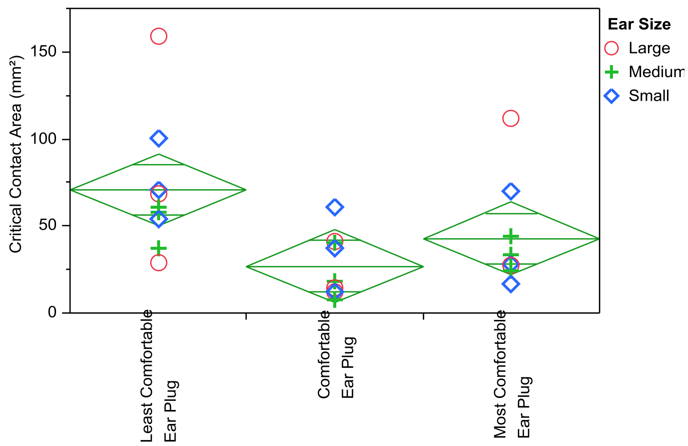

Figure 9. Chart showing poor correlation between the total surface area that was at a pressure above 25kPa and the perception of discomfort.

The hypothesis that discomfort was related to the contact area that was greater than a 'critical pressure' of 25kPa was not supported by the data. The data graphed in figure 9 shows the critical contact area for each of the three different ear plugs on each subject.

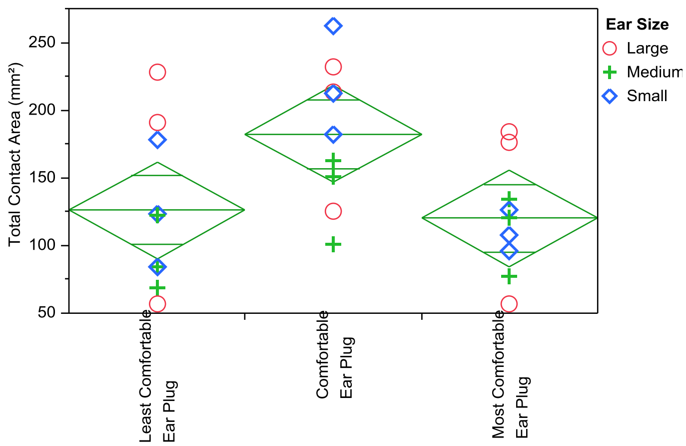

Figure 10. Relationship between ear plug comfort and total contact area is insignificant. There was also no discernable correlation between ear size as rated by an audiologist and the total contact area of the ear plugs.

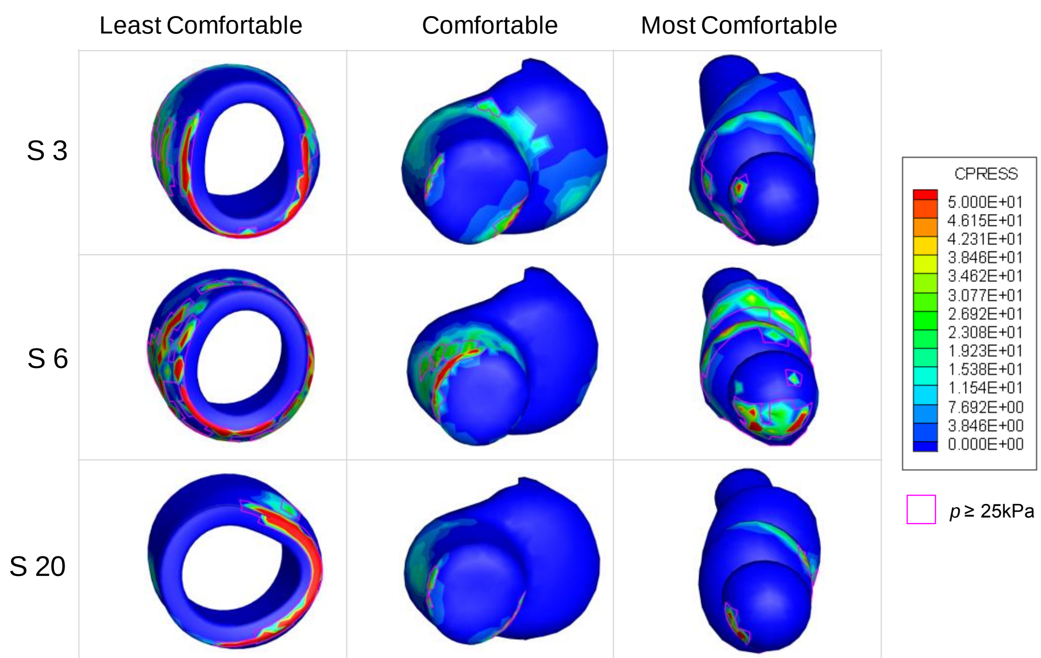

Figure 11. Examples of contact pressure contours on deformable portion of the ear plugs. Each row is data from a different subject (s3, s6, and s20). Contact Pressure is shown in kPa. The pink outline shows the 25kPa boundary.

A subset of the model results is shown in Figure 11. The colors represent contact pressure and demonstrate the differences between subjects. In the figure each row is data from the same subject ear geometry. The least comfortable product (left column) shows large zones where contact pressure is at or above 50kPa. Note the differences in location of high pressure regions.

5. Conclusions

This initial modeling work has demonstrated that it is reasonable to assume that a model like the ones shown here can be used to predict user discomfort of ear plugs. Additional work should be conducted to include a wide range of hearing protection devices and to conduct a use study that includes these products so an absolute measure of comfort can be made. Several aspects of this work were demonstrated to be successful while improvements should be made in others.

5.1 Recommended Improvements

The use of the 3DMD scanning system to measure the insertion distance and angle for each of the ear plugs was a successful approach to generating input parameters for the model. This method however requires physical versions of the ear plugs to be tested on actual ears. An ideal development tool would use some other method. It is recommended that future work be done to determine sensitivity to insertion angle and to determine whether an insertion force rather than a fixed insertion distance is equally accurate.

There was no evidence that ear canal size as determined by a trained audiologist provided any additional information about the subject. The intent of choosing three each of small, medium, and large ear canal geometries was to help provide a uniform population. Additional work should be done to identify more appropriate method for selecting representative geometries.

Discomfort due to contact pressure is likely dependent on not only the absolute magnitude of the pressure but also the location of that pressure. Future work should consider this as a possible way of improving the predictive power of the model.

Contact pressure and contact force are continous variables whereas comfort ratings in use studies are typically ordinal. Ordinal regression models are well suited to provide statistical correlations for this type of data. Future work should investigate this as a way to improve predictive power of the overall model.

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