ORIGINAL ARTICLE

Defining Nasal Cartilage Elasticity

Biomechanical Testing of the Tripod Theory Based on a Cantilevered Model

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Objective: To define the modulus of elasticity for nasal septum, auricular, upper lateral, and lower lateral cartilages.

Methods: Prospective enrollment of sequential patients undergoing septorhinoplasty. Test samples were obtained through routine surgical interventions using atraumatic harvesting techniques. The modulus of elasticity was determined using a customized biomechanical testing device. A clinical analysis of nasal tip strength and "ethnic" nasal categorization was performed.

Results: Five sequential patients were enrolled; 4 underwent biomechanical testing of harvested cartilage. All 4 patients were classified as having a leptorrhine nasal architecture. The modulus of elasticity for the lower lateral cartilages was 1.82 to 15.28 MPa. Values for auricular, nasal septum, and upper lateral cartilages (medial and caudal) were also determined.

Conclusions: This is the first biomechanical study performed on human auricular, lower lateral, and upper lateral cartilages. The elastic modulus can be determined from samples obtained during routine septorhinoplasty. The modulus of elasticity for all areas was significantly higher than values previously demonstrated for bioengineered elastic cartilage and carved human nasal septal specimens. Shaving the lateral portions of the nasal septum may significantly reduce tensile strength, which may affect graft performance in vivo. Further refinement of testing methods and an increase in the number of analyzed samples are required for formal statistical analysis and further determination of clinical relevance in different nasal subtypes.

Arch Facial Plast Surg. 2007;9(4):264-270

Maintaining the stability of the nasal base has remained one of the more challenging aspects of primary and revision rhinoplasty. Since the introduction of the tripod theory by Anderson[1] in the 1960s, little has been done to further investigate the structural integrity of the elements of the nasal tip. Although an exhaustive body of literature exists describing techniques for modifying nasal anatomical variations, a thorough analysis of intrinsic and extrinsic forces that affect the nasal tip has not been performed.

There have been many publications since the landmark article by Janeke and Wright[2] that classify the major and minor support elements of the nasal tip (**Table 1**). In this body of literature, wide differences exist between findings. Most researchers agree on the components, but many differ in their categorization as major vs minor factors. Specific differences include the inclusion of the anterior septal angle or dorsal septum,[3,4] the degree of contribution of the intercrural ligament,[5] and the importance of the medial crural attachment to the caudal septum.[2,6-8] These differences may reflect ethnic demographics, as clinical and experimental differences seem to exist between racial groups.[9-14]

Although most authors agree on the importance of the intrinsic strength of the lower lateral cartilages, to date, no scientific examination of the biomechanical properties of these cartilages has been performed. Accordingly, we undertook determination of the modulus of elasticity (E) (the Young modulus) of the various cartilaginous elements of the nose. We then explored the relevance of these values by relating the lower lateral cartilage to a spring and qualitatively assessed the various forces one must consider in relation to tip position. Initial data from a pilot group of 4 patients are presented herein.

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METHODS

EXPERIMENTAL DESIGN

Consecutive patients undergoing primary rhinoplasty were enrolled in the study according to Mount Sinai Hospital institutional review board/Grants and Contracts Office protocols.

All the operations were performed by one of us (W.L.) according to usual standards, and no additional cartilage harvesting was performed for the purpose of this study. Cartilage samples from the auricle, septum, and upper and lower lateral cartilages (lateral crura) were taken for biomechanical testing. The modulus of elasticity (*E*) was determined following standard protocols.

Cartilage specimens were cut using a double-bladed device such that they had a 3-mm-wide gauge region in the middle (**Figure 1**). Samples were tested immediately after harvest in most cases. Several samples that could not be analyzed within 3 hours were frozen at −4°C until testing could be performed. These samples were harvested using a water bath and standard protocols.

Tensile testing was performed using a custom-designed mechanical testing system (**Figure 2**). The actuator was a high-precision linear positioning stage driven by a piezoceramic motor (Nanomotion Ltd, Yokneam, Israel). Displacement of the actuator was measured using a linear optical encoder (Renishaw, Gloucestershire, England) that has a resolution of 0.1 μm. Motion control and data acquisition were provided by a personal computer–based servo motor controller (National Instruments, Austin, Texas).

