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Finite Element Model Analysis of Cephalic Trim on Nasal Tip Stability

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Abstract

IMPORTANCE—Alar rim retraction is the most common unintended consequence of tissue remodeling that results from overresection of the cephalic lateral crural cartilage; however, the complex tissue remodeling process that produces this shape change is not well understood.

OBJECTIVES—To simulate how resection of cephalic trim alters the stress distribution within the human nose in response to tip depression (palpation) and to simulate the internal forces generated after cephalic trim that may lead to alar rim retraction cephalically and upward rotation of the nasal tip.

DESIGN, SETTING, AND PARTICIPANTS—A multicomponent finite element model was derived from maxillofacial computed tomography with 1-mm axial resolution. The 3-dimensional editing function in the medical imaging software was used to trim the cephalic portion of the lower lateral cartilage to emulate that performed in typical rhinoplasty. Three models were created: a control, a conservative trim, and an aggressive trim. Each simulated model was imported to a software program that performs mechanical simulations, and material properties were assigned. First, nasal tip depression (palpation) was simulated, and the resulting stress distribution was calculated for each model. Second, long-term tissue migration was simulated on conservative and aggressive trim models by placing normal and shear force vectors along the caudal and cephalic borders of the tissue defect.

RESULTS—The von Mises stress distribution created by a 5-mm tip depression revealed consistent findings among all 3 simulations, with regions of high stress being concentrated to the medial portion of the intermediate crus and the caudal septum. Nasal tip reaction force marginally decreased as more lower lateral cartilage tissue was resected. Conservative and aggressive cephalic trim models produced some degree of alar rim retraction and tip rotation, which increased with the magnitude of the force applied to the region of the tissue defect.

CONCLUSIONS AND RELEVANCE—Cephalic trim was performed on a computerized composite model of the human nose to simulate conservative and aggressive trims. Internal forces were applied to each model to emulate the tissue migration that results from decades of wound healing. Our simulations reveal that the degree of tip rotation and alar rim retraction is dependent on the amount of cartilage that was resected owing to cephalic trim. Tip reaction force is marginally reduced with increasing tissue volume resection.

LEVEL OF EVIDENCE—NA.

Cephalic trim is an effective method for reducing bulk in the nasal tip. This technique has been used by generations of rhinoplasty surgeons, and its short- and long-term complications are sufficiently characterized. Alar rim retraction is the most common unintended consequence of tissue remodeling that results from overresection of the lateral crural cartilage[1,2]; however, the complex tissue remodeling process that produces this shape change is not well understood.

The commonly accepted practice guidelines posit that a complete lateral crural strip of 6 to 8 mm must be retained to optimize aesthetic and functional outcomes. These figures are derived from decades of astute observation and clinical experience,[3–5] but, to our knowledge, objective analysis via a structural mechanical model has yet to be achieved. Resection of the cephalic portion of the lower lateral cartilage creates a volume defect, which the surrounding soft tissue will remediate during the next several decades. The lower lateral cartilage is a structure sandwiched between the skin and soft-tissue envelope that provides stability and shape to the alar lobule or lateral nasal tip. The size of the lower lateral cartilage is often large and creates aesthetic deformities, so the cephalic portion of

this cartilage is variably resected (Figure 1). If the resected volume of tissue is excessive, localized tissue remodeling and contraction during the lifetime of the patient results in alar rim retraction and increased rotation of the nasal tip (Figure 1). The alar rims surround the nostril aperture (entry to the nose), and their retraction is generally not an acceptable or desired outcome of tip rhinoplasty and is usually considered a complication. Aggressive cephalic trim can also lead to upward rotation of the nasal tip (Figure 1). Understanding how these internal forces produce shape change over time is important to achieve an optimal aesthetic and functional surgical outcome.[6]

