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An Active Motion Compensation Instrument for Beating Heart Mitral Valve Surgery

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***Abstract*—New 3D ultrasound visualization has enabled minimally invasive, beating-heart intracardiac procedures. However, rapid motion of internal heart structures limits the realization of these new procedures. This paper investigates the concept of using a single actuator to compensate for tissue motions which occurs largely in one direction. We characterize mitral valve annulus motion and show that it is well approximated by a 1D model. The subsequent development of a motion-compensating tool (MCT) is described. The resulting instrument was tested in user trials under a series of positional error and tracking delay conditions. Results indicate that the MCT provides an approximately 50% increase in dexterity and 50% decrease in applied force in comparison to a solid tool. The study also shows that MCT tracking efficacy is highly dependent on tracking delays, indicating the importance of predictive, cyclical control algorithms.**

I. Introduction

THE development of real-time 3D ultrasound imaging has enabled new minimally invasive beating-heart procedures not possible with current endoscopic technology [1]. These new procedures avoid cardiopulmonary bypass with its attendant dangers, and consequently promise faster recoveries with fewer complications [2, 3, 4]. While beating-heart surgery has clear benefits and has been successfully demonstrated in certain procedures in an experimental setting [5], the motion of the heart during surgery presents serious challenges. This is especially true of procedures involving intracardiac structures such as the mitral valve, which recoils rapidly with each heartbeat.

One appealing approach to beating-heart intracardiac procedures is robotic assistance. Here the robot controller tracks the motion of the heart tissue and drives the robot to compensate for this motion, so the surgeon can interact with a "virtual" stopped heart [6, 7, 8]. This approach should be distinguished from recent clinical application of commercial surgical robots for performing minimally invasive mitral valve repair, with cardiopulmonary bypass [9, 10]. Prior work has focused on developing robust tracking controllers intended for multi-degree-of-freedom (DOF) robots and extracardiac procedures. Implementing a 6 DOF robot for intracardiac applications, however, entails many challenges, including the development of a manipulator with sufficient mechanical bandwidth, creating a wrist that can operate in the restricted workspace within the heart, and ensuring safety for such a system. These requirements are beyond the capabilities of current commercial surgical robots.

To avoid these difficulties, we have developed an actuated instrument with a single linear DOF for intracardiac repairs. This device can be used in situations where motion of the cardiac tissue is largely in a single direction. As shown below, this includes the motion of the mitral valve annulus, and thus the device can be used for beating-heart mitral annuloplasty, the most frequently-performed element of mitral valve repair. This instrument may be mounted on a teleoperated robotic arm or incorporated into a hand tool to allow positioning of the instrument by surgeons.

We begin this paper by characterizing the motion of the mitral annulus to determine instrument performance requirements. Next, we present the design and testing of the motion-compensating tool (MCT). A subsequent user study serves two purposes. First, it evaluates the efficacy of the MCT against traditional nontracking tools in a simulated surgical task. The study also provides data on how accurately the MCT must track the valve in order to aid operators. This information will be essential in future work including the development of predictive mitral valve tracking algorithms.

II. Motion of the Mitral Valve Annulus

To guide the development of the MCT, the mitral valve annulus motion was analyzed using ultrasound data like that available for real-time surgical guidance. A transthoracic 3D ultrasound (3DUS) image sequence of the mitral annulus was acquired at 24 volumes per second (SONOS 7500, Philips Medical Systems, Andover, MA, USA). This data was manually segmented to extract tracking information. For each time-stamped 3D volume, points were selected from the mitral valve annulus and used to locate the annulus centroid and find the annulus centroid position over the cycle of the heartbeat. Because this process was labor intensive, data from only two patients were analyzed.

Using singular value decomposition (SVD), a line was fit

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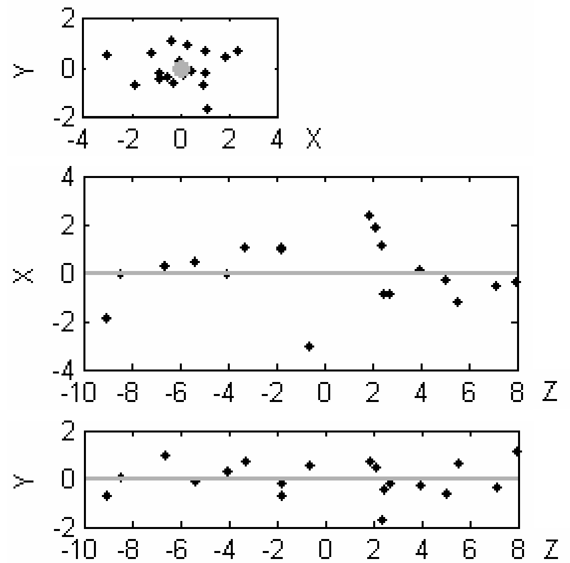


