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Numerical analysis of costal cartilage warping after laser modification

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ABSTRACT

Grafts obtained from peripheral regions of costal cartilage have an inherent tendency to warp over time. Laser irradiation provides a potential method to control the warping process, thus yielding stable grafts for facial reconstructive surgery. In our current study, we propose a simple and well-fitting model that numerically describes the degree of warping of laser irradiated costal cartilage grafts. Using a Nd:YAG laser (λ=1.32μm) at various exposure settings, grafts harvested from the peripheral regions of porcine costal cartilage were irradiated. The resulting graft geometry was objectively fitted to a curve using a quadratic regression model. The coefficient of determination (R^2) demonstrated a very strong fit for all grafts modeled. A quadratic regression is simple to perform and results in a single numerical value that appropriately describes the degree of cartilage warping. Our proposed model is valuable in assessing the effect of laser irradiation on the warping process of costal cartilage.

Keywords: costal, rib, cartilage, warping, laser, irradiation, numerical, curve, fitting, regression

1. INTRODUCTION

Several important structures of the head and neck are supported by cartilage framework. In the event that these structures are malformed or damaged, costal cartilage provides an abundant supply of tissue for repair. Because of its ample supply, costal cartilage grafts are the only practical autogenous option when auricular and septal cartilage are insufficient. However, costal cartilage grafts obtained from peripheral regions of the rib have a tendency to warp over time following the harvest[1-3]. In order to minimize warping, current practice conventionally relies on using carving methods introduced by Gibson and Davis[4], in which grafts are obtained from balanced cross-sections typically from the central core[2, 5-6]. These balanced grafts are challenging to carve precisely and also lead to discarding valuable cartilage.

The use of lasers offers a potential method to control the warping process in peripheral costal cartilage grafts. The interactions between lasers and cartilage have been extensively studied in the setting of laser cartilage reshaping[7-11]. Advances in laser cartilage reshaping have led to the successful use of lasers in the correction of septal[12-13] and auricular[14-15] malformations in humans. A recent study by our group particularly investigated the use of laser irradiation to control the warping of costal cartilage. Our initial attempt accelerated the warping process to a steady state. Specifically, the irradiated grafts underwent the majority of their total warping within the first 30 minutes, while the control grafts continued to demonstrate significant shape change throughout the 24 hour observation period.

In order to accurately analyze the results of warping experiments, it is imperative to utilize a proper method to quantify the amount of warping in a cartilage specimen. In a study on peripheral warping by Lopez et al.[6], warping was numerically estimated using the angle formed by the intersection two line segments (Figure 1). Each line segment originated at the opposite ends of the concave surface of the specimen, and met at the lowest point of the concave surface. Kim et al.[2] used an angle to describe warping by modeling the curvature of the specimen as a line segment of a triangle. The angle of warping was calculated using an inverse tangent function. Both methods described are simple to perform; however, they are hampered by subjectivity due to manual drawing of lines and curves. Furthermore, line

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segments and triangles do not precisely describe a curve. Developing a better fit, Gray et al.[9] modeled the curvature of the cartilage specimen as an arc segment of a circle. In addition, the subjectivity of this method was limited to manual measurement of the length of the cartilage specimen. However, like the prior methods described, this method lacked a description of the accuracy and limitations of the curve fit. A circular regression is complex and can be performed via numerous techniques, all of which that can potentially lead to varying results. A comprehensive search of the literature provided no reports to our knowledge of a simple, completely objective, and precise method to numerically model cartilage warping with confirmation of the goodness of fit.

The objective of this study is to establish a simple, objective, and well-fitting model that numerically describes the degree of warping in laser irradiated costal cartilage specimens. Furthermore, we aim to utilize a method that provides information on the goodness of fit of the model. We hypothesize that this can be achieved using a quadratic regression.