The ends of the cartilage specimens were clamped between metal plates lined with coarse emery cloth (Figure 2). One end was attached to the actuator and the other end to a 45-N capacity force transducer (Transducer Techniques, Temecula, California). Test gauge length was 3 mm. Specimens were loaded at a constant displacement rate of 0.03 mm/s, corresponding to a strain rate of 1% per second. Force and displacement data were recorded at 200 samples per second until specimen failure occurred. Cartilage specimens were imaged using a video camera (RH1100; Duncan Technologies, Auburn, California) to determine their exact length and thickness. A video zoom (×4.5) microspore lens (Edmund Industrial Optics, Barrington, New Jersey) was attached to this microscope.

Specimen dimension analyses were conducted using a software program (IMAQ Vision Builder; National Instruments). Force data were converted to stress data by dividing each force value by the resting cross-sectional area of each specimen. Strain was calculated by dividing sample deformation by initial undeformed gauge length.

The Young modulus (*E*) describes tensile elasticity, or the tendency of an object to deform along an axis when opposing forces are applied along that axis; it is defined as the ratio of stress to strain. Because all other elastic moduli can be derived from the Young modulus, it is often referred to simply as the elastic modulus, but it is also known as a material's stiffness. For calculation in this study, tensile stress values were plotted against tensile strain values, and the slope of the linear region of each plot was calculated. The slope value was, therefore, equal to the elastic modulus (stiffness) of the specimen pulled along its long axis.

Preoperative photographic analysis was undertaken, as was visual assessment of nasal subtype. Two separate examiners' (W.L. and R.W.W.) perceptions of nasal type (leptorrhine, platyrrhine, mesorrhine, or other) and subjective grade of tip cartilage strength (1=poor, 2=average, and 3=high) were recorded. Correlation coefficient and comprehensive statistical analyses of cartilage strength could not be performed owing to the limited sample size.

BIOMECHANICAL AND FORCE ANALYSIS

For this evaluation we used a simplified model of the nasal tip. In essence, nasal tip cartilages exhibit certain properties that are analogous to a spring and a cantilever. The lower lateral cartilages demonstrate deformation, recoil, and elasticity. Anatomically, the cartilage has a single stable point of fixation, typically at either the base of the columella or elsewhere along the caudal septum. Although other forces (such as ligaments, cartilaginous scrolls, mimetic muscles, soft tissue attachments, and gravity) act on this system, measure-

Table 1. Classic Subdivision of Major and Minor Tip Support Mechanisms

Major Tip Support Mechanisms	Minor Tip Support Mechanisms
Intrinsic shape and strength of lower lateral cartilages	Interdomal ligament
Attachment of the medial crura to the caudal septum	Ligament of Pitanguy
Attachment of the upper and lower lateral cartilages	Septum
	Sesamoid cartilages and their lateral pyriform attachment
	Nasal skin and superficial musculoaponeurotic system
	Nasal spine
	Membranous septum

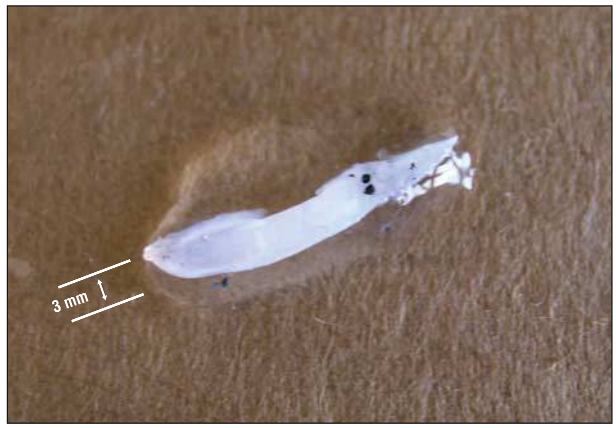

Figure 1. A representative 3-mm-wide segment of the cephalic edge of a left lower lateral cartilage specimen after processing. The specimen was cut using a double-bladed device with a 3-mm spacer. Cuts were made under loupe magnification (×2.5) to ensure precision. The perichondrium and soft tissue were removed, taking care to avoid sample damage.