Fig. 1. Orthogonal views of 3DUS tracking data centroid positions plotted with fitted line. The axes are scaled in mm. Note the dominance of motion in the Z direction.

to each data set. The relative sizes of the singular value of each orthonormal vector generated by SVD (e.g. 21.75, 5.49, 2.97) suggest that the valve's motion is strongly constrained to this principle axis (Fig. 1). Using sheep, Gorman et al. generated data indicating that rotational movements around this primary axis are negligible [11]. Subsequent analysis therefore focuses on motion components along this axis.

Velocity and acceleration were estimated by considering relative motion between 3DUS samples. This method found centroid velocity and acceleration maxima of 210 mm/s and 3800 mm/s^2 respectively with a travel of roughly 20 mm at 76 beats per minute. While only two subjects were analyzed in this way, work by Kamigaki et al. on the mitral valve leaflets reports similar velocity and amplitude results [12].

Spectral decomposition (Fig. 2) indicates major motion components at 1.3, 2.6, and 5.2 Hz with further components of decreasing amplitude at higher frequencies. This is consistent with the findings of Nakamura et al. which show frequencies of 1.5 Hz and 3.0 Hz in the motion of porcine epicardium [6]. Ginhoux et al. found the same frequency components in porcine epicardium [7]. This paper also noted higher frequency transients it deemed significant, concluding that 25 Hz sampling would be insufficient to track the epicardium accurately [7]. Bebek and Cavusoglu found similar frequencies, but concluded that lower sampling frequencies could adequately characterize the motion [8].

III. Design of the Motion Compensating Tool

The MCT is intended to compensate for the major component of mitral annulus motion and allow surgeons to counter the relatively minor motions along the remaining axes. The surgical procedure we are developing for the MCT is a modification of a minimally invasive beating-heart

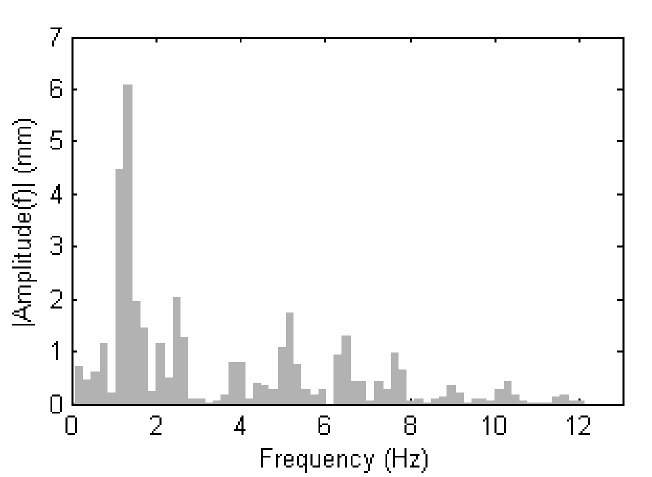


Fig. 2. 3DUS tracking data spectral decomposition.

procedure for the repair of atrial septal defects [13]. The instrument will be inserted through the left atrial appendage, controlled by pursestring sutures. A custom annuloplastry ring will be inserted through an adjacent incision and positioned over the mitral annulus (Fig. 3). Compliance in the ring holder shaft will allow it to follow the annulus motion. The actuated instrument will be tipped with an anchor driver that will "staple" the annuloplasty ring to the annulus. The surgeon will then maneuver the ring and anchor driver to the appropriate locations over the annulus and repeatedly fire the anchor driver to attach the ring and reshape the annulus.

The high velocity and acceleration requirements of mitral annulus tracking lead to a linear motor-based design which benefits from low friction and low moving mass (Fig. 4). This design format also produces a surgical tool similar in design and function to typical endoscopic tools, supported by a port and maneuvered by hand. Consequently, the MCT will be intuitive to operate for trained endoscopic surgeons.

