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**PRACTICAL, NON-INVASIVE MEASUREMENT OF URINARY CATHETER
INSERTION FORCES AND MOTIONS**

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ABSTRACT

Catheter associated urinary tract infections (CAUTI) are among the most common nonpayment hospital acquired conditions. Inexperienced health care providers placing indwelling urinary catheters are associated with an increased risk of CAUTI. The creation of high-fidelity simulators may reduce CAUTI risk during critical early learning. As a first step toward the creation of accurate simulators our group set out to characterize the mechanical aspects of urethral catheterization. This work presents an inexpensive, yet practical means of acquiring motion and force data from urethral catheter insertion procedures using OpenCV ArUco markers. Evaluation of the video system's accuracy was done to understand the performance characteristics within the boundaries of the procedure's target workspace. The tracking accuracy was validated to be roughly ± 3 mm in the plane of the camera, and $\pm 10 - 25$ mm along its axis depending on the distance. Feasibility of using this platform in a clinically relevant setting was demonstrated by capturing the force and motion data when performing urinary catheterization on cadaveric donors (N=2).

INTRODUCTION

Catheter associated urinary tract infections (CAUTI) are the most commonly reported hospital acquired infection. CAUTI arise secondary to indwelling urinary catheter placement and cause increased hospital cost and patient morbidity [1]. While a great deal is known about patient and environmental factors that contribute to an increased CAUTI risk, only recently have studies begun assessing providers who are placing indwelling catheters. Most notably, inexperienced health care providers placing indwelling urinary catheters are associated with a 4-fold increased risk of CAUTI [2]. One potential avenue to reduce CAUTI rates is to provide proper instruction, objective assessment, and accurate simulation during early clinical training or remedial testing.

Realistic simulators may better facilitate skill transfer into practice settings but this requires accurate knowledge of the mechanical responses of tissues to clinician motions such as friction force. This should span both typical and atypical anatomy as well as tissue responses resulting from proper motions and improper motions that lead to injury or potentially CAUTI's. Urinary insertion force has been subjectively self-reported by healthcare providers after completing a procedure [3]. To our knowledge, no research that has investigated the mechanics of urinary catheter insertion objectively and there is no readily-available device to measure required forces and motions. The objective of this work is to i) introduce a system to practically cap-

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ture motion and force of typical urinary catheterizations, ii) determine the accuracy of this inexpensive motion capture method, and iii) demonstrate feasibility of clinically meaningful data acquisition on cadaveric donors.

METHODS

The mechanical characteristics tracking platform in this work leverages our prior work [4] which describes a catheter insertion force assessment tool. In short, this inexpensive device is comprised of a 3D-printed handle instrumented with two 780 g load cells (Phidgets Inc., Calgary AB, Canada) and two HX711 load cell amplifiers (SparkFun Electronics, Inc., Niwot, CO) to measure the insertion force. A Teensy 3.2 microcontroller (PJRC, Sherwood OR, USA), and bluetooth modem (SparkFun Electronics, Inc., Niwot, CO) served as a means to communicate data back to the host PC.

ArUco markers [5] were used to measure the 3 dimensional motion of the operator during the procedure with the Open Source Computer Vision Library (OpenCV) [6]. Video capture of the markers was facilitated by a GoPro Hero7 Black camera (GoPro Inc., San Mateo, CA) set to record 