

Original Investigation

Estimation of Nasal Tip Support Using Computer-Aided Design and 3-Dimensional Printed Models

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IMPORTANCE Palpation of the nasal tip is an essential component of the preoperative rhinoplasty examination. Measuring tip support is challenging, and the forces that correspond to ideal tip support are unknown.

OBJECTIVE To identify the integrated reaction force and the minimum and ideal mechanical properties associated with nasal tip support.

DESIGN, SETTING, AND PARTICIPANTS Three-dimensional (3-D) printed anatomic silicone nasal models were created using a computed tomographic scan and computer-aided design software. From this model, 3-D printing and casting methods were used to create 5 anatomically correct nasal models of varying constitutive Young moduli (0.042, 0.086, 0.098, 0.252, and 0.302 MPa) from silicone. Thirty rhinoplasty surgeons who attended a regional rhinoplasty course evaluated the reaction force (nasal tip recoil) of each model by palpation and selected the model that satisfied their requirements for minimum and ideal tip support. Data were collected from May 3 to 4, 2014.

RESULTS Of the 30 respondents, 4 surgeons had been in practice for 1 to 5 years; 9 surgeons, 6 to 15 years; 7 surgeons, 16 to 25 years; and 10 surgeons, 26 or more years. Seventeen surgeons considered themselves in the advanced to expert skill competency levels. Logistic regression estimated the minimum threshold for the Young moduli for adequate and ideal tip support to be 0.096 and 0.154 MPa, respectively. Logistic regression estimated the thresholds for the reaction force associated with the absolute minimum and ideal requirements for good tip recoil to be 0.26 to 4.74 N and 0.37 to 7.19 N during 1- to 8-mm displacement, respectively.

CONCLUSIONS AND RELEVANCE This study presents a method to estimate clinically relevant nasal tip reaction forces, which serve as a proxy for nasal tip support. This information will become increasingly important in computational modeling of nasal tip mechanics and ultimately will enhance surgical planning for rhinoplasty.

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The nasal tip is an important structure for the aesthetics and function of the nose. The definition of the nasal tip is often outlined as the region overlying the medial and lateral crura of the lower lateral cartilages.¹⁻⁹ Extensive literature has described the complex nature of nasal tip support; however, most sources cite the seminal descriptions by Tardy and Brown^{1,2} as the most important in identifying the specific contributing support structures. These structures and their contributions to tip support mechanisms are usually evaluated subjectively based on the surgeon's experience and interpretation of the patient's anatomy as described by Tardy.³ Tip support has been variously defined, but most descrip-

tions focus on the intrinsic ability of the nasal tip to counteract the forces of gravity, and in the case of the postoperative nose, the forces of contracture. Tip support is commonly evaluated by depressing the lobule and gauging the *integrated reaction force*, which resists this deformation.

Numerous attempts have been made to quantify the biomechanical properties of the nasal tip. Beaty et al,¹⁰ Wilson et al,¹¹ and Dobratz et al¹² developed tools to measure the reaction force of the nasal tip to displacement before and after rhinoplasty. Gassner et al¹³ developed a rhinomanometric device to calculate nasal tip resilience in cadavers. Other investigators¹⁴⁻¹⁹ have used computational modeling and

finite element analysis (FEA) to model nasal tip mechanics and to estimate the relative contributions of the classic nasal tip support mechanisms.