The MCT uses a voice coil motor (NCC20-18-020-1X, H2W Technologies, Inc., Valencia, CA, USA) and a high linearity potentiometer (P3 America, San Diego, CA, USA) for position sensing. These components are mounted on a linear ball-bearing stage (BX4-3, Tusk Direct, Inc., Bethel, CT, USA). The MCT prototype has a 5.4 cm range of motion and is powered by a linear power amplifier (BTA-28V-6A, Precision MicroDynamics, Victoria, BC, Canada). PID servo control is implemented in a 1 kHz servo loop on a personal computer under Windows XP.

The resulting system has the characteristics required to track the mitral valve. The MCT has demonstrated velocities and accelerations up to 290 mm/s and 17500 mm/s^2 respectively. Controller gains were tuned to achieve good stiffness and response. To avoid dangerous overshoot and instability, the system is overdamped. The tool has a static stiffness of 0.23 N/mm and a friction force less than 0.009 N. The system's frequency response is adequate for the tracking task (Fig. 5). The system has a -3dB point of 20.6 Hz and roll off rate of 40 dB/decade. The system is capable of maintaining a commanded position with a root

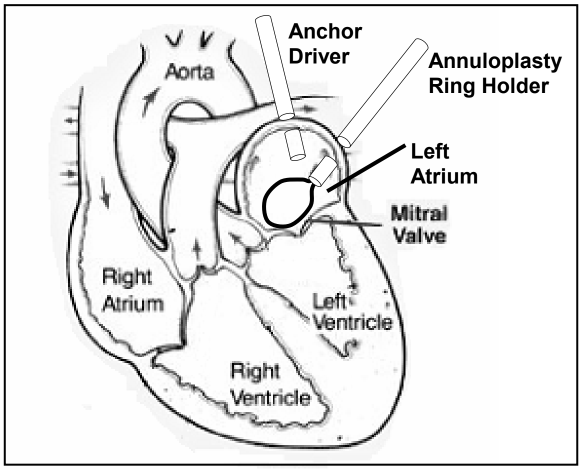


Fig. 3. Diagram of proposed surgical procedure. Note that the anchor driver approaches along the valve's axis, which corresponds to the valve's major component of motion.

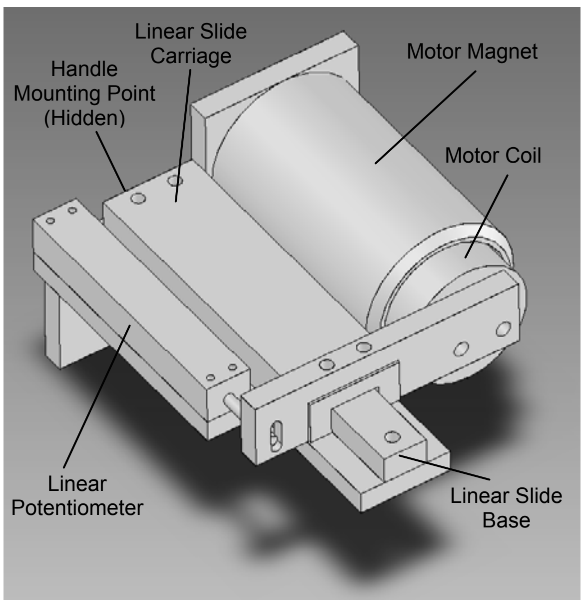


Fig. 4. A CAM model of the MCT. The MCT may be mounted by its base (at the upper left of this image) to a robot or handle. The surgical anchor driver will be mounted on the linear slide carriage.

mean square error (RMSE) of 0.009 mm. The system measures position with a RMSE of 0.004 mm.

The tracking abilities of the MCT were demonstrated by commanding the system to follow the mitral valve motion at 60 beats per minute (Fig. 6). This motion was determined from the 3DUS data above. It reliably replicated the motion profile of the valve with an effective delay of 14 ms.