A previous study[7] from our laboratory reported the use of a computational model with the finite element method to estimate how stress is distributed within the soft tissues of the nose, lower lateral cartilages, and caudal septum during nasal tip depression. This study represents a step forward from previous work performed in our laboratory using a finite element model (FEM) to estimate internal stress distribution in the lower lateral cartilage when a load is placed on the nasal tip.[8] Structural analysis reveals how stress is distributed and how tissue geometry changes when subjected to a deformation or load. With the use of a multicomponent FEM (soft tissue, cartilage, bone), it may be possible *in silico* (via computer simulation) to estimate what might occur long term in the nasal tip after performing common rhinoplasty maneuvers. In this study, FEM was used to simulate how resection of the lateral crural cartilage alters the stress distribution within the human nose in response to tip depression (palpation). More important, we explore how internal forces generated after cephalic trim may lead to alar rim retraction cephalically and upward rotation of the nasal tip.

Methods

Creation of Cephalic Trim Models

This study was performed in accordance with the guidelines of the institutional review board at the University of California, Irvine. Informed consent was not required. The multi-component FEM was derived from maxillofacial computed tomography of a healthy patient undergoing rhinoplasty with 1-mm axial resolution. From these data, bone, skin and soft-tissue, and cartilage components (Figure 2) were constructed as described previously.[7] Of note, there is a significant deviation of the caudal septum to the right. The 3-dimensional editing function in Mimics (Materialise NV) was used to trim the cephalic portion of the lower lateral cartilage to emulate that performed in typical rhinoplasty. Three models were created: a control, a conservative trim, and an aggressive trim (Figure 3). Lateral crural width for the control model was 8 mm, measured in the typical fashion where a line is drawn perpendicularly to the caudal border of the lateral crus of the alar cartilage. For the conservative trim model, a 2-mm cephalic resection was performed and a lateral crural width of 6 mm was retained to simulate a typical resection in rhinoplasty. For the aggressive trim model, a 4-mm cephalic resection was performed to simulate the consequences of overresection, for which the clinical outcomes are widely known (ie, alar retraction).[3–5]

Material Properties Assignment

The FEMs were constructed in COMSOL Multiphysics software (COMSOL Inc) and assumed linear elastic properties for skin (density = 980 kg/m^3, Young modulus = 0.5 MPa, Poisson ratio = 0.33), cortical bone (density = 1900 kg/m^3, Young modulus = 15 GPa, Poisson ratio = 0.22), and cartilage (density = 1080 kg/m^3, Young modulus = 0.8 MPa, Poisson ratio = 0.15).[7] Physical properties of skin, including the mass density and Poisson ratio, were approximated and applied to the soft-tissue envelope. Articular cartilage mechanical properties were used in this model because of the sparse information and limited quality of the data on the mechanical properties of facial cartilage.

The tissue dead space that resulted from the resected lower lateral cartilage was assigned specific material properties for the 2 simulations: (1) nasal tip depression (palpation) and (2) long-term effects of tissue migration over time. To simulate the immediate postoperative effect of cephalic trim on nasal tip palpation, we assigned the resected tissue volume very soft material properties (density = 980 kg/m^3, Young modulus = 0.01 Pa, Poisson ratio = 0.33). To simulate tip rotation and alar rim retraction years after cephalic trim, the resected tissue volume was assigned material properties slightly softer than what was assigned for cartilage (density = 980 kg/m^3, Young modulus = 0.05 MPa, Poisson ratio = 0.3).

Calculation of Stress Distribution Resulting From Simulated Nasal Tip Compression

To simulate a mechanical tip depression test (palpation) routinely performed by surgeons, an approximate 1-cm^2 region at the surface of the nasal tip (Figure 4) was prescribed a displacement of 5 mm in the posterior direction. The bone in the model was held fixed while the cartilage and overlying skin were free to move. The resulting von Mises stresses of the model were calculated to identify key load-bearing and displaced regions for each anatomy. von Mises stress is a scalar value that combines the x, y, and z components of stress into one value that can be compared to the yield stress of the material. This calculation allows us to determine whether the material will yield or fail at a particular location in response to a given load or displacement. A value of 180 kPa was used as the cartilage yield stress to compare with the stresses generated by the computer models.[9] In addition, the nasal tip reaction force (the force generated in the tissue that counters depression) in the same axis opposing tip depression was calculated.