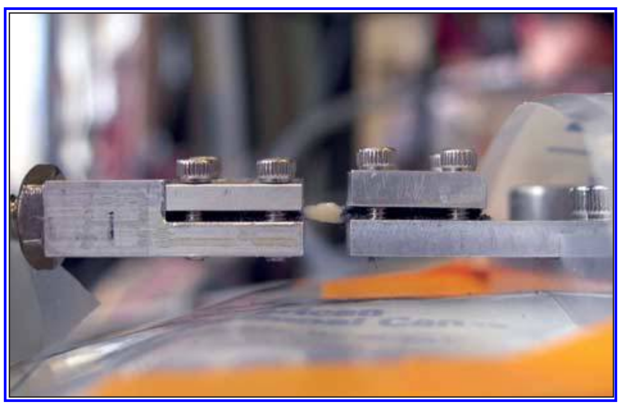

Figure 2. Testing device with cartilage sample in place. Samples were clamped sufficiently to avoid slippage while avoiding damage at the contact points at the end of the test gauge. The force transducer is shown on the left, and the motor is shown on the right.

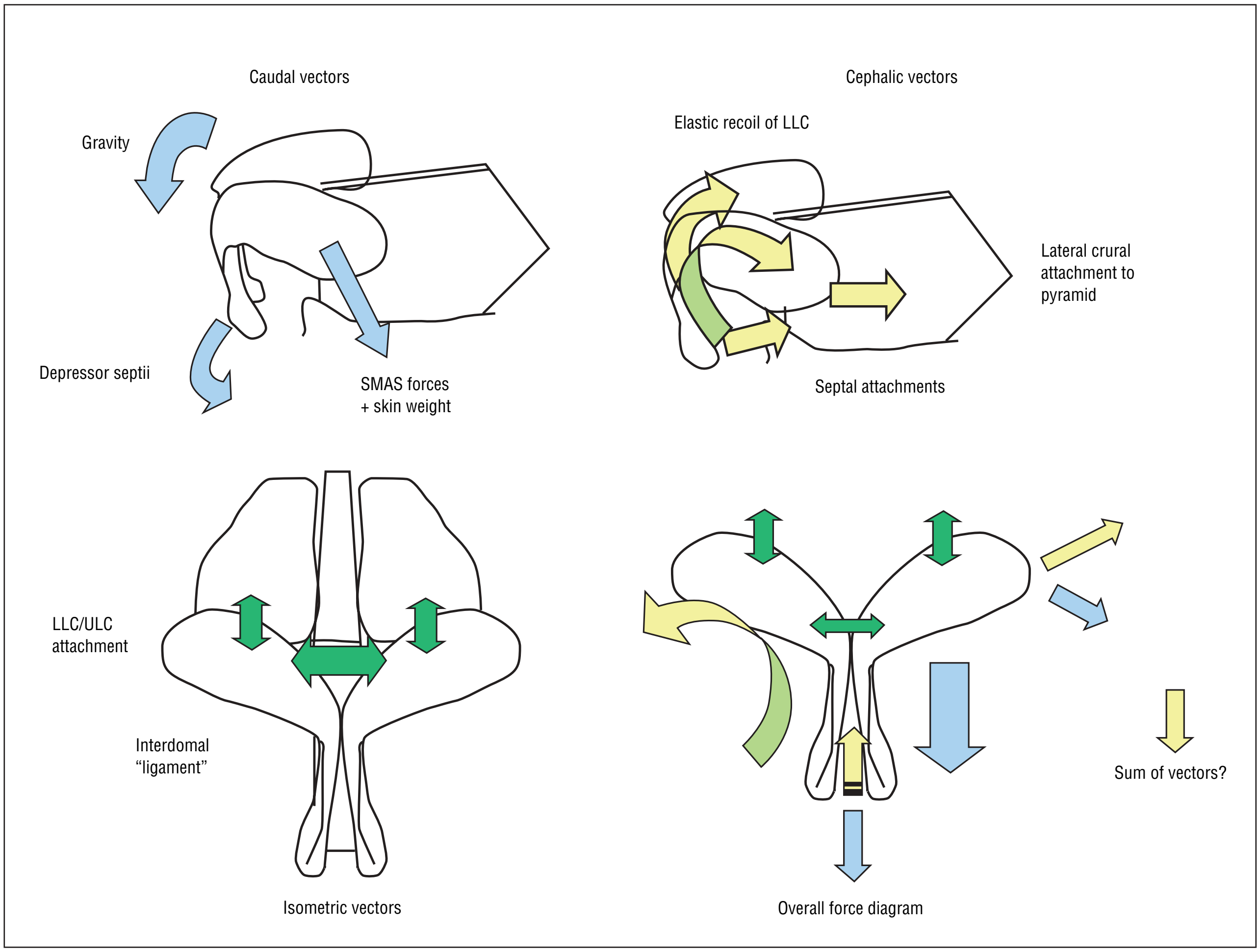

Figure 3. Qualitative force diagram for the nasal tip. The summary of forces was simplified into a single vector: the craniocaudal direction. At any given time, the upward and downward forces should be balanced. Because, across time, nasal tip ptosis occurs in many patients, there is a possibility that the slight inferior imbalance is present in most patients. LLC indicates lower lateral cartilage; SMAS, superficial musculoaponeurotic system; ULC, upper lateral cartilage.