IV. Evaluation of MCT Mitral Valve Tracking

In Vitro user trials were run to quantitatively evaluate the effectiveness of the MCT at assisting operators working on a moving target. These trials also provide information on the quality and accuracy required of tracking data that will help guide the development of real-time tracking and control algorithms. The effects of two tracking error types, time delay and random positional error about the true target

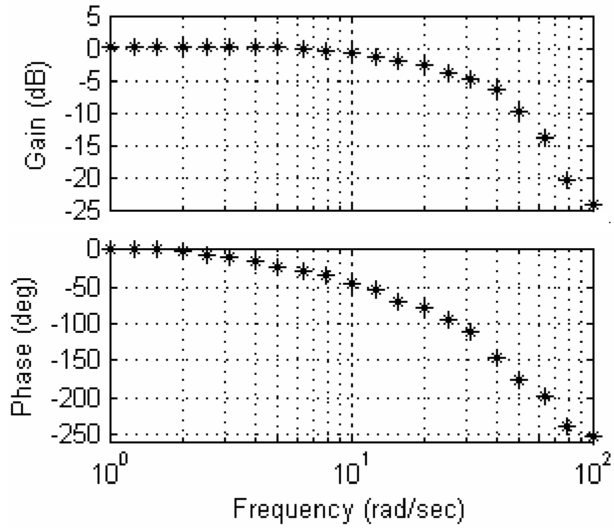


Fig. 5. Frequency response of the MCT. Note that the system is overdamped and has a -3dB point of 20.6 Hz.

position, were investigated. These errors types are of interest because both positional accuracy errors and computational delays may develop while generating 3DUS tracking data in real-time. A total of eight test subjects (five male, three female, 22-28 years) performed a drawing task on a moving target using the MCT under different tracking conditions. Both dexterity and force were used to evaluate performance.

A. Experimental Setup

The tests used a setup which emulates the expected surgical task. To simulate the moving valve, a target platform was mounted on a cam follower that replicates the previously characterized 1D motion of the mitral annulus centroid. A paper target affixed to this platform recorded the subject's drawing. A 0.5 cm hard foam rubber pad between the target paper and platform provides compliance. In combination with the pen used in the trials, the pad had a stiffness of 4.5 N/mm. The cam simulated a heart rate of 60 beats-per-minute. Opposite the target, the MCT was mounted in a gimbal allowing both angular motion and translation towards the target (Fig. 7). A rod was mounted on the MCT with a ballpoint pen affixed to one end and a force sensor incorporated along its length. The force sensor had a stiffness of 10 N/mm. In place of the 3DUS-based tracking that would be used in surgery, target position was measured by a contact arm with potentiometer attached to the target. This method provides the accurate tracking data necessary to evaluate the efficacy of MCT mitral valve tracking and the requirements of 3DUS-based tracking algorithms. Operators viewed the target directly rather than via filtered and stabilized images proposed for surgery

B. User Task

Subjects were instructed to draw a circle on the moving platform between two concentric target circles with 2.29 cm and 2.92 cm diameters. Subjects started at the top of the circle and proceeded in a clockwise direction. If the pen bounced off the target surface or out from between the target

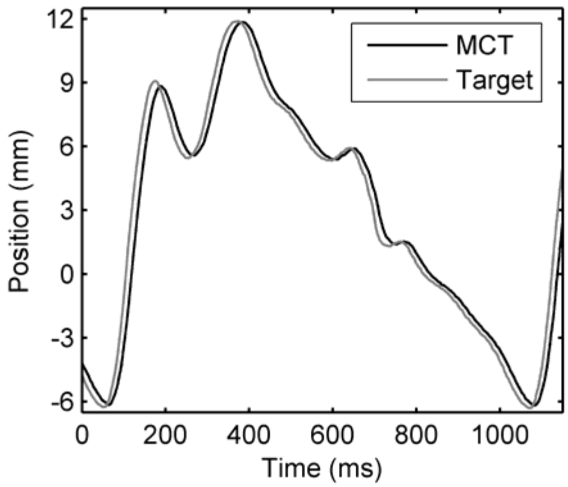


Fig. 6. MCT tracking a simulated mitral valve annulus. The MCT motion profile mimics the target with approximately 14 ms delay.