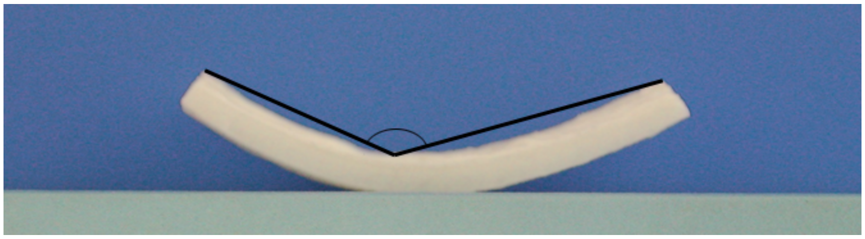

Figure 1. A simple method to represent warping using the angle created by two line segments.

2. METHODS

2.1 Tissue specimens

Porcine costal cartilage was obtained from a local packing house. The cartilaginous regions of ribs numbered two through five were stripped of all tissue except for the perichondrium. Then, peripheral slices having a length of 4cm, width of 1cm, and thickness of 2mm were carved from the concave side of the rib.

2.2 Laser irradiation

The cartilage slices were placed in one of three laser exposure groups: 1) 4 laser spots, 6 watts, 2 seconds (n=6); 2) 4 laser spots, 8 watts, 3 seconds (n=6); 3) 8 laser spots, 6 watts, 2 seconds (n=8). The laser dosimetry settings utilized are similar to those used in laser cartilage reshaping. The cartilage slices receiving 4 laser spots were irradiated at 4 evenly spaced points along the central axis of the length. The cartilage slices receiving 8 laser spots were irradiated at staggered points along two parallel rows along the length. A silica fiber (600 μm) was used to direct light from an Nd:YAG laser (λ = 1.32 μm, 50 Hz PPR, New Star Lasers Inc, Roseville, CA) to the perichondrial surface of the cartilage slice. The fiber was positioned perpendicular to the surface of the slice, and at a distance to produce a spot size of 2mm as measured by burn paper (Kentak, Pittsfield, NH). After irradiation, the specimens were stored in 0.9% saline at 22 degrees C.

2.3 Photography

The slices were photographed using a digital camera (Coolpix 990, Nikon Inc., Melville, NY) immediately after carving, immediately after irradiation, at 30 minutes, at 1 hour, at 5 hours, and at 24 hours. This yielded a total of 120 photographs of specimens to model using a quadratic regression. Each specimen was photographed while laying on its 2mm edge. The convex 10mm edge was placed against a guide to precisely position the specimen and prevent it from tipping over. The camera was mounted so that the lens was perpendicular to and a distance of 12 inches above the slice. The positioning of the camera was not disturbed during the entire study. The camera was set to macro mode with automatic focusing.

2.4 Measurement of warping

Each photograph was opened using Photoshop CS3 (Adobe Systems Inc., San Jose, CA) (Figure 2A). Any point within the cartilage slice was clicked using the magic wand tool set at a tolerance of 75. This resulted in the entire cartilage specimen being selected, since the white cartilage contrasts with the blue background. The selection was stroked at 2 pixels on a new transparent image layer, creating an outline of the cartilage slice. The layer with the original photograph was then set to hidden, so that only the outline of the specimen was visible (Figure 2B). The sides and concave surface of the cartilage slice were removed using the eraser tool (Figure 2C). The remaining curve representing the convex surface of the cartilage slice was saved as a jpeg file and imported into Engauge Digitizer 4.1 (Freeware, Mark Mitchell). The digitizer software automatically plots points along the curve, and exports the points as X-Y coordinate tabular data in a comma-separated values (.csv) format. The tabular data was opened with SigmaPlot 11 (Systat Software Inc., San Jose, California) and a scatter plot was generated. The scatter plot creates a curve identical to the concave surface of the cartilage specimen. The regression wizard was then used to fit a quadratic function, of the form $y = ax^2 + bx + c$, to the curve. The coefficient b and c only describe the relative position of the fitted parabola. However, the coefficient a describes the width of the fitted parabola, and thus was used to numerically describe the amount of warping. Increased curvature of a specimen yields a higher value of the coefficient a. The coefficient of determination, R^2, also obtained from the regression analysis, confirms the goodness of fit of the parabola, with a value of 1 being a perfect fit.