ment of these individual components is impractical. Also, the geometry of the lower lateral cartilage is unique in each patient, making universal analysis impossible. We, therefore, simplified the system and analyzed the lower lateral cartilage as a straight cantilevered spring with a single point of fixation and a single external force representing the summation of all downward force vectors. The tip cartilages produce elastic potential energy to counteract these external forces and keep its position relatively static. This concept of potential energy was recently alluded to in an article by Adamson et al, where they referred to the nasal tip cartilages as a "sprung horseshoe."[15(p17)]

The elastic potential energy of a spring can be calculated as follows: $Es = 1/2kx^2$, where k represents the material's stiffness, which for a cantilevered spring can be calculated as follows:

$$K = [3E(\text{Width} \times \text{Height})^3/12)]/\text{Length}^3.$$

Therefore, elastic potential energy in this system can be calculated as

$$Es = (1/2)[3E(\text{Width} \times \text{Height})^3/12)\ x^2]/\text{Length}^3.$$

We calculated the material's modulus of elasticity E using our testing system. Because the nasal tip lies in a static position when viewed for a short period, the overall forces acting on it must be in balance. Qualitatively, the summation of forces is equal and opposite in all directions. For simplicity's sake, we used a single axis of displacement in the vertical direction, which is qualitatively shown in **Figure 3**.

The qualitative simplified force equation would, for a stable and unchanging nasal tip, therefore be

$$\text{Downward Forces} = \text{Upward Forces}$$

or

$$\text{Downward Forces} = \text{Cantilevered Spring Potential Energy} + \text{Other Tip Support Elements}.$$

RESULTS

Table 2 lists the results of biomechanical testing obtained in the study population. Five patients were included in the initial pilot cohort, with 1 patient not yielding sufficient material for analysis. Several specimens visibly slipped at the clamping site, and data from these tests were not included in the analysis. Significant variability was seen in paired specimens, raising questions about the sample preparation and clamping techniques. However, modification of these techniques did not result in significant changes to calculated E values or sample variability in subsequent preparations.

Table 2. Four Samples From Patients With Relevant Calculations, Including Modulus of Elasticity (*E*)

Patient No.	Anatomical Region	Gauge Length, mm	Specimen Area, mm^2	Stiffness (*E*), MPa
1	Left lower lateral	4	1.18	1.82[a]
1	Left lower lateral	4	1.15	15.28[a]
1	Right lower lateral	4	1.87	5.63
1	Septum	4	0.28	4.82
1	Right upper lateral	4	0.37	28.63
2	Ear	4	0.41	25.55
3	Left lower lateral	3	0.83	13.79[b]
3	Left lower lateral	3	1.05	2.31[b]
3	Septum	3	0.59	30.32
3	Left upper lateral	3	0.75	19.16
3	Right lower lateral	3	1.22	9.12
5	Right upper lateral	3	1.11	7.82
5	Left lower lateral	3	1.70	5.43
5	Left upper lateral paraseptal portion	3	0.59	25.32
5	Septum	3	0.63	32.76

[a]Paired samples from the same surgical specimen.
[b]Paired samples from the same surgical specimen.

All the patients were classified as leptorrhine nasal subtype. Various anatomical differences existed between patients, requiring different surgical maneuvers in each case. Nasal tip strength was determined by 2 separate examiners (W.L. and R.W.W.) and was scored on a subjective scale of from 1 to 3 (**Table 3**).

Table 3. Clinical Preoperative Analysis of Patients[a]

Patient No./Sex	Tip Strength[b] Examiner 1	Tip Strength[b] Examiner 2
1/M	3	3
2/M	2	2
3/F	3	3
5/M	2	1

[a]All the patients were white and were classified as leptorrhine nasal subtype.
[b]Tip strength was assessed using a scale of 1 to 3 (1 = poor, 2 = average, and 3 = strong).