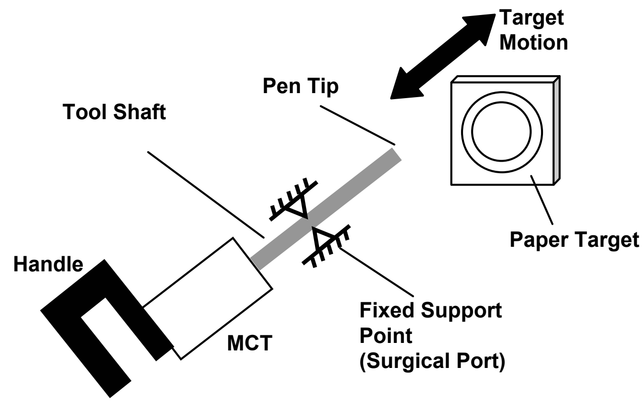


Fig. 7. Diagram of user trial setup. The bold arrow indicates the cyclical motion of the simulated valve target. The tool shaft has free angular and sliding motion at the fixed support point.

circles, the subject continued drawing from the clockwise-most mark between the circles. Subjects traced the circle once. They could not retrace any gaps. A 25 s time limit was set, but all subjects finished every trial before time expired.

In all trials, dexterity was characterized by digitally scanning the target and computing the drawn line's "angular surround" value. This value indicates what percentage of 360 discrete 1° arc segments the user's line covered between the two concentric target circles. This metric reflects positioning accuracy both in the plane of the target and in tracking the motion of the target. If the user-drawn line strayed from the target circles, it earned a low angular surround score. Similarly, if the user and MCT were unable to track the target, the pen tended to bounce on the target surface, producing widely spaced marks and a low score.

For four subjects, the axial force applied by the subject to the target was also recorded. In all eight cases, subjects were informed of both evaluation metrics. They were instructed that their foremost objective was to draw continuous circles conforming to the angular surround metric and only secondly to use the minimum amount of force necessary.

This task was selected to emulate the requirements of placing a surgical anchor. In order to apply the anchors developed for this procedure, the tip of the anchor driver, consisting of 14 gauge hypodermic tubing, must be accurately located and pressed against the target surface with a force of at least 1.5 N [14]. This contact must be maintained for several seconds as the surgeon inserts the anchor, tests whether it is properly deployed, and finally releases it. This process requires both accuracy and prolonged contact with the surface. At the same time, forces must be minimized so as not to damage the valve.

C. *Independent Variable: Tracking Condition*

Subjects completed the task under eight different tracking conditions. The "solid" condition rigidly locked the motion of the MCT to simulate a traditional, solid endoscopic tool. For the "baseline" MCT tracking condition, the current position of the target (RMSE = .015 mm) was sent to the MCT as a position command. This baseline condition resulted in a 14 ms delay. The remaining six tracking conditions are divided into two groups.

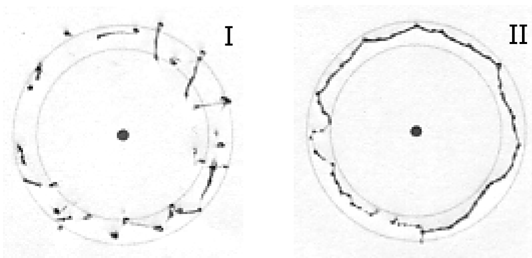
Random positional error was simulated by the superposition of a time varying error value with the cam position command used in the baseline tracking state. A new positional error was calculated at 8 Hz. These errors were uniformly distributed random values $\in [-1, 1]$ multiplied by an amplitude factor of 0.35, 0.70, or 1.05 mm, denoted as "error1," "error2," and "error3" respectively.

Delay error was implemented by recording the target position and holding it before sending this position to the MCT as a command. Three levels of added delay were used: 25, 35, and 45 ms. Including the effective delay of 14 ms, these delay conditions of 39 , 49, and 59 ms will be described as "delay1," "delay2," and "delay3" respectively. This range of times was chosen as representative of the transmission and computational delays expected with real-time 3DUS-based mitral valve tracking [15].

D. *Testing Protocol*

Each subject test consisted of a practice period followed by eight trials. Practice was intended to familiarize the user with the MCT and the evaluation task in order to limit learning effects during trials. Practice was divided into three one-minute segments during which the user subject was free to use the MCT to draw on a target paper. During the first minute, the target was stationary and the tool was set in the solid condition. The second involved a moving target and a solid tool. In the third, the target was moving and the MCT was in the baseline tracking condition. Following training, each subject completed eight trials corresponding to the eight tracking conditions. Trial presentation was ordered in a balanced Latin square to minimize learning effects.

