Developing a Training Tool for Intraoperative Mitral Valve Analysis

Neil A. Tenenholtz, Robert D. Howe

School of Engineering and Applied Sciences, Harvard University

ntenenh@seas.harvard.edu

INTRODUCTION

The mitral valve is one of the four valves of the human heart. Serving as a passive check valve, a healthy mitral valve permits the flow of oxygenated blood from the left atrium to the left ventricle while preventing backflow. This is accomplished via the mutual collision of the leaflets and the tethering forces of the chordae tendineae (Figure 1). When backflow occurs, the preferred method of treatment is mitral valve repair.

Mitral valve repair is a technically challenging procedure in which the surgeon modifies the native valve tissue through a series of tissue resections and suturing. While the goal is to restore valve function, i.e., ensure proper valve closure under systolic load, doing so is difficult as the heart is arrested during the operation. As a result, rather than being directly observed, closed valve shape must be predicted through analysis of the flaccid valve and the surgeon's past experience.

In analyzing the valve, the goal is to identify regions of abnormal leaflet mobility. This is achieved by pulling the chordal insertions upward using a nerve hook. Regions of excessive or restricted leaflet motion are recorded [1]. With this information, the surgeon can then visualize and predict the shape of the loaded valve. In a pathological valve, the prediction is used to develop a repair plan to restore valve function. Therefore, not only must a surgeon be capable of implementing a desired set of valve modifications, he or she must also be able to analyze a valve intraoperatively to predict closed valve shape.

This work presents the first steps towards the development of a computer-based training platform for mitral valve repair. In it, we demonstrate it is feasible to construct a platform for assessing a user's ability to predict the closed valve shape of a flaccid valve.

MATERIALS AND METHODS

Simulation: In prior work, we have developed and validated an interactive computer-based surgical simulator for valve repair [2]. The system accepts a subject-specific valve image as input and permits user interaction using a haptic input device (PHANTOM Omni). This allows for the valve to be rendered both visually and haptically. However, the use of a haptic device necessitates a 1 kHz update rate to ensure stability and haptic transparency. To produce such a fast simulation, a mass-spring approximation of a finite element model is implemented as mass-spring models are more computationally efficient than their finite element counterparts with a minimal change in accuracy [3]. Model parameters such as leaflet stiffness are taken from the results of ex-vivo mechanical testing found in literature.

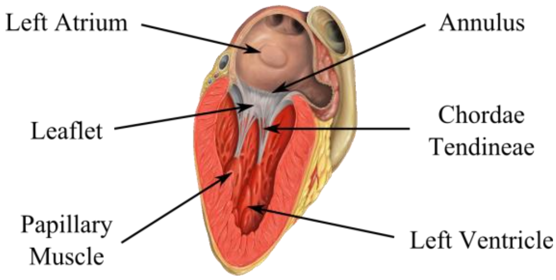

Fig. 1 The mitral valve is a key cardiac structure that regulates the flow of oxygenated blood. (Image source: Patrick J. Lynch, medical illustrator, C. Carl Jaffe, MD, cardiologist).

Using the haptic stylus, not only can the user feel the leaflet tissue, but can also pull on a desired chordal-leaflet insertion point. To do so, a stiff spring-damper is engaged between the cursor and insertion point allowing for the stable bilateral application of forces to the user and the mesh (Figure 2) [4]. Prior to being rendered to the user, forces are scaled and transformed to align with the user's viewpoint.

Evaluation: This platform was used to assess the ability of subjects, namely 3rd year medical students and cardiac surgeons, to predict closed valve shape from an unpressurized valve. Subjects were first presented with visual-only renderings of four closed valves (Figure 3) with valve closure induced using the simulation platform prior to being presented to the user. Variations in closed valve shape resulted from differences in chord lengths and papillary locations (also generated with the

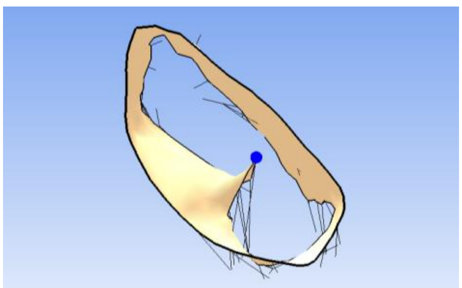

Fig. 2 Subjects use the surgical simulator to analyze the mobility of leaflet segments. The blue sphere serves as the subjects' cursor.

