Quantitative biomechanical optimization of neochordal implantation location on mitral leaflets during valve repair

Pearly K. Pandya, BS,[a,b] Robert J. Wilkerson, BS,[a] Annabel M. Imbrie-Moore, PhD,[a,b] Yuanjia Zhu, MD, MS,[a,c] Mateo Marin-Cuartas, MD,[a,d] Matthew H. Park, MS,[a,b] and Y. Joseph Woo, MD[a,c]

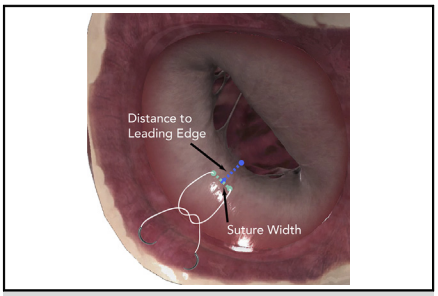
ABSTRACT

Objective: Suture pull-out remains a significant mechanism of long-term neochordal repair failure, as demonstrated by clinical reports on recurrent mitral valve regurgitation and need for reoperation. The objective of this study was to provide a quantitative comparison of suture pull-out forces for various neochordal implantation locations.

Methods: Posterior leaflets were excised from fresh porcine mitral valves (n = 54) and fixed between two 3-dimensional–printed plates. Gore-Tex CV-5 sutures (WL Gore & Associates Inc) were placed with distances from the leading edge and widths between anchoring sutures with values of 2 mm, 6 mm, and 10 mm for a total of 9 groups (n = 6 per group). Mechanical testing was performed using a tensile testing machine to evaluate pull-out force of the suture through the mitral valve leaflet.

Results: Increasing the suture anchoring width improved failure strength significantly across all leading-edge distances ($P < .001$). Additionally, increasing the leading-edge distance from 2 mm to 6 mm increased suture pull-out forces significantly across all suture widths ($P < .001$). For 6-mm and 10-mm widths, increasing the leading-edge distance from 6 mm to 10 mm increased suture pull-out forces by an average of 3.58 ± 0.15 N; in comparison, for leading-edge distances of 6 mm and 10 mm, increasing the suture anchoring width from 6 mm to 10 mm improves the force by an average of 7.09 ± 0.44 N.

Conclusions: Increasing suture anchoring width and leading-edge distance improves the suture pull-out force through the mitral leaflet, which may optimize postrepair durability. The results suggest a comparative advantage to increasing suture anchoring width compared with leading-edge distance. (JTCVS Techniques 2022;14:89-93)



Schematic of the studied parameters to optimize artificial chordae implantation location.

CENTRAL MESSAGE

Increasing neochordal anchoring width increases resistance to suture pull-out. Optimizing neochordal implantation location may translate into improved durability of MV repair.

PERSPECTIVE

Suture pull-out remains a significant mechanism of long-term neochordal repair failure, as demonstrated by clinical reports on recurrent MV regurgitation. This study provides a quantitative comparison of suture pull-out forces for various neochordal implantation locations, providing data-driven guidance to optimize suture placement and allow for improved durability of MV repair.

Repair techniques for treating degenerative mitral regurgitation (MR) range from leaflet resections to geometric reconstructions to nonresectional techniques.[1,2] Various nonresectional mitral valve (MV) repair techniques have been developed with the goal of preserving bileaflet function.[1] There is growing evidence that these techniques can provide preserved leaflet mobility, a larger surface of coaptation, and preserved annular geometry.[3] The most common

From the Departments of [a]Cardiothoracic Surgery, [b]Mechanical Engineering, [c]Bioengineering, Stanford University, Stanford, Calif; and [d]University Department of Cardiac Surgery, Leipzig Heart Center, Leipzig, Germany.

Pandya and Wilkerson contributed equally to this article.