COMMENT

Rhinoplasty is one of the most difficult cosmetic operations owing to the extreme variability in the underlying anatomy and the delicate nature of the supporting structures. In addition, the dynamic nature of the nose makes predictability difficult, with aesthetic changes often occurring during a patient's lifetime. Consequently, maintaining nasal support is of greatest importance. The increasing use of columellar struts, complete strip procedures, and suture remodeling is a testament to our increasing knowledge of, and concern about, nasal support mechanisms.

In the 1960s, Anderson[1] proposed the tripod model of the nasal base. Since its inception, the basic tenets of this theory have been applied by many rhinoplasty surgeons and have helped improve operative results. Simultaneously, its major advantage and drawback is its simplicity of concept and design.

The classic descriptions of tip support mechanisms assume a tripod with reasonably balanced contributions arising from the medial and lateral crural elements. However, many ethnic noses do not fit this anatomical standard and may have significant differences regarding which elements contribute major and minor tip support. It is also unclear whether the modulus of elasticity of the cartilages themselves varies in different patient populations.

Recently, several researchers investigated the immediate clinical effects of various surgical maneuvers using instruments to quantify the strength of the nasal tip. Customized testing instruments were utilized, and each study used different devices and distinct test points.[3-5] The entire complex, including skin, nasal superficial musculoaponeurotic system (SMAS), cartilage, perichondrium, and mucosa, was evaluated in each patient. No testing of individual structures was performed. No ethnic subgrouping was included in their methods. In analyzing their findings, it is apparent that results between and within studies conflict. However, several key findings can be extrapolated from their investigations.

Using cadaveric dissection, Adams et al[3] found that dorsal reduction of 4 mm or greater resulted in a 3.33-mm loss of tip projection using an open rhinoplasty approach. Similar changes were not seen using closed approaches. Additional findings included an increased loss of tip projection (2.3 mm) after cephalic trim in open rhinoplasty compared with closed nondelivery techniques.[3]

These findings are in contrast to the clinical experience of surgeons routinely performing open rhinoplasty.[16] Assuming that a real and significant loss of tip support occurs with open rhinoplasty elevation alone, one must question the validity of Janeke and Wright's major and minor categories (Table 1). However, this study may simply reflect the immediate behavior of cadaveric tissue. In clinical situations, wound healing plays a major role in determining the ultimate tip position in open and closed techniques.

Beaty et al[5] analyzed clinical cases and cadaveric dissections. In living patients, the raising of skin and soft tissue gave 25% and 60% loss of tip support in primary and revision cases, respectively. Paradoxically, this was not seen in cadaveric studies. This finding clinically supports but directly conflicts the cadaveric dissection findings of Adams et al.[3] Intercartilaginous incision with lower lateral cartilage delivery gave a 35% loss of tip support in cadavers. No living patients were tested using closed techniques. No loss of tip support was seen with cephalic trim until 80% of the lateral crura were removed.[5] Their ultimate conclusion was that the intercrural ligament was a major tip support element.

Finally, Gassner et al[4] tested 6 patients preoperatively, intraoperatively, and postoperatively. They showed the strongest region of the nose to be the anterior septal angle, followed by the columella and the interdomal region. This study and that of Adams et al[3] agree on the importance of the anterior septal angle or the cartilaginous dorsum as providing major tip support. Beaty et al[5] point to the intercrural ligament, which acts as a sling over the anterior septal angle, as a major element.

Collectively, these studies, which represent the only quantified clinical or experimental data to date, implicate the nasal septum as a major tip support element and perhaps the skin soft tissue attachments. More specifically, the entire caudal septum and the interaction of the anterior septal angle with the paired domal elements provided a significant level of nasal tip support in the populations studied. These studies indirectly challenge Janeke and Wright's classification of nasal tip support elements and mandate a reevaluation of currently accepted models.

STUDY FINDINGS: SEPTUM

Recently, due to the growing interest in tissue-engineered cartilage, the modulus of elasticity has been documented for native nasal septal and engineered cartilage.[17,18] In the study by Richmon et al[17] of human nasal septal cartilage, the authors set out to define a standard modulus that could be used for assessing tissue-engineered cartilage. They did not quantify the in vivo values for intact nasal septum. In their preparation, the lateral or subperichondrial aspects of the samples were excised to test the most histologically uniform central portion of the septum. Comparison of *E* values with those of the tissue-engineered cartilage of Park et al[18] demonstrated a similar value of approximately 5 MPa.