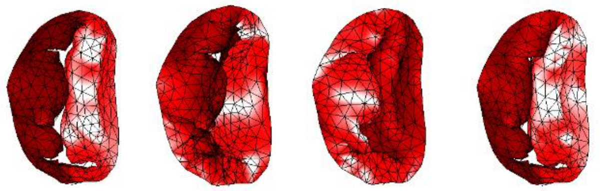

Fig. 3 For each trial, subjects were presented with four choices of closed valve geometry and asked to select which one corresponded to the open valve presented. Note the differing locations of regurgitant orifces and/or prolapsing segments.

simulator). In an attempt to isolate the subjects' ability to predict closed valve shape, accompanying lesions typically associated with these conditions, such as changes in leaflet and annular geometry, were intentionally excluded. This was done to prevent the surgeons from integrating advanced pathology-specific knowledge that medical students might not possess.

After examining the four choices from all angles, the subjects were presented with an atrial view, that which is seen intraoperatively, of a single open, unpressurized valve on the simulation platform. They were allotted a maximum of 3 minutes to pull on various chordal insertion points using the haptic device with the goal of identifying regions of restricted and excessive leaflet motion. Upon completion of valve analysis, the subjects were again presented with the four closed valve choices and asked to select the one that he or she believed corresponded to the open valve presented. Answers and time elapsed during valve analysis were recorded. This process was repeated for a total of 10 trials per subject.

RESULTS

Nine subjects were tested: 6 medical students and 3 cardiac surgeons. The average number of correct responses among the medical students and surgeons was 2.5 and 6.3 respectively (Figure 4). Surgeons performed better at a statistically significant level ($p=0.012$).

Time to perform valve analysis also varied between surgeons and medical students. While surgeons always used the full allotment of time (180s), medical students finished in less time ($p<0.001$), averaging only 90s per trial. This increase in speed was trial-dependent with later trials requiring less time to complete.

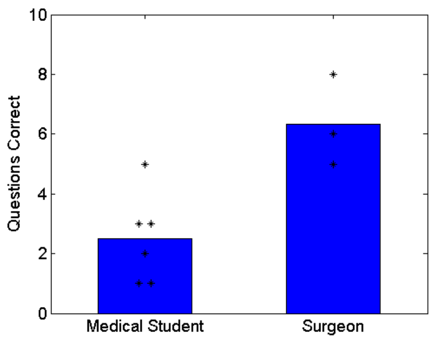

Fig. 4 Mean performance of the subject populations is shown via the bar graph with individual subjects' scores overlayed.

DISCUSSION

Despite a small sample size, the difference in accuracy between the two populations was statistically significant. This demonstrates not only the difficulty of the task, but also the importance of training. Even after three years of study, including coursework on cardiac pathophysiology, the medical students' responses were equivalent to random guessing. While this can be partially attributed to a less thorough understanding of mitral valve physiology, the different manner in which the two groups analyzed the valve was notable.

The cardiac surgeons were significantly more systematic in their analysis. The process was highly repeatable and consistent, always starting in the same region of the valve and progressing identically with variations occurring only after the entire valve was inspected. While this provided a consistent baseline for comparison, it also was more time-consuming explaining the significant difference in elapsed time. Conversely, the medical students used a more ad-hoc approach, pulling on all regions of the valve but in inconsistent orders and directions. Therefore, it was not surprising to see the best scores achieved by the cardiac surgeons with the top score achieved by the most experienced surgeon. All of this occurred despite the absence of traditional accompanying lesions and a preoperative diagnosis that cardiac surgeons typically receive.

In this work, we have demonstrated that our simulation platform is capable of assessing a subject's ability to analyze a mitral valve and predict closed valve shape. Given the demonstrated value of formalized training in valve analysis, we aim to couple this assessment technology with automated, personalized instruction to improve and accelerate the education of future cardiac surgeons.

ACKNOWLEDGEMENTS

This work was supported by NIH grant R01 HL073647 and the Link Foundation Fellowship for Advanced Simulation and Training.

REFERENCES

[1] Carpentier A, Adams DH, and Filsoufi F. Carpentier's Reconstructive Valve Surgery. Maryland Heights: Saunders Elsevier, 2010. Print.

[2] Tenenholtz NA, Hammer PE, Schneider RJ, Vasilyev NV, and Howe RD. On the Design of an Interactive, Patient-Specific Surgical Simulator for Mitral Valve Repair. IEEE/RSJ Intl. Conference on Intelligent Robots and Systems. 2011 Sept;1327-32.

[3] Hammer PE, Sacks MS, Del Nido PJ, and Howe RD. Mass-Spring Model for Simulation of Heart Valve Tissue Mechanical Behavior. Annals of Biomedical Engineering. 2011 June;39(6):1668-1679.

[4] Colgate JE, Stanley MC, and Brown JM. Issues in the Haptic Display of Tool Use. IEEE/RSJ Intl. Conference on Intelligent Robots and Systems. 1995 Aug:140-145.