This work was supported by the National Institutes of Health (NIH R01 HL152155, Y.J.W.), Thoracic Surgery Foundation Resident Research Fellowship (Y.Z.), National Science Foundation Graduate Research Fellowship Program (DGE-1656518, A.M.I.), and Stanford Graduate Fellowship (A.M.I.). Donald and Sally O'Neal provided a generous donation and supported this project. The content is solely the authors' responsibility and does not necessarily represent the official views of the funders.

Received for publication Dec 9, 2021; revisions received April 1, 2022; accepted for publication May 10, 2022; available ahead of print May 21, 2022.

Address for reprints: Y. Joseph Woo, MD, Department of Cardiothoracic Surgery, Falk Cardiovascular Research Center, Stanford University School of Medicine, 300 Pasteur Dr, Stanford, CA 94305 (E-mail: joswoo@stanford.edu).

2666-2507

https://doi.org/10.1016/j.xjtc.2022.05.008

Abbreviations and Acronyms
ePTFE = expanded polytetrafluorethylene
MR = mitral regurgitation
MV = mitral valve

nonresectional technique is neochordal implantation, which replaces ruptured or elongated chordae tendinae with expanded polytetrafluorethylene (ePTFE) sutures.[4]

Although neochordal implantation has been conducted with ePTFE sutures since the 1980s, the outcomes can be dependent on the implantation technique used.[5-7] Reports have demonstrated recurrent MR and need for reoperation due to suture rupture or pull-out.[5,7] Suture rupture refers to the failure of the neochordal material itself, whereas suture pull-out is when the neochord tears through the MV leaflet. This detachment of the implanted neochord at the leaflet is caused by inappropriate chordal placement or partial leaflet grasping,[7] and it can result from even a slight mismatch in suture placement due to the cumulative fatigue damage occurring with every cardiac cycle. Therefore, a better understanding of the effect of ePTFE suture placement is key to biomechanically optimizing MV repair durability.

Although previous studies have examined variation of technique and anchoring location on the subvalvular apparatus,[8,9] this study seeks to understand the biomechanical effects of suture placement on the leaflet. During neochordal implantation, distance from the leaflet leading edge is manipulated to reestablish the coaptation plane. Anchoring width between the 2 suture ends can also be controlled. The objective of this study was to use mechanical testing to optimize artificial chordae implantation location on the mitral leaflet.

MATERIALS AND METHODS

Sample Preparation

MVs (n = 54) were explanted from porcine hearts obtained fresh from a local abattoir (Animal Technologies) in accordance with institutional guidelines. Posterior leaflets were excised and fixed between 2 custom-designed textured plates designed to ensure the leaflet remained in tension. The plates were 3-dimensionally printed in a biocompatible resin (MPU 100, Carbon). Each plate featured an orifice to implant artificial chordae at varying locations and widths. Suture loops of Gore-Tex CV-5 ePTFE artificial chordae (WL Gore & Associates Inc) were placed at different locations on the leaflet to simulate variation in suture placement (Figure 1). The distance from the leaflet leading edge and width between anchoring sutures were each varied at 2 mm, 6 mm, and 10 mm for a total of 9 groups (n = 6 per group). These parameters were chosen to accommodate both clinical relevance and measurement error during sample preparation.

Biomechanical Testing

The mounted leaflets were positioned in an Instron 5565 tensile testing machine equipped with a 100 N load cell. The suture loop was held by an opposing fixture, which simulated the papillary muscle implantation locus (Figure 2). Suture loop size was kept constant throughout samples. The fixturing was configured to mimic systolic conditions, with a papillary angle of 13.78° and chordal insertion angle of 126° as derived from previous studies.[10,11] Preconditioning was performed at 0.4 mm/s with an amplitude of 2 mm for 10 cycles; the suture was then tensioned at 0.4 mm/s until ultimate failure occurred. Failure was defined as when the suture tore through the posterior leaflet specimen. A total of 54 posterior leaflets were tested, with a distinct specimen used for each test run.