Simulation of the Consequences of Wound Healing After Cephalic Trim

Throughout this article, any reference to *wound healing* refers to the simulation of the steady-state outcome of the cumulative effects of internal forces over time that cause tissue contraction. To simulate the cumulative effects of wound healing (or tissue contracture, ie, alar rim retraction and increased nasal tip rotation) on nasal shape decades after surgery, normal and shear forces were prescribed on the caudal and cephalic borders of the defect created by resection of the cephalic portion of the upper lateral cartilage (Figure 1). These force vectors were intended to emulate the natural tissue-healing process during which localized tissue contraction occurs to "close" the volume defect[10] (ie, retraction of alar rim and rotation of nasal tip cephalically). So the progression of this shape change can be observed, a range of forces was applied individually starting from 0N and incrementing 1N to 10N, resulting in 11 simulations per model. For example, the first simulation used a 1N

force, the next simulation used 2N, and so on. The resulting distribution of von Mises stress was calculated along with equilibrium strain. The geometric changes in the model are tracked at discrete locations (Figure 4).

Results

Stress Distribution and Tip Reaction in Response to Nasal Tip Palpation After Cephalic Resection

The von Mises stress distribution created by a 5-mm tip depression revealed consistent findings among all 3 simulations, with regions of high stress being concentrated to the medial portion of the intermediate crus and the caudal septum (Figure 5). An increase in peak stress and a marginal decrease in nasal tip reaction force were noted as more lower lateral cartilage tissue was resected (Table 1). This finding makes sense because there is a smaller force required to obtain the same 5-mm tip compression after cartilage resection (ie, there is less tip support after cartilage depression).

Simulation of Alar Rim Retraction After Overresection of Cephalic Cartilage

Conservative and aggressive cephalic trim models produced some degree of alar rim retraction and tip rotation, which increased with the magnitude of the force applied to the region of the tissue defect (Figure 1). The changes to the cartilage peak stress, tip rotation, tip displacement, and alar displacement as a result to 10N of applied tissue force are listed in Table 2 along with the defect volume and surface area of applied force. Of note, the right alar rim shifted upward more than the left alar rim in both experimental models (eFigure 1 and eFigure 2 in the Supplement). This asymmetric displacement of each alar rim is attributed to a small right caudal septal deviation present in this individual's nasal septum.

The cartilage von Mises stresses with 10N applied to the caudal and cephalic borders of the volume defect are shown in Figure 6. Both models exhibit stress concentration along the border of the volume defect and where the cephalic border of the upper lateral cartilage meets the nasal bone. The stress in the cartilage in the conservative trim model localized around the volume defect with a peak of 1.5 MPa (Figure 6). A profile view of the stress distribution along with the change in rotation is illustrated in Figure 6 and eFigure 3 and eFigure 4 in the Supplement.

We observed the stress distribution change with both the aggressive cephalic trim and elevation of stress along the columella. Stress was reduced surrounding the volume defect and increased near the medial crura footplates, with the highest concentration at the anterior nasal spine (Figure 6). As expected, this is the fulcrum or pivot point around which the tip rotates. Of the alar cartilage footplates, stresses above 125 kPa can be seen on the left side of the cartilage, which is contralateral to the side of the nasal septum deviation (Figure 6). This simulation produced greater tip rotation (Figure 6).

The overall movement of the nose can be seen in Figure 7. In both simulations, the displacement is to the right side toward the side of the septal deviation. A conservative trim preserving an alar cartilage width of 6 mm produced up to 1.6 mm of soft-tissue displacement (Figure 7). Alar rim displacement was observed. The overall displacement, as

seen in the conservative trim model, was more pronounced in the aggressive trim simulation with displacement of the rim and, most notably, in the nasal tip, with a peak displacement of to 3.85 mm (Figure 7).