Finite element analysis allows surgeons to estimate the changes in nasal stress and strain after the application of a load or displacement and can be used to simulate the effects of some rhinoplasty maneuvers.¹⁸⁻²⁰ Finite element analysis can provide estimates of short- and long-term steady state outcomes.¹⁸⁻²¹ For example, applying FEA to study septal L-strut design illustrated the value in enhanced surgical planning.²¹ To our knowledge, no nasal finite element model to date has undergone validation. Validation is needed to determine whether the model is accurate. Modeling involves physical experiments that are in turn used to refine the model. In experiments, the mechanical properties and form factor of phantoms (physical models) can be precisely specified. A validated computational model can be used to interpret data obtained *in vivo*. No physical models have been reported to date that are anatomically accurate and have gross mechanical properties that approximate those of a human nose. This lack of a physical model can now be addressed with the relatively recent emergence of low-cost 3-dimensional (3-D) printing technology that has enabled rapid prototyping by incorporating computed tomographic (CT) imaging data. The first medical application for 3-D-printed prototypes was demonstrated in the construction of common dental implants.²² In rhinoplasty, Kim et al²³ reported the feasibility of 3-D printing to create lower lateral cartilage models with different mechanical properties that could be evaluated by a focus group of surgeons prompted to identify the ideal cartilage stiffness. This focus group method has also been used to identify ideal mechanical properties (eg, stiffness) for columellar, lateral crural strut, and L-strut replacement grafts.^{23,24}

No studies, to our knowledge, have compared surgeons' qualitative assessments of tip support with actual mechanical behavior. In addition, no minimum and ideal requirements for good tip support of the nose have been quantified, let alone posited, among different rhinoplasty surgeons. In this study, we demonstrate the use of 3-D printing to create silicone nasal models and survey rhinoplasty surgeons to gauge the adequacy of tip support. Our objective is to identify the specific mechanical parameters for minimum and ideal nasal tip support.

Methods

Design

We used a single CT scan and a computer-aided design program (3-D Slicer open-source software) to generate a digital nasal model (Figure 1) as previously described.^{14,15} The patient was a woman of northern European descent with classic facial and nasal features, a relatively thin skin-soft-tissue envelope, and near ideal projection and rotation as outlined by Ahmed et al.²⁵ This study was approved by the institutional review board of the University of California, Irvine, School of Medicine, and all participants provided oral informed consent.

Key Points

Question What are the minimum and ideal mechanical properties associated with nasal tip support?

Findings In this survey of 30 rhinoplasty surgeons, the estimated minimum thresholds for the Young modulus for adequate and ideal tip support were 0.096 and 0.154 MPa, respectively. The estimated thresholds for the reaction force associated with the absolute minimum and ideal requirements for good tip recoil were 0.26 to 4.74 N and 0.37 to 7.19 N, respectively, during a 1- to 8-mm displacement.

Meaning This method estimates clinically relevant nasal tip reaction forces, which serve as a proxy for nasal tip support.

To create the physical model, the bone and soft-tissue components underwent 3-D printing (Replicator; MakerBot) in acrylonitrile butadiene styrene plastic. The printed model of the nasal soft tissue was converted into a negative mold made of silicone (Smooth-On, Inc) that formed a hollow cavity corresponding to the nasal soft-tissue structures. The soft-tissue component of our model was created by pouring different mixtures of silicone into the negative mold to create a range of different nasal tip stiffnesses (Figure 2). The stiffness of each model was controlled by adding a silicone fluid thinner (Smooth-On, Inc) with the standard silicone mixture to interfere with cross-linking of the silicone in varying degrees. The models were then allowed to cure for 12 hours. All models had identical bone and soft-tissue form factors, differing only in the elastic modulus of the polymer component that constituted the soft tissue (eFigure in the Supplement).