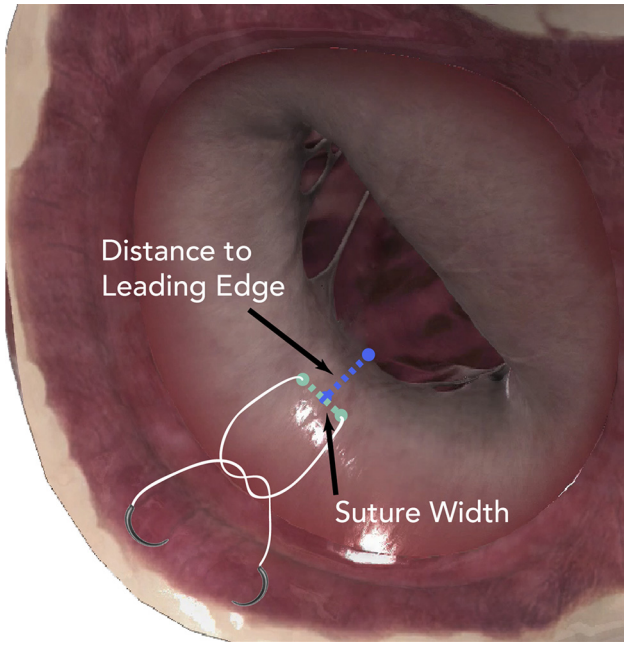


FIGURE 1. Suture loops of Gore-Tex CV-5 ePTFE artificial chordae (WL Gore & Associates Inc) were placed at varied locations on the leaflet to simulate variation in suture placement. The distance from the leaflet leading edge and width between anchoring sutures each varied 2 mm, 6 mm, and 10 mm.

Statistical Analyses

All data are presented as mean ± standard error throughout the article, and no data were missing from the "Results" section. Statistics were performed with a 2-way analysis of variance test examining groupings by distances to leading edge and suture anchoring widths. Tukey post hoc comparisons were conducted with a P value threshold of .05; no additional Type I error controls were implemented. Data were assumed to be normally distributed given our sample size (n > 30) with P values greater than .05 after conducting Shapiro–Wilk tests across all data groupings.

RESULTS

The maximum suture pull-out forces for 2 mm, 6 mm, and 10 mm leading-edge distances were 4.19 ± 0.21 N, 6.48 ± 0.83 N, and 6.21 ± 0.44 N for 2-mm suture width, respectively; 4.99 ± 0.36 N, 7.70 ± 0.53 N, and 12.17 ± 0.63 N for 6-mm width, respectively; and 7.02 ± 0.26 N, 15.68 ± 0.91 N, and 18.36 ± 1.13 N for 10-mm width, respectively (Figure 3). Post hoc comparisons revealed that increasing the suture anchoring width from 2 mm to 6 mm and from 6 mm to 10 mm improved failure strength significantly across all leading-edge distances

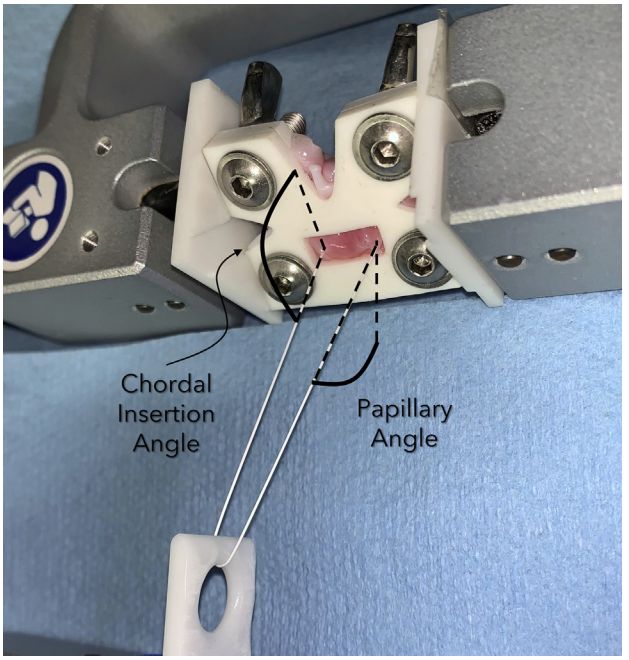


FIGURE 2. The mounted leaflets were positioned on an Instron 5565 tensile testing machine with the suture loop held by an opposing fixture to simulate the papillary muscle implantation locus. To mimic systolic conditions, the specimen was configured to a papillary angle of 13.78° and chordal insertion angle of 126°.