Discussion

Rigorous, objective analysis on the effects of various rhinoplasty maneuvers is nearly impossible to perform directly on patients when experimental design is constrained by the extremely long intervals during which change in nasal shape occurs in the short and long terms. Each year, new and innovative techniques are developed, refined, and then widely adopted, only to be rejected years, if not decades, later because the long-term consequences appear most often as the result of progressive tissue remodeling and contracture throughout decades. Estimating long-term outcomes is at best guesswork. However, the use of the FEM may provide a means to more clearly estimate equilibrium shape change by simulating the effect of the wound-healing process. The FEM isused across the industry to predict how a physical structure will respond to various stress and shearing forces and routinely is used to model deformation, fatigue, and failure. We have revealed the potential of FEM use to analyze the mechanical consequences of various surgical maneuvers and also simulate how the internal forces generated by long-term tissue remodeling and wound contracture may produce shape change. In this study, simulation of long-term macroscopic changes after conservative and aggressive cephalic trim was successfully modeled.

The present FEM builds on concepts introduced in earlier work by others who used modeling to predict the structural and functional outcomes of various nasal and rhinoplasty maneuvers.[11–14] In this study, cephalic trim was selected for examination because the long-term clinical consequences are widely known and understood. Hence, there is a qualitative means of validating the present model. As shown in Figure 6, Figure 7, eFigures 1 through 4 in the Supplement, and Table 2, the simulation demonstrated that increasing amounts of resection produced greater upward displacement of the alar rim and nasal tip.

As a means of assessing how nasal tip support is affected by cephalic trim, a 5-mm posterior displacement of the nasal tip was simulated to mimic nasal tip depression (palpation). The resulting changes in stress distribution and nasal tip reaction force were calculated to detect differences in each simulated model. Although the stress distribution was consistent throughout all simulations, the regions of high stress were located at the intermediate crura and caudal septum. Consistent with clinical observation, there was a marginal decrease in the nasal tip reaction force (the force generated in the tissue that counters depression) that corresponded with the amount of cartilage that was resected at the scroll region. There was a 1% and 3% decrease in nasal tip reaction force of the conservative and aggressive trim models, respectively (Table 1).

Detailed simulation of the wound-healing process at a macroscopic level has received limited attention in the literature.[10,15–17] There is sparse information with respect to (1) time-dependent evolution of force across a healing surgical incision, (2) the magnitude of these forces as a function of time, and (3) the way these changes alter tissue mechanical properties locally and at a distance over time. Hence, experimental data are inadequate to

simulate true wound healing. However, with respect to the cephalic trim maneuver, a massive body of clinical data delineate the long-term steady-state changes. It is known that contraction occurs perpendicularly to the long axis of the volume defect, resulting in alar retraction and upward rotation of the nasal tip. From this motion, the direction of the force vectors can be inferred, and from clinical observation, the amount of displacement at steady state is known as well (20-30 years of wound healing). Hence, in the model, force vectors in the direction of contracture can be created *in silico* and allowed to act until equilibrium is achieved (Figure 4). No assumptions are made with respect to the time dependency of this process, and again linear isotropic tissue behavior is assumed. Obviously, mechanical properties change over time, and isotropy is a broad assumption; however, we understand that these are limitations of the model and believe that information obtained from these simulations can inform clinical understanding. The focus of this simulation is on the cumulative effect of these internal forces over time and the general trend with respect to shape change. With the increase of open structure rhinoplasty, many maneuvers have been neither performed broadly nor evaluated for decades, and the long-term outcomes are not known. This approach provides a means to potentially estimate these outcomes.