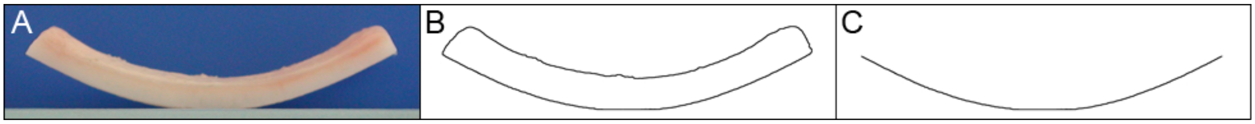

Figure 2. Converting the cartilage slice into a single curve. A) The original photograph is opened in Photoshop. B) The outline is automatically traced using the magic wand tool. C) The eraser tool is used so that only the curve on the convex side of the specimen remains.

3. RESULTS

Figure 3 demonstrates the excellent fit of a quadratic regression to the curved cartilage specimens. The black curve is the plot of the original cartilage specimen, and the gray curve is the fitted parabola using a quadratic regression. The R^2 values for all specimens modeled ranged between 0.90 and 1.00, and had a mean value of 0.98 (Figure 4). The coefficient that describes the amount of warping ranged from 0.0002 to 0.0016 among all samples modeled.

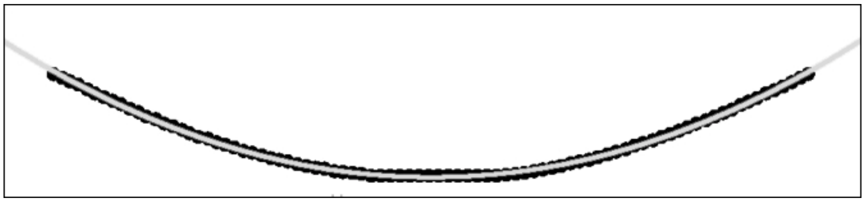

Figure 3. Results of a quadratic regression. The black curve is the original shape of the cartilage specimen. The grey curve is the fitted parabola using a quadratic regression.

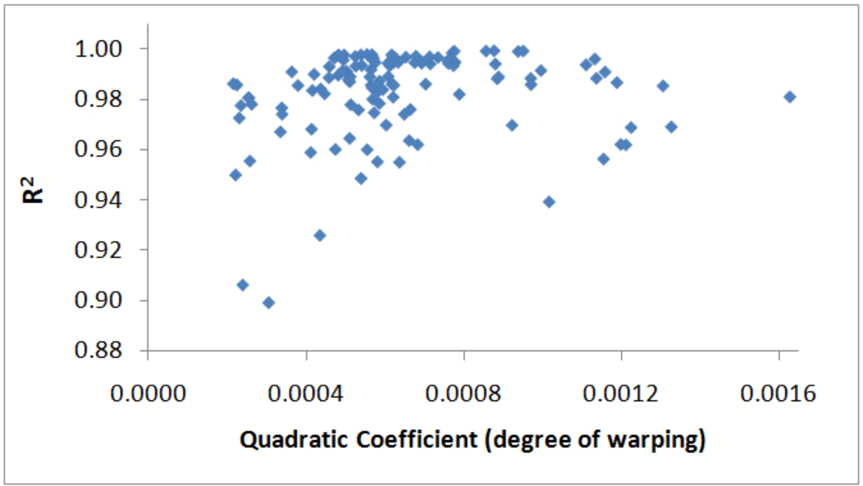

Figure 4. R^2 vs. Quadratic Coefficient for all samples modeled. The R^2 value demonstrates the goodness of fit of the quadratic regression model. The quadratic coefficient describes the degree of warping of the cartilage specimen.