The means of collected angular surround scores were compared for statistically significant differences using the SPSS statistical analysis software package (Version 14.0, SPSS Inc., Chicago, IL, USA). These comparisons were



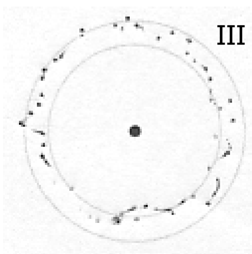


Fig. 8. Targets with median angular surround scores under solid (I), baseline (II), and delay3 (III) tracking conditions. Note that the baseline circle is the most continuous and round. While the solid target has more continuous lines than the delay3 target, it also has heavy dots and dimpling indicative of high forces.

made using *t*-tests and ANOVA with an LSD post hoc test. In all cases, significance corresponds to $p < 0.05$.

V. Results

Mean angular surround scores (Fig. 9A) for baseline tracking (81.9 ± 4.5% (mean ± standard error)) were over 50% greater than for the solid condition (53.8 ± 5.0%), with clear statistical significance ($t(14) = .1987$, $p = 0.0009$). Similarly, axial force data indicates that subjects applied less than 50% as much force and spent less time at elevated forces under the baseline MCT tracking condition. Aggregating the data from all four subjects (Fig. 10), the 90^{th} percentile for force samples using the solid tool (17.5 N) is about double the 90^{th} percentile for the baseline tracking condition (8.5 N). These results are confirmed by the targets with median angular surround scores (Fig.8).

The mean angular surround scores related to the delay error type (Fig. 9B) demonstrate performance increases of 33% to 67% with decreasing delay ($f(3, 28) = 16.005$, $p < .001$). Statistically significant differences were indicated between the baseline condition, and delay1 (61.2 ± 1.5%), delay2 (56.0 ± 3.7%), and delay3 (48.8 ± 3.8%). A significant difference also exists between the means of the delay1 and delay3 conditions ($p = 0.02$). Trend analysis indicates that a linear model fits the data well ($p < 0.001$).

An analysis of mean angular surround scores related to positional error did not demonstrate significant differences under ANOVA analysis ($f(3, 28) = 0.638$, $p = 0.597$). The mean score under the baseline condition differed very little from those of the error1 (81.7 ± 3.3%), error2 (78.0 ± 5.5%), and error3 (74.2 ± 4.6%) conditions (Fig. 9C).

VI. Discussion

This study demonstrated that the MCT is an effective aid for working on moving targets. MCT motion synchronization allowed users to operate with increased dexterity and lower forces. Angular surround scores indicative of dexterity increased by over 50% between the solid and baseline conditions while the 90^{th} percentile for force decreased by a similar ratio. These performance gains were maintained when increasing levels of positional error were inserted, but disappeared when delays were added.

The strong dependence of performance on tracking delay emphasizes that precise timing is essential for successful motion compensation. Tracking delay was most problematic during the rapid recoil of the target associated with the ventricular contraction. During this motion (100-200 ms in Fig. 6), the valve covers almost its entire 2 cm range. Because of delay, the MCT continued to servo towards the oncoming target and collided with it. Qualitatively, while subjects did not always notice added positional error, they all identified and lamented tracking delay. Note that the baseline condition contained an effective 14 ms delay. If this delay is removed, extrapolation from the linear model fitted to delay data predicts angular surround scores above 90%, although other factors may preclude such gains. These findings underscore the importance of synchronization with the valve's large-scale motion.

The levels of positional error explored had negligible effect on MCT tracking efficacy. No statistically significant differences were found between user performance under all three positional error conditions and the baseline condition. All four of these conditions included the baseline condition's effective 14 ms delay. These results suggest that, if timing with the valve's abrupt motion is maintained, the value of MCT tracking is robust in the face of positional errors up to ±1 mm. This may be attributed, in part, to compliance in the system: in the MCT's mechanism, in the cam, and in the foam target pad, which introduced compliance similar to cardiac tissue. An *in vivo* test of MCT performance on the mitral valve is necessary to determine whether compliance acts in the same way to assist operation on the valve annulus.

The efficacy of the MCT is based on the assumption that the motion being tracked is well modeled by a 1D approximation. Previous research on augmenting surgical procedures with robotic tracking have focused on coronary artery bypass grafting (CABG), requiring a 3D model of surface motion [6, 7, 8]. Our characterization of the mitral valve strongly suggests that it satisfies this 1D requirement. The MCT must be tested *in vivo* to demonstrate that the assumption of a 1D motion approximation holds.