($P < .001$). Additionally, increasing the leading-edge distance from 2 mm to 6 mm increased suture pull-out forces significantly across all suture widths ($P < .001$). Increasing the leading-edge distance from 6 mm to 10 mm increased suture pull-out forces significantly for the 6 mm and 10 mm width ($P < .001$). At a suture width of 2 mm, no statistically significant difference was found.

When comparing 6 mm and 10 mm suture anchoring width and leading-edge distances, increasing suture width had a significantly greater effect on suture pull-out force than the distance of the suture from the leading edge. Increasing the leading-edge distance from 6 mm to 10 mm increased the force by an average of 3.58 ± 0.15 N, whereas increasing suture width improves the force by an average of 7.09 ± 0.44 N. The suture pull-out forces of every neochordal implantation location included in this study are shown in Table 1. A visual summary of the results is provided in Figure 4.

DISCUSSION

An increase in pull-out forces suggests increased suture attachment strength and may correlate with improved post-repair durability of the chordal reconstruction. As seen from the recorded forces for the 6-mm and 10-mm groups, increasing suture width is likely to be a more effective strategy of increasing MV repair durability rather than increasing leading-edge distance. Increasing the width between the anchoring sutures provides a larger tissue-to-suture contact area, which allows for a homogenous distribution of force over greater tissue footprint. In comparison, suture placed over a shorter width can increase stress from the neochordae on the leaflet. By decreasing the cross-sectional area of tissue between the neochordae anchors, the same forces would cause increased stresses, which we believe would cause accumulated fatigue damage with every cardiac cycle. This study demonstrates that increasing the suture width over various distances from the leaflet leading edge can provide greater resistance to tissue-suture abrasion. By increasing resistance to suture pull-out, we may mitigate fatigue damage caused by leaflet stresses,

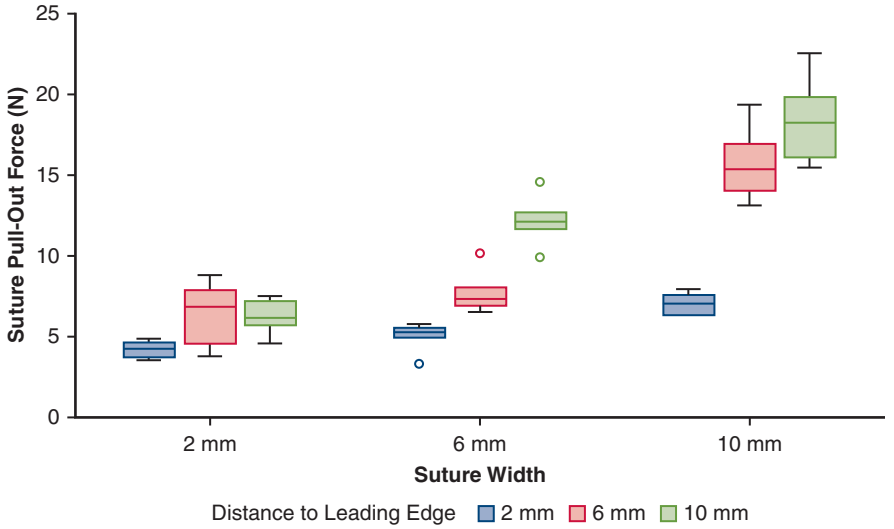


FIGURE 3. Biomechanical testing revealed that increasing the suture anchoring width and leading-edge distance increases suture pull-out force (N) through the leaflet (n = 54). Statistics were performed with a 2-way analysis of variance test examining groupings by distances to leading-edge and suture anchoring widths. Tukey post hoc comparisons were conducted with a P value threshold of .05.