4. DISCUSSION

Grafts obtained from peripheral regions of costal cartilage have a tendency to warp over a period of hours to days after harvesting[1-6]. Recent advances in the use of lasers to reshape cartilage[9-15] provide the potential to use laser irradiation to control the warping process. Specifically, in a prior study, our group used laser irradiation to rapidly accelerate the warping process to a steady state. Although this did not prevent the warping process, it provided stable cartilage specimens that can be used in reconstructive procedures with minimal post-graft warping.

Research involving the warping process of costal cartilage requires an appropriate method to measure the amount of warping. Several methods to measure warping have been utilized in prior studies; however these methods typically consist of a certain degree of subjectivity or do not accurately describe the curvature associated with the warping process. Most importantly, none of the proposed methods provided means to determine the goodness of fit of the model utilized.

This study models the warping of peripheral slices of costal cartilage using a quadratic regression. The fitted parabola is described by three coefficients, where two of the coefficients only describe the relative position of the parabola. The third coefficient describes the width of the parabola, and was therefore used to represent the degree of warping of the cartilage specimens. This coefficient ranged from 0.0002 to 0.0016 for specimens measured at various time points between 0 and 24 hours. The 8 fold difference between the smallest and largest value allows precise differentiation between degrees of warping.

A quadratic regression provides an R^2 value that describes the goodness of fit of the model. An R^2 value can range from 0 to 1, with 1 representing a perfect fit. The average R^2 value for all the specimens modeled was 0.98, which represents an excellent fit.

Upon modeling and analyzing our specimens, we determined two improvements that would enhance the fit of the quadratic regression model, and further increase the associated R^2 value. First, it is imperative to use a background and guide color that contrasts with the white cartilage specimens. In our study, the color of the guide that the cartilage specimens were placed against was light blue. This color did not provide enough contrast to sharply delineate the border between the guide and the specimen, resulting in minor inaccuracies in the outline of the specimen that was automatically created using the magic wand tool. Ideally, the color of the background and the guide should be a dark color, such as black, in order to provide the maximum contrast. Secondly, contact between the cartilage specimen and the guide may potentially lead to minor flattening of the bottom of the curved specimen due to surface tension. Using a smaller guide would minimize the flattening effect. Figure 5A demonstrates the setup utilized in the current study and Figure 5B demonstrates the proposed improvements.

Our proposed method of using a quadratic regression to model warping of costal cartilage is simple and completely objective. Photographs of warped cartilage specimens are digitized automatically using software. A quadratic regression is then performed on the digitized data with ease using a regression wizard. The entire process can be completed within several minutes using common software packages.

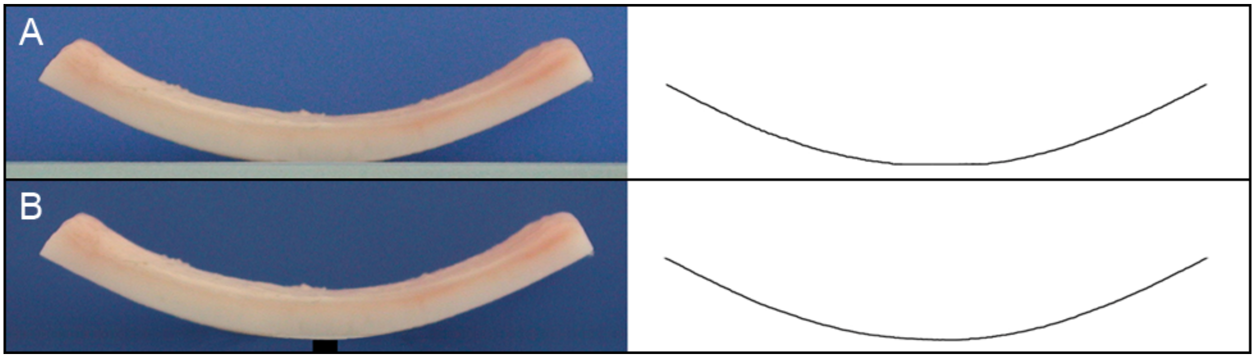

Figure 5. Improving the photography method. A) The setup used in the study. The automatically traced curve using the magic wand tool has a flattened bottom. B) A darker and smaller guide is used. This results in a more accurate tracing of the cartilage specimen.