The interpretation of the results of our FEMs has certain limitations. As discussed previously, we assumed linear isotropic behavior to simplify our model and for practical analysis. Although modeling the viscoelastic behavior of soft tissue and cartilage would better emulate natural tissue, it adds significantly more complexity to the modeling process and is even more challenging in the setting of sparse or nonexistent values for material properties of these tissues. Next, determining where cartilage would undergo plastic deformation is difficult without having an accurate value for the cartilage yield stress. Because of the limited information on the yield stress of facial cartilage, we used a porcine articular cartilage as an approximation and for the sake of comparison.[9] As such, the regions above 180 kPa in Figure 5 and Figure 6 would undergo plastic deformation. We hope a more accurate yield stress value of nasal cartilage will be elucidated to enhance the applicability and validity of the FEM simulations in the future. Last, we are limited by the paucity of experimental data to validate our computer models. Although it is beyond the scope of this study, our laboratory also aims to validate the computerized model with a physical phantom starting with 2 materials to approximate soft tissue and bone.

Of note, simulation of tissue migration secondary to wound healing for conservative and aggressive resections resulted in a slightly larger alar rim retraction on the patient's right side. This asymmetry results from the rightward deviation of this patient's caudal septum. This finding was consistent throughout all simulations and is a limitation of creating a model from this patient's true anatomy. Our laboratory aims to develop an ideal model with symmetric geometries although the departure from true anatomy may limit its translatability to the clinical setting. Nonetheless, we believe ideal models of a leptorhine or platyrhine nose will be informative in their own right and compared with our present model as well.

The use of computer models in the analysis and development of new rhinoplasty maneuvers and techniques may provide a means to estimate long-term effects provided that the regions where tissue remodeling occurs can be accurately prescribed. Ongoing research in our

laboratory is focusing on validation of our FEM simulations with the use of a composite model of the nose.