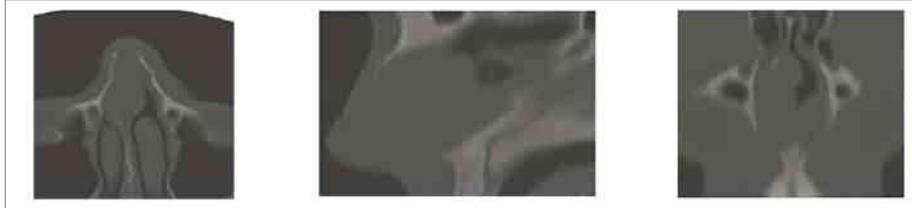
The elastic modulus of the silicone used ranged from 0.042 MPa for nose 1 to 0.086 MPa for nose 2, 0.098 MPa for nose 3, 0.252 MPa for nose 4, and 0.302 MPa for nose 5. Owing to the complex shape of the nose, performing accurate measurements of the modulus by directly measuring stress and strain was not possible. Therefore, mechanical testing was performed on uniform rectangular specimens (9 × 9 × 90 mm) cast from the identical silicone mixture used in each individual model. The elastic (Young) modulus is an intrinsic material property that is independent of a model's shape. Tensile testing (Enduratec ElectroForce 3200; Bose) was used to generate stress-strain curves and thus calculate the Young modulus as previously described.²⁴ To estimate the tip support of each model, we measured the reaction force associated with tip displacement. Each model was placed on a load cell platform, and a cylindrical plunger (diameter, 15 mm; length, 45 mm) was aligned vertically over the nasal tip (Figure 3). The force on the load cell platform was recorded during a 0- to 8-mm depression of the nasal tip performed at 0.25 mm/s. This reaction force to deformation was used to evaluate the nasal tip recoil force and was used as a proxy for a surgeon's concept of nasal tip support.

Participants

A group of 30 surgeons evaluated all 5 models at a regional rhinoplasty course on May 3 to 4, 2014. All participants were board certified in otolaryngology or plastic surgery, and 19 of 30 had

Figure 1. Creation of a Digital Nose Model From an Individual Computed Tomographic (CT) Scan

A Acquisition of CT scan



B Segmentation of CT scan



C Composite digital model



After acquisition of the CT scan, a computer-aided design program (3-D Slicer) is used to segment the bone and soft-tissue components. Addition of the bone and soft-tissue volumes is used to render the composite digital model.

Figure 2. The Silicone Casting Process

A Application of silicone



B Silicone soft-tissue mold



C Printed bone and soft tissue



D Final model



A, Silicone is poured over printed nasal soft tissue. B, After silicone has set for 12 hours, the printed nasal soft tissue is removed from the negative mold. C, Silicone of the desired stiffness is poured into a sealed negative mold, and then

the casted silicone is removed and placed on the printed nasal skeleton. D, A complete nasal model.

Figure 3. Nose Model Undergoing Reaction Force Testing



The nasal tip was depressed by cylindrical plunger (CP) while on a platform paired to a load cell (LC) to determine reaction force to nasal tip depression.

completed an American Academy of Facial Plastic and Reconstructive Surgery fellowship. Each surgeon indicated their years in practice and their self-described competency in rhinoplasty (novice, intermediate, advanced, or expert). Each surgeon was surveyed individually and was blinded to the results of other participants. Each surgeon was presented with all nasal models simultaneously and asked to palpate the nasal tip as if evaluating a patient's nose. Subsequently, they were asked to select which models satisfied their absolute minimum and ideal requirements for good nasal tip support. Each surgeon was told that their choices would be used to gauge the minimum and ideal tip recoil in the model nose and that they should make the assessment independently of any planned surgical procedure. The surgeons were told the nose represented a near ideal nose based on its shape and form factor.

Statistical Analysis

We calculated the Fleiss κ statistic to assess the interrater reliability among the evaluating surgeons. Using the survey data, the degree of acceptability was calculated for each model. A binary logistic regression with categories of mechanically acceptable and unacceptable was used to estimate the threshold for the absolute minimum and the ideal requirements for nasal tip support. The data were best fit to a logistic equation curve for each category in the form of $p(x) = 1/(1+e^{-(a+bx)})$, where $p(x)$ represents the probability of x (a given elastic modulus) being considered mechanically acceptable; a and b are constants in the logistic curve equation; and e is the mathematical constant. The thresholds for absolute minimum and ideal stiffness for nasal tip support were determined at a 50% acceptability rating based on the 30 survey responses. This same method was used to estimate the threshold for the absolute minimum and ideal requirements for the reaction force associated with good nasal tip recoil. The only difference was that, owing to the complex geometry of the nose, stress and strain were not calculated, and we used the force-displacement curves to represent the integrated responses of the nose models. A logistic curve was calculated based on the reaction force to vertical depression (newtons per millimeter). These forces are inherently dependent on the form factor of the nose models.