5. CONCLUSION

Studies that aim to examine the warping of irradiated peripheral costal cartilage grafts require a proper method to numerically describe the curvature of the warped grafts. Our proposed method of using a quadratic regression generates a parabola that models the warping of the cartilage specimens extremely well. The shape of the parabola is represented by a single number that is used to determine the degree of warping of the cartilage specimen. A quadratic regression is simple to perform and can be accomplished using an objective method.

REFERENCES

[1] Gillies HD. *Plastic surgery of the face*. London: Frowde; 1920.
[2] Kim DW, Shah AR, Toriumi DM. Concentric and eccentric carved costal cartilage: a comparison of warping. *Arch Facial Plast Surg.* Jan-Feb 2006;8(1):42-46.
[3] Adams WP, Jr., Rohrich RJ, Gunter JP, Clark CP, Robinson JB, Jr. The rate of warping in irradiated and nonirradiated homograft rib cartilage: a controlled comparison and clinical implications. *Plast Reconstr Surg.* Jan 1999;103(1):265-270.
[4] Gibson T, Davis WB. The distortion of autogenous cartilage grafts: Its cause and prevention. *Br J Plast Surg.* 1958;10:257-274.
[5] Harris S, Pan Y, Peterson R, Stal S, Spira M. Cartilage warping: an experimental model. *Plast Reconstr Surg.* Oct 1993;92(5):912-915.
[6] Lopez MA, Shah AR, Westine JG, O'Grady K, Toriumi DM. Analysis of the physical properties of costal cartilage in a porcine model. *Arch Facial Plast Surg.* Jan-Feb 2007;9(1):35-39.
[7] Li C, Protsenko DE, Zemek A, Chae YS, Wong B. Analysis of Nd:YAG laser-mediated thermal damage in rabbit nasal septal cartilage. *Lasers Surg Med.* Jun 2007;39(5):451-457.
[8] Protsenko DE, Zemek A, Wong BJ. Temperature dependent change in equilibrium elastic modulus after thermally induced stress relaxation in porcine septal cartilage. *Lasers Surg Med.* Mar 2008;40(3):202-210.
[9] Gray DS, Kimball JA, Wong BJ. Shape retention in porcine-septal cartilage following Nd:YAG (lambda = 1.32 microm) laser-mediated reshaping. *Lasers Surg Med.* 2001;29(2):160-164.
[10] Karam AM, Protsenko DE, Li C, et al. Long-term viability and mechanical behavior following laser cartilage reshaping. *Arch Facial Plast Surg.* Mar-Apr 2006;8(2):105-116.

[11] Wong BJ, Milner TE, Harrington A, et al. Feedback-controlled laser-mediated cartilage reshaping. *Arch Facial Plast Surg.* Oct-Dec 1999;1(4):282-287.

[12] Ovchinnikov Y, Sobol E, Svistushkin V, Shekhter A, Bagratashvili V, Sviridov A. Laser septochondrocorrection. *Arch Facial Plast Surg.* Jul-Sep 2002;4(3):180-185.

[13] Bourolias C, Prokopakis E, Sobol E, Moschandreas J, Velegrakis GA, Helidonis E. Septal cartilage reshaping with the use of an Erbium doped glass fiber laser. Preliminary results. *Rhinology.* Mar 2008;46(1):62-65.

[14] Trelles MA, Mordon SR. Correction of ear malformations by laser-assisted cartilage reshaping (LACR). *Lasers Surg Med.* Aug 2006;38(7):659-662; discussion 658.

[15] Leclere FM, Petropoulos I, Mordon S. Laser-Assisted Cartilage Reshaping (LACR) for Treating Ear Protrusions: A Clinical Study in 24 Patients. *Aesthetic Plast Surg.* May 30 2009.