TABLE 1. Suture pull-out force (N) through the leaflet measured using Instron tensile testing

		Width		
		2 mm	6 mm	10 mm
Distance	2 mm	4.19 ± 0.21	4.99 ± 0.36	7.02 ± 0.26
	6 mm	6.48 ± 0.83	7.70 ± 0.53	15.68 ± 0.91
	10 mm	6.21 ± 0.44	12.17 ± 0.63	18.36 ± 1.13

Sutures were placed with distances from the leading edge and widths between anchoring sutures with values of 2 mm, 6 mm, and 10 mm for a total of 9 groups (n = 6 per group).

which could ultimately correlate to prolonged long-term durability. However, increasing the suture width may come with increasing difficulty if implanting multiple artificial chordae. Further care should be taken to avoid tissue plication with increased suture anchoring widths.

Additionally, increasing the distance from the leading edge was also found to provide improved resistance to suture pull-out. No statistically significant improvement was found from the 6-mm to 10-mm leading-edge distance at the 2-mm suture width. Increasing the leading-edge distance may decrease postrepair coaptation surface area, so a tradeoff must be made between increased distance and decreased coaptation surface area. The diminishing advantage of increasing the leading-edge distance beyond 6 mm means that increasing the distance further would cause a decreased coaptation area with no durability improvement. As discussed previously, increasing the suture width beyond 6 mm continues to increase suture pull-out forces. In addition, manipulating suture anchoring width during surgery may be more feasible than adjusting the leading-edge distance, because the latter depends on the location at which the coaptation plane is restored. This is especially relevant when neochordal implantation occurs after resection, because the geometrical differences will dictate the required neochordal distance from the leading edge. Although both parameters are equally relevant, the results suggest that the optimal implantation configuration would be a 10-mm suture width at 6-mm distance from the leading edge.

The observed suture pull-out forces for all the implantation locations studied in the current experimental work exceeded the forces incurred in the mitral subvalvular apparatus under normal physiological conditions.[12,13] Based on Jensen and colleagues' 2014 study,[12] under