Results

Of 30 respondents, 4 surgeons had been in practice for 1 to 5 years; 9 surgeons, 6 to 15 years; 7 surgeons, 16 to 25 years; and 10 surgeons, 26 or more years. Six surgeons trained exclusively in otolaryngology. Nineteen surgeons trained in otolaryngology and completed a facial plastic surgery fellowship. One surgeon trained in otolaryngology and plastic surgery and 4 surgeons trained in plastic surgery only. Seventeen surgeons considered themselves in the advanced to expert skill levels. Thirteen surgeons considered themselves in the novice and intermediate skill levels. When asked to select which model satisfied their absolute minimum requirement for good nasal tip support, 12 surgeons selected model 2, 17 selected model 3, and 1 selected model 4. When asked to select which model satisfied their ideal requirement for good nasal tip support, 1 surgeon selected model 2, 16 selected model 3, and 13 selected model 4. The Fleiss κ values of 0.74 and 0.77 indicated a high level of interrater reliability among the surgeons' responses. The threshold for the elastic modulus of the absolute minimum requirement for good nasal tip support was 0.096 MPa. The threshold for the elastic modulus for the ideal requirement of nasal tip support was 0.154 MPa. The thresholds calculated based on the surgeon's skill level are displayed in **Figure 4**. The reaction force curves of all 5 models to tip depression are shown in **Figure 5**. The threshold for the reaction force of the absolute minimum requirement for good tip recoil was 0.26 to 4.74 N for a 1- to 8-mm displacement. The threshold for the reaction force of the ideal requirement for good tip recoil was 0.37 to 7.19 N for a 1- to 8-mm displacement. We found no significant differences between the

thresholds selected based on the surgeon's skill level or number of years in practice ($P > .05$).

Discussion

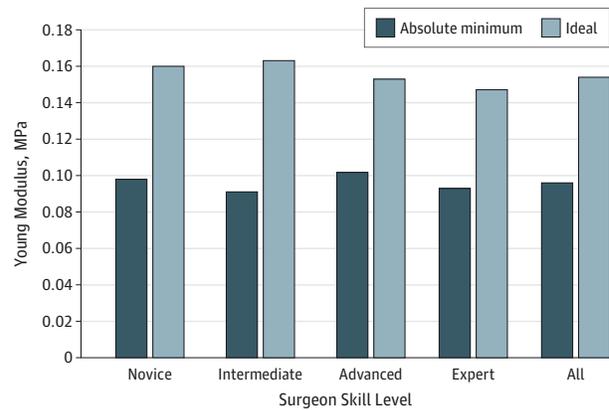
Our study demonstrates that 3-D-printed nasal models can be used to quantify the minimum and ideal requirements for nasal tip support. Our study also examined whether any differences were based on skill level, but we did not find any statistically significant difference ($P > .05$) in the thresholds selected based on this parameter. However, we found that more of the advanced and expert surgeons identified a lower threshold value for their requirement for good tip support. This finding may reflect a propensity for more junior surgeons to make more conservative selections.

Previously, the approach used herein has been applied to only simple structures, and this study represents the progression from rectangular slab to crural model to intact nasal model.^{23,24} This approach also provides a link between experimental measurements or modeling and the rhinoplasty surgeon's evaluation of nasal tip support. The force or recoil to palpation that surgeons perceive is difficult to quantify. The force is also difficult to measure in vivo because the nose is a composite structure, is anisotropic in mechanical behavior, and consists of nonlinear viscoelastic material with an irregular geometry. In clinical settings, surgeons also compress the tip with variable strain rates and displacements.