Conclusions

The FEM can be used to simulate tip depression and mimic tissue migration due to cephalic trim. Tip reaction force is marginally reduced with increasing tissue volume resection. Our models indicate that a minimum width of lower lateral cartilage is necessary to minimize tip rotation and alar rim retraction. This form of analysis has the potential to elucidate the effects of other rhinoplasty maneuvers on nasal tip mechanics. Through the use of FEM analysis, our structural simulations will inform the surgeon how the mechanics of the nasal tip are affected by structural changes to the lower lateral crura.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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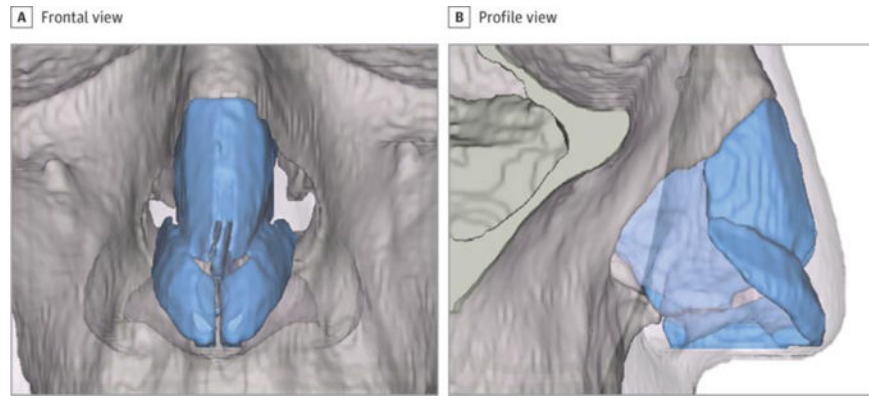
Figure 1. Control Finite Element Model of the Human Nose
Gray indicates bone; light blue, cartilage, and semitransparent, soft tissue.
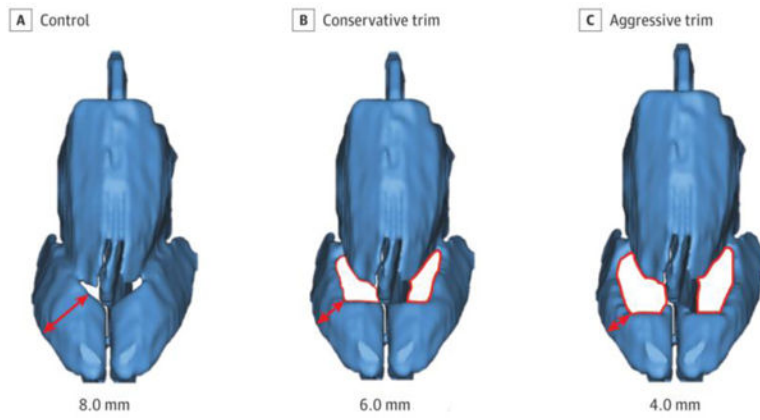
Figure 2.
Frontal View of Simulated Resection of Cephalic Lower Lateral Cartilage
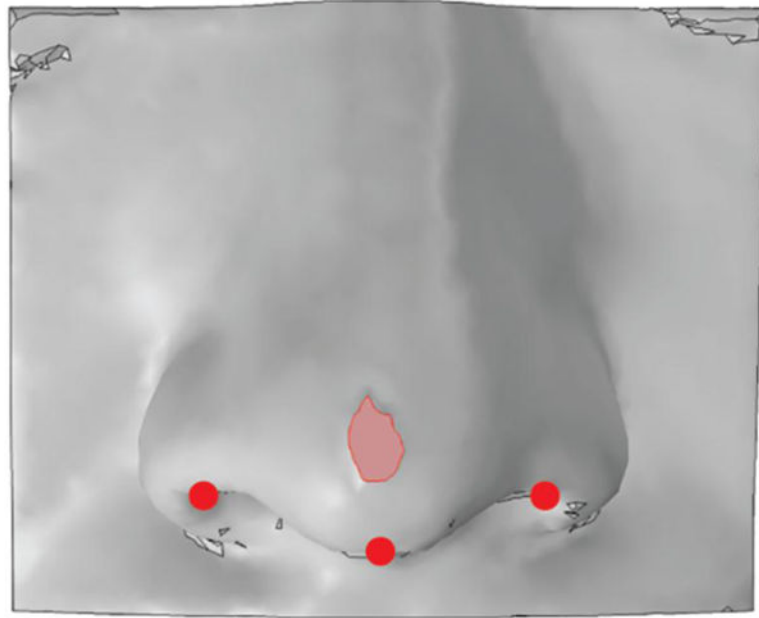
Figure 3. Area of the Tissue Being Depressed and Points to Measure Nasal Tip Movement
Pink region indicates surface area where the displacement was prescribed for nasal tip depression. Red dots indicate points on the alar rim and nasal tip where displacement is recorded and its data are used to calculate tip rotation.
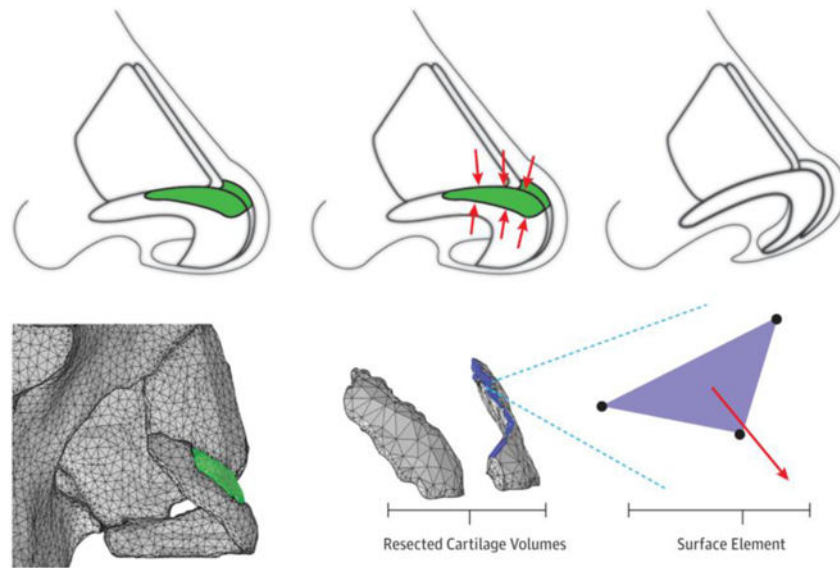