While the current MCT design is adequate for tracking the mitral valve, this study has demonstrated that it is not optimal. The actuator has more than twice the necessary travel. Consequently, both the size and moving mass of the MCT could be greatly reduced, resulting in improved performance. A more refined controller would also improve performance. While effective, the controller currently does not provide such features as feedforward accelerations.

Future work will focus on developing and testing suitable 3DUS tracking algorithms incorporating predictive, cyclical control. Previous work has demonstrated the benefits of

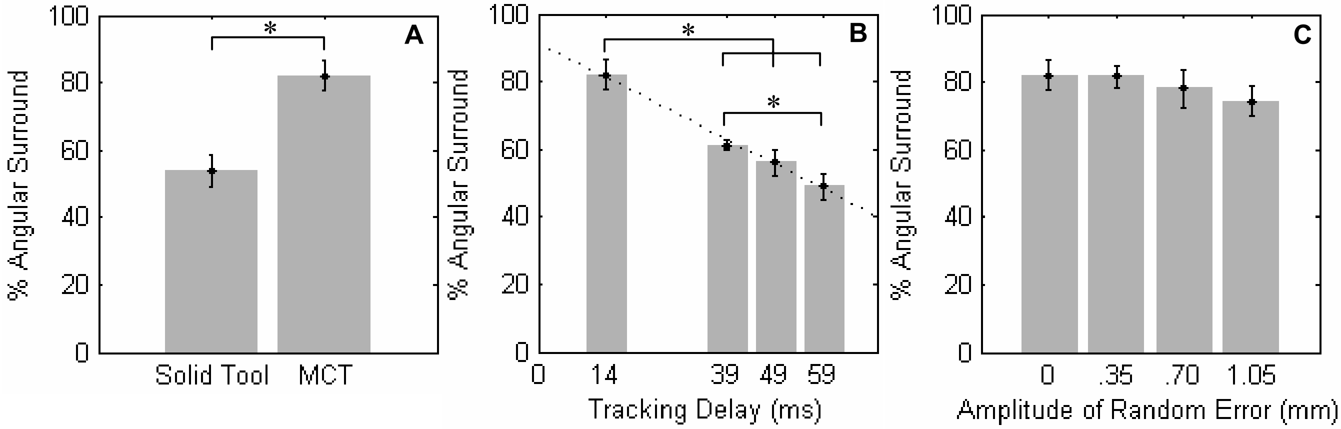


Fig. 9. Angular Surround Performance Scores. Error bars indicate standard error. "*" marks statistical significance. (**A**) Baseline MCT and solid tool tracking conditions. (**B**) Delay tracking conditions. Note fitted linear model ($R^2 = 0.9937$). (**C**) Positional error tracking conditions.

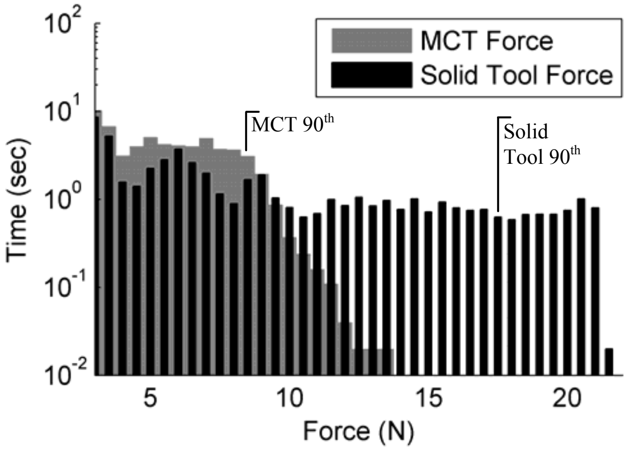


Fig. 10. Histogram of applied force samples under baseline MCT and solid tool tracking conditions. Smaller forces are consistently applied under the baseline condition. 90th percentiles are marked. The zero force bin is not shown.

such predictive algorithms in CABG applications [6, 7, 8]. Our user study indicates that robust timing is essential for helpful MCT tracking. The inclusion of ECG data, as demonstrated by Bebek and Cavusoglu, should satisfy this requirement [8]. An MCT control algorithm based on these models would provide the feedforward accelerations necessary to synchronize with the mitral valve's abrupt motions and eliminate the 14 ms delay observed here. The development of such a control algorithm will facilitate *in vivo* user studies, which will indicate the MCT's suitability for mitral valve procedures and similar 1D motion tasks.

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