Standardization of these elements of the physical examination between surgeons is extremely difficult. Some work in this area has been performed. Beaty et al,¹⁰ Dobratz et al,¹² and Wilson et al¹¹ were able to measure this reaction force to displacement using novel devices. Beaty et al¹⁰ found that 35.54, 61.24, and 89.40 g were required to displace the nasal tip 1, 2, and 3 mm, respectively, along the vector of the columella. Dobratz et al¹² found that 25 and 50 g were needed to depress the nasal tip approximately 1 and 2 mm, respectively. Wilson et al¹¹ found that a mean of 1.0 to 3.4 N were needed to compress the nasal tip of a fresh-thawed cadaver from 0.5 to 2.5 mm, respectively. Our models' recoil forces were measured in newtons and converted to grams using Earth's gravitational constant (9.807 m/s^2) to enable comparison to the measurements of Beaty et al¹⁰ and Dobratz et al.¹² Our series of models required 0.09 to 0.66 N (10-67 g) to be displaced 1 mm, 0.34 to 2.03 N (34-206 g) to be displaced 2 mm, and 0.62 to 3.84 N (62-391 g) to be displaced 3 mm. Using logistic regression, the threshold for the force the nasal tip should support for the absolute minimum requirement for good tip recoil was 0.26 N (27 g), 0.78 N (80 g), and 1.41 N (144 g) at 1, 2, and 3 mm of displacement, respectively. The threshold for the force the nasal tip should support for the ideal requirement for good tip recoil was 0.37 N (38 g), 1.13 N (115 g), and 2.07 N (211 g) at 1, 2, and 3 mm of displacement, respectively. Our data overlap with those of Beaty et al¹⁰ and Dobratz et al¹² and are fairly close to those of Wilson et al.¹¹

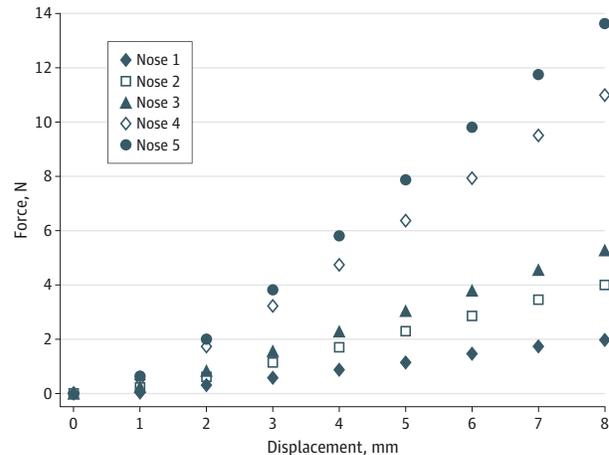
Our data also establish a minimum and ideal requirement for the reaction force associated with good nasal tip recoil. These results provide a tangible sense of the response that a nose with good nasal tip support should elicit. However, in

Figure 4. Young Modulus Selected Based on Surgeon Skill Level



The Young modulus is selected for the absolute minimum and ideal requirements for good nasal tip support.

Figure 5. Reaction Force to Nasal Tip Depression



Reaction force (0-8 mm) is depicted for all 5 nasal models.

humans and in our models, the integrated reaction forces are as much a function of form factor as intrinsic material properties, and thus we should expect some variation. Owing to these complexities of the human nose, conversion of our data into the equivalent of a spring constant did not make sense, because a spring constant would only hold true for the equivalent of a 1-dimensional object such as a piano wire.

In contrast, FEA is another means to examine this same question. Finite element analysis is precise, because the model's structure is derived from patient-specific clinical CT data. Finite element analysis has been used to model complex nasal mechanics and quantify the relative contributions of the classic major nasal tip support mechanisms,¹⁴⁻²⁰ shape change in laser-cartilage reshaping,²⁶ cephalic trim on lower lateral cartilage and nasal tip stability,^{16,18} and the impact of caudal septal resection.¹⁴ The linkage between physician assessment and outcomes derived from FEA can be established using this 3-D-printed rapid prototype approach.²³ This process

opens the possibilities for preoperative detailed computational analysis of the nose before surgery. Recent studies have used computational fluid dynamics to perform virtual simulations on digital 3-D renderings of the nose designed from clinical CT scans.²⁷⁻³⁰ These computational methods have provided a novel means to estimate airway changes in the nose after simulated surgery. An experimentally validated fluid-structure interaction model would serve as a powerful tool for surgeons to better select and design surgical procedures for their patients.³¹