Figure 4. Simulating the Movement of the Nose Decades After a Cephalic Trim
Top row: Green region marks the resected portion of cartilage. Red arrows indicate direction of migration of surrounding tissue. Last image in the top row is the net finding after decades of tissue remodeling, resulting in increased tip rotation and alar retraction. Bottom row: Green region is region of resected cartilage within the model. Superior and inferior edge of resected tissue volume were selected as boundary conditions. So the progression of this shape change can be observed, a range of forces (inward normal forces around the border of the resected tissue volume) was applied individually along these surfaces. The net force vector was normal to the triangular surfaces selected. The dots indicate nodes of the triangular element, and the purple highlighted region is where the stress is applied in minimal and maximal trim models. The dashed blue lines indicate the area of the surface element being described.
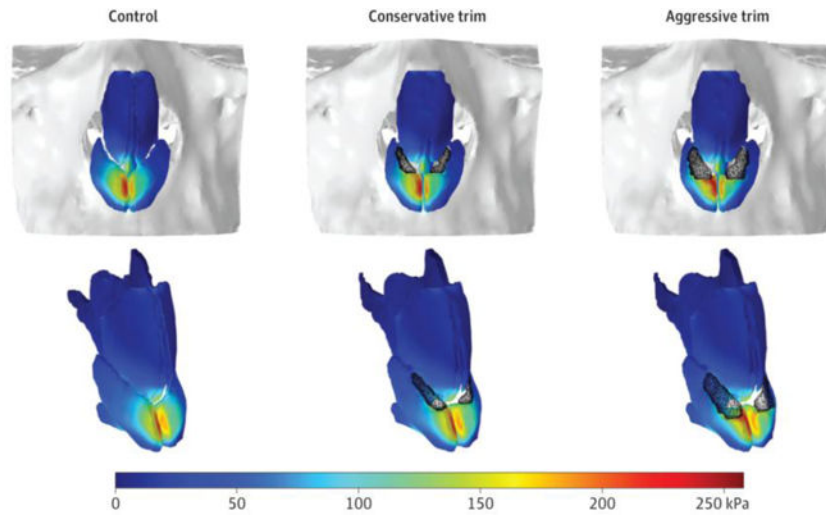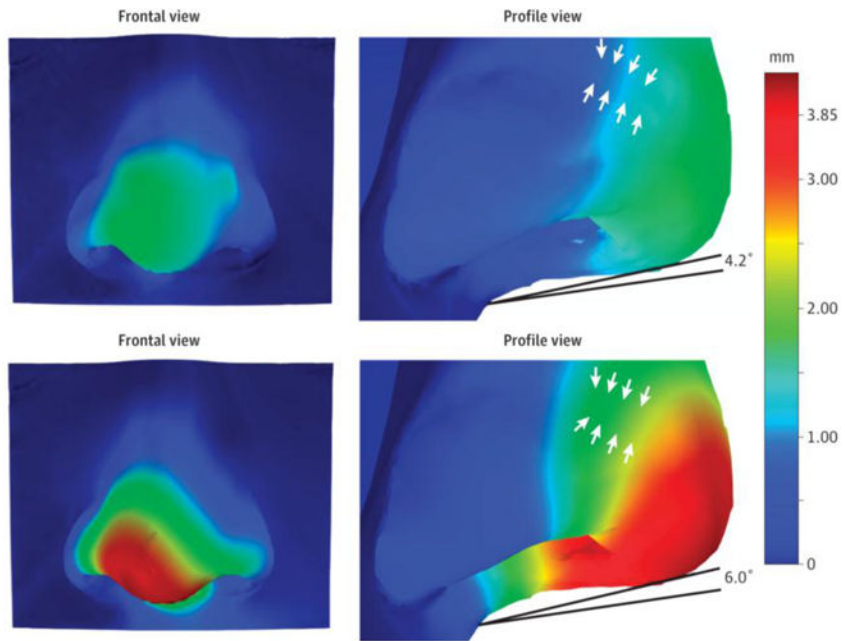
Figure 5.
Stress Distribution in Response to Nasal Tip Depression
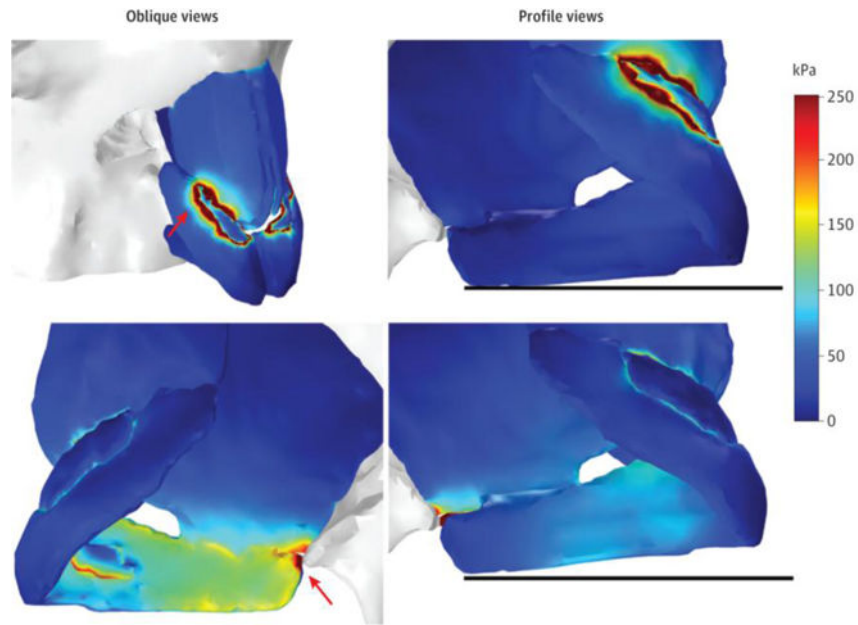
Figure 6. Simulated Tissue Migration of Conservative and Aggressive Trim Models
Oblique views: arrow indicates peak stress of 1.5 MPa (top row) and 1.3 MPa (bottom row) at 10N of tissue retraction force. Profile views: line denotes original location of columella.