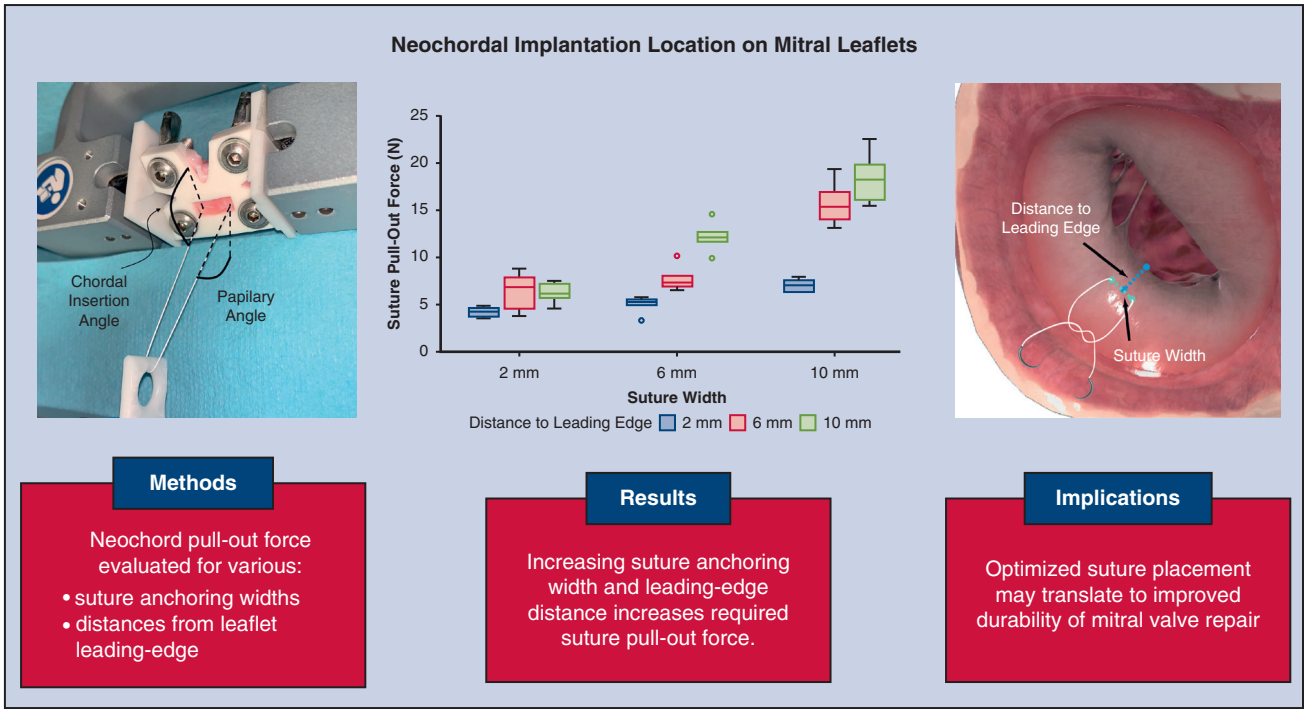


FIGURE 4. In this study, biomechanical testing was performed to quantify the effects of artificial chordae implantation location on the leaflet. Suture anchoring widths and distances from leaflet leading edge were varied. Although increasing both parameters resulted in increased suture pull-out forces, the results reveal a comparative advantage to increasing suture anchoring width. Optimizing suture placement may allow for improved durability of the MV repair.

physiological loading (95 ± 21 mm Hg), the peak force applied by the artificial chordae is 0.41 ± 0.30 N. Likewise, the peak force applied by native chordae has been reported to be lower than 1 N.[13] The lowest recorded suture pull-out force for all our mechanical testing experiments was 3.31 N. In comparison, our proposed optimal suture placement at 10-mm suture width and 6-mm leading-edge distance provides an even greater safety factor, with a failure strength of 15.68 N. Millimetric errors in width or distance may not cause residual regurgitation at saline injection, and thus may not be detected intraoperatively.[14] However, any biomechanical unbalances and undesired tissue tensions can accumulate with cyclic loads,[7] so increasing the force required to ultimate failure corresponds to less fatigue damage accumulation. Because this study was a static ex vivo model, additional studies are necessary to quantify fatigue damage from cardiac cyclic loading at the tested widths and distances.

Study Limitations

One limitation of this study is the use of explanted porcine hearts, due to the variability in tissue quality between leaflet specimens. Compared with porcine hearts, the material properties of human MV leaflets have been noted to be slightly stiffer.[15] Nonetheless, both human and porcine MVs share a similar tissue microstructure and degree of anisotropy, supporting the conclusions drawn from comparing leaflet strengths at various suture widths and distances even if the reported maximum force values are not representative.[15,16] Another limitation is that anterior leaflets were not tested in this model. We chose to study posterior leaflets because posterior leaflet prolapse is more common in causing MV dysfunction.[1] As described previously, increasing either parameter may be increasingly difficult when implanting multiple sutures. For this reason, future studies will test the effects of multiple chordae implantation on the same leaflet to ensure accurate in vivo translation.

CONCLUSIONS

Although increasing both parameters increased failure strength, the results reveal a comparative advantage to increasing suture anchoring width compared with leading-edge distance. According to the suture pull-out force testing, the optimal implantation configuration was found to be a 10-mm suture width at 6 mm from the leading edge. This study provides biomechanical evidence to aid in suture placement of artificial chordae implantation in chordal reconstruction. By increasing suture anchoring width, postrepair suture attachment strength may be increased, which may provide improved durability of the MV repair. Because suture pull-out has been reported to cause recurrent MR, optimizing suture placement may preclude the need for reoperations.

Conflict of Interest Statement

The authors reported no conflicts of interest.

The *Journal* policy requires editors and reviewers to disclose conflicts of interest and to decline handling or reviewing manuscripts for which they may have a conflict of interest. The editors and reviewers of this article have no conflicts of interest.