This study extends the work of Kim et al²³ used for evaluating lower lateral cartilage adequacy and applies the same method to the entire nose. Evaluating nasal tip support in vivo is extremely difficult because the investigator must have multiple patients in a setting where a large group of surgeons could examine them quickly. In addition, because each patient has a unique nasal geometry, we cannot control for intrinsic form factor. The integrated reaction forces an examiner's fingertip experiences are a function of form factor and the intrinsic material properties of each component of the nasal tip. These multiple confounding variables that present in vivo make it impossible to derive any reliable conclusions. Using a fresh cadaver as a model allows for more detailed analysis, but the investigator does not have the ability to control the mechanical parameters of the nose, let alone securing fresh (not fresh-frozen and thawed) specimens. By using 3-D-printed phantoms, we were able to control the material properties of the elastomer and maintain a uniform form factor.

Rhinoplasty surgeons traditionally rely on their clinical experience to subjectively assess nasal tip support; however, to our knowledge, no studies have compared the surgeons' expert opinion with actual mechanical behavior. Previous studies that attempted to quantify nasal tip support used patients undergoing nasal surgery, cadavers, or FEA.^{4,6,10-21,32-36} Surgical studies had the limitation of only being able to test a small sample of cartilage that was already being excised from the patient.³²⁻³⁵ Cadaver models have been extremely valuable in showing the main anatomic structures of nasal tip support but do not allow the manipulation of mechanical parameters of human tissue.^{6,10-13,36} Our model has the advantage of being customizable in that the mechanical properties can be specified without disturbing the intrinsic form factor, which allows us to create 5 models with varying stiffness. Our ability to create a customizable 3-D-printed physical model rapidly that allows for manipulation of mechanical parameters further complements what an investigator can perform digitally through FEA. The ability of a surgeon to validate an FEA model quickly with a 3-D-printed physical model will greatly en-

hance the surgeon's understanding of the nose and provide an additional tool to ensure the best outcomes for patients.

Our study has limitations. First, only 30 rhinoplasty surgeons from a wide range of skill levels underwent evaluation. Although the surgeons demonstrated substantial agreement in their responses as reflected by the Fleiss' κ statistics, more robust results might be drawn from a larger sample size biased toward a cohort of advanced and expert surgeons. Second, the silicon model was derived from a CT scan of a patient with classic nasal features, ideal projection and rotation, and a very refined tip with a thin skin-soft-tissue envelope. Because form factor is important in this study, a different nasal shape alone may lead to slightly different outcomes. In addition, our model was a simplified proof-of-concept approach that used only the following 2 components: the nasal skeleton and a lumped-parameter soft-tissue component that represented the skin, cartilage, mucosa, and other soft tissues. The bone component was kept in its printed form of rigid acrylonitrile butadiene styrene plastic and the soft-tissue component was cast in silicone to mimic nasal tissue. Owing to the limitations of our 2-component model, evaluators palpate the nose, and their analysis represents an integrated response to a lumped structure representing the individual soft-tissue and cartilaginous components. With this simplified approach, we demonstrated the feasibility of this modeling technique and its immediate use for mechanical testing. Because the nasal soft-tissue component was modeled in silicone, the interplay among skin, fat, muscle, and cartilage was not represented. Future research will strive to develop more complex models with specific elastomers made to represent the individual nasal cartilages. Although the integrated values that were identified to represent the minimum and ideal requirements for good nasal tip support have limitations, this model is the first in what we believe will be a series of increasingly more complex 3-D-printed models that will better represent the real and unique anatomic structure of the nose.

Conclusions

This novel study attempts to correlate nasal tip support with actual mechanical behavior. We used 3-D printing to create nasal simulacrum that allows for changing overall mechanical behavior while preserving intrinsic form factor. This process allows analysis of mechanical response independent of the object shape. This information will become increasingly important as sophisticated modeling techniques continue to enhance surgical planning.

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