As demonstrated by Murakami et al[19] using the theory of interlocking stresses, the outer layer of cartilage has significant tensile properties. Removal of this portion of the specimen would result in significantly lower stiffness values. Our data showed correlation with tissue-engineered cartilage elasticity only when septal samples were peripherally shaved. Higher values were seen with intact specimens. Another related but animal-based study[20] looked at the contribution of perichondrium to the moduli in porcine auricular cartilage and found a 50% increase in stiffness when left intact unilaterally.

The present data show significant variation from the stiffness values of 5 MPa for the nasal septum found in the aforementioned studies. The modulus from patients 3 and 5 were almost 7-fold higher (30.32 and 32.76 MPa). One value for the nasal septum in patient 1 was comparable (4.82 MPa). The reason for this likely relates to sample preparation. The harvested sample from patient 1 was thicker than 3 mm and was reduced using the double-bladed device in a similar manner to the preparation of samples in the study by Richmon et al.[17] This resulted in a calculated modulus close to their values. The thickness of the other 2 septum test samples (patients 3 and 5) was not modified. The higher moduli likely represent true differences in stiffness when the high-tension regions of the peripheral septum are left intact.

Further testing of this finding is critical because its relevance may affect how we prepare columellar struts. Surgeons routinely carve the septal cartilage toward its center, removing small irregularities and normalizing overall thickness. However, this maneuver may significantly decrease the strength of the implant. Maintaining the elastic modulus and the strength of the strut is critical in its ultimate performance.

Evaluation of the various calculated moduli in this study shows differences in the strengths of the cartilaginous elements of the nose. The present findings again point to the nasal septum as a major nasal support element. The unaltered septum has the highest stiffness, which likely results from its fibrocartilage histologic makeup and its role as an immobile central support structure in the lower two-thirds of the nose. The upper lateral cartilage has a lower modulus than the septum but a higher modulus than the lower lateral cartilage. This finding may relate to the semirigid and mobile nature of the structures they support, as well as the caudal septum's role as a cantilever point for nasal tip rotation.

STUDY FINDINGS: LOWER LATERAL CARTILAGES

When 2 tests were run on the same sample material (patients 1 and 3, left lower lateral cartilage), we obtained significantly different moduli (1.82 vs 15.28 MPa and 2.31 vs 13.79 MPa). The reliability and repeatability of the testing method may be questioned on those grounds. However, in each pair, the smaller moduli approximated historical controls[17,18] for nasal septum. Since errors related to sample preparation or fixation problems usually result in lower-than-normal values, we were encouraged that the calculated stiffness values approximated and exceeded historical control values.

We attempted to address the possibility that these lower values represented slippage at the clamp site, but we could not determine a better method for sample stabilization given the small nature of their size and the need to avoid sample damage from the clamps themselves. Another possibility is that microfracture during harvest or sample preparation may have contributed to weakening of these specimens. Finally, these discrepancies may represent true topographic variability in cephalic lower lateral cartilage moduli.

When 2 samples were taken from the lower lateral cartilages, the second sample was taken from a more cephalic position, in the region of the scroll. These disparate moduli, therefore, may represent a true variation of the cartilage strength in the lateral crura themselves, which tend to thin out in the region of the scroll. If these values continue to be seen with additional samples, then the scroll's importance in tip support should be reclassified as minor, because the tensile cartilage strength in this region is the lowest of all the calculated nasal cartilage values. Softer cartilage in this region makes sense, since it is a point of mobility and contact between the mobile and more rigid segments of the nose.[21]

Further testing is required to resolve these questions. The presence of a thin layer of perichondrium on the samples may also explain the higher values of *E*. Histologic preparations using hematoxylin-eosin staining on cartilage fragments after testing may help determine whether the presence of perichondrium affected these results.

FORCE ANALYSIS

The lower lateral cartilages are composed of cartilage that is presumed to have a relatively uniform composition in all patients. Homicz et al[22] showed the histologic makeup of the nasal septum to be similar among patients of different sexes, although a decrease in some factors was noted with advancing age. Similar consistency should also be found in the paired tip cartilages, and the calculated *E* for a linear sample of equal dimensions should be relatively similar between patients and ethnicities if the underlying histologic makeup is consistent.