Figure 7. Displacement Plot of Simulated Tissue Migration for Conservative and Aggressive Trim Models

A total force of 10N was applied along the caudal and cephalic boundaries of the tissue defect. Lines indicate amount of rotation.

Table 1

Nasal Tip Peak von Mises Stress and Reaction Force in Response to 5-mm Nasal Tip Depression for Each Simulated Model

Model Type	Peak von Mises Stress, kPa	Reaction Force, N	Change of Reaction Force Compared With Control, %
Control model	290	11.82	NA
Conservative trim	329	11.71	1
Aggressive trim	397	11.50	3

Abbreviation: NA, not applicable.

Table 2

Tissue Movement Data of Cephalic Trim Models

Tissue Movement	Control (No Trim)	Conservative Trim	Aggressive Trim
Lateral crural width, mm	8	6	4
Mesh elements, No.	368 423	365 620	367 621
Volume defect, mL	NA	0.03	0.07
Surface area of applied force, mm^2	NA	26	153
Cartilage peak stress, kPa	NA	1455	1079
Tip rotation, °	NA	4.22	6.01
Tip displacement, superior direction, mm	NA	1.16	1.87
Vertical displacement of left alar rim, mm	NA	0.29	0.00
Vertical displacement of right alar rim, mm	NA	0.29	0.74

Abbreviation: NA, not applicable.