References

1. Woo YJ. Minimally invasive valve surgery. *Surg Clin North Am*. 2009;89:923-49.
2. Paulsen MJ, Imbrie-Moore AM, Wang H, Bae JH, Hironaka CE, Farry JM, et al. Mitral chordae tendineae force profile characterization using a posterior ventricular anchoring neochordal repair model for mitral regurgitation in a three-dimensional-printed ex vivo left heart simulator. *Eur J Cardiothorac Surg*. 2020;57:535-44.
3. Bacco L, Miceli A, Glauber M. Mitral valve repair techniques with neochords: when sizing matters. *Innovations*. 2020;15:22-5.
4. Marin-Cuartas M, Davierwala PM. Minimally invasive mitral valve repair. *Indian J Thorac Cardiovasc Surg*. 2020;36(Suppl 1):S44-52.
5. Mutsuga M, Narita Y, Tokuda Y, Uchida W, Ito H, Terazawa S, et al. Predictors of failure of mitral valve repair using artificial chordae. *Ann Thorac Surg*. 2022;113:1136-43.
6. David TE. Replacement of chordae tendinae with expanded polytetrafluoroethylene sutures. *J Card Surg*. 1989;4:286-90.
7. Colli A, Besola L, Bizzotto E, Fiocco A, Denas G, Bellu R, et al. Mechanisms of recurrent regurgitation after transapical off-pump mitral valve repair with neochord implantation. *Eur J Cardiothorac Surg*. 2019;56:479-87.
8. Imbrie-Moore AM, Paulsen MJ, Thakore AD, Wang H, Hironaka CE, Lucian HJ, et al. Ex vivo biomechanical study of apical versus papillary neochord anchoring for mitral regurgitation. *Ann Thorac Surg*. 2019;108:90-7.
9. Marin-Cuartas M, Imbrie-Moore AM, Zhu Y, Park MH, Wilkerson R, Leipzig M, et al. Biomechanical engineering analysis of commonly utilized mitral neochordae. *J Thorac Cardiovasc Surg Open*. 2022;8:263-75.
10. Oliveira D, Srinivasan J, Espino D, Buchan K, Dawson D, Shepherd D. Geometric description for the anatomy of the mitral valve: a review. *J Anat*. 2020;237:209-24.
11. Nielsen SL, Nygaard H, Mandrup L, Fontaine AA, Hasenkam JM, He S, et al. Mechanism of incomplete mitral leaflet coaptation—interaction of chordal restraint and changes in mitral leaflet coaptation geometry: insight from in vitro validation of the premise of force equilibrium. *J Biomech Eng*. 2002;124:569-608.
12. Jensen H, Jensen MO, Waziri F, Honge JL, Sloth E, Fenger-Gron M, et al. Transapical neochord implantation: is tension of artificial chordae tendineae dependent on the insertion site? *J Thorac Cardiovasc Surg*. 2014;148:138-43.
13. Paulsen MJ, Bae JH, Imbrie-Moore AM, Wang H, Hironaka CE, Farry J, et al. Development and ex vivo validation of novel force-sensing neochordae for measuring chordae tendineae tension in the mitral valve apparatus using optical fibers with embedded Bragg gratings. *J Biomech Eng*. 2020;142:0145011-9.
14. Sturla F, Votta E, Onorati F, Pechlivanidis K, Pappalardo O, Gottin L, et al. Biomechanical drawbacks of different techniques of mitral neochordal implantation: when an apparently optimal repair can fail. *J Thorac Cardiovasc Surg*. 2015;150:1303-12.
15. Pham T, Sun W. Material properties of aged human mitral valve leaflets. *J Biomed Mater Res A*. 2014;102:2692-703.
16. Barber JE, Kasper FK, Ratliff NB, Cosgrove DM, Griffin BP, Vesely I. Mechanical properties of myxomatous mitral valves. *J Thorac Cardiovasc Surg*. 2001;122:955-62.

Key Words: Biomechanics, mitral valve repair, neochordal repair