We chose a cantilevered force model, because the nasal tip has the ability to rotate in response to alterations that do not actually shorten the legs of the nasal tip tripod. To rotate, it must therefore have a single point of fixed stability around which to move. The nasal septum, with its high modulus of elasticity and immobile nature, is an excellent candidate for this cantilever point. Furthermore, because the nasal tip cartilages demonstrate the spring properties of anisotropicity (varied behavior in different directions of displacement) and viscoelasticity (creep, fatigue, and cantilever bending), we concluded that the lower lateral cartilage, as a whole, approximates a spring system. The combination of these 2 concepts resulted in our force analysis.

The stiffness equation presented in this article demonstrates that the geometry, including thickness, length, and width, is of more importance than the modulus itself in determining the elastic potential energy of the cartilage and therefore the intrinsic strength of the nasal tip. We know from clinical practice and anecdotal experience that some patients tolerate cephalic trim and others collapse from more conservative procedures. We also know that patients with short or weak medial crura or a displaced caudal septum are at high risk for deprojection unless caudal septal correction or grafting techniques are used. This can be assessed by appreciating the length of the medial crura preoperatively and their width during delivery or open rhinoplasty approaches. Finally, some patients (such as those with infantile lobules), despite conservatism and the use of columellar struts, do not maintain the desired amount of rotation and projection across time, requiring the use of premaxillary, shield grafts, cap grafts, or vertical dome division techniques.

The elastic potential energy equation (see the "Biomechanical and Force Analysis" subsection), when coupled with the simplified force equation (see the "Biomechanical and Force Analysis" subsection), may help explain these challenging scenarios in a more scientific manner. If the geometry of the cartilage is unfavorable in thickness, width, or length, then the patient is at high risk for unwanted cosmetic or functional sequelae if aggressive excision of cartilage is performed or if grafting procedures are not used. In addition, if other tip support mechanisms are deficient, then the relative strength of the lower lateral cartilages, based on their moduli and geometry, must be carefully assessed intraoperatively in each unique case.

If ultimate tensile testing proves that the elastic modulus is not constant among patients of different ethnicities, ages, or sexes, this would help explain the variable clinical behavior that is sometimes encountered. If these data were available, an additional known variable could be taken into consideration when determining an individual patient's major tip support elements.

The last and potentially most important question to consider is whether the patient's nasal tip is cantilevered at the tripod theory's assumed location—the base of the columella—or whether the most stable point of fixation is at another location. Alternate possibilities include the anterior septal angle (in a tension nose), the sesamoid attachments of the lateral crura to the pyriform aperture (in some Middle Eastern noses), or some other ill-defined point (in some platyrrhine and mesorrhine noses). Some patients require columellar struts or strip division techniques to move the cantilever point to a more favorable location, achieving more predictability during the healing phase. In that way, the tripod theory, when viewed as a cantilevered tripod, explains more types of anatomy and clinical behavior.

The summation of forces in any individual nose involves many elements, which will vary from patient to patient. The physician must determine the relative impact of each component. Our analysis helps to simplify this thought process. This may directly influence the surgical plan, especially decisions related to the limits of excision or the need for additional supporting grafts.

CONCLUSIONS

A thorough understanding of the elements that provide tip strength is critical to successful rhinoplastic surgery using any approach. Our current knowledge of nasal tip biomechanics is insufficient to explain the frequently encountered anatomical variants and clinical deviations from the standard. Redefining our concepts of the classic tip support mechanisms to include the caudal nasal septum seems to be supported by the available experimental evidence.

Determining the *E* for nasal tip cartilages is a critical initial step in furthering our understanding of nasal tip support mechanisms. This is the first study, to our knowledge, to evaluate the biomechanical properties of these cartilages. The calculated modulus was highest for the septum, followed by the upper and lower lateral cartilages. Auricular cartilage was similar to upper lateral cartilage in its stiffness. Planar shaving of harvested septum to remove its lateral subperichondrial aspects may significantly reduce its stiffness when used as a columellar strut.

Additional investigation should include a larger group of samples, histologic analysis of tested material, subdivision and analysis using ethnicity and anatomical abnormalities, and comparison with materials often used in reconstruction. With this information, the preparation, choice, and performance of routine grafts may be modified by applying known biomechanical properties rather than relying on clinical and anecdotal evidence. More important, one of the most basic and universal principles of rhinoplasty—that the strength of the lower lateral cartilages is a major tip support mechanism—can be assessed for its validity and universal application.

Accepted for Publication: January 25, 2007.
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Financial Disclosure: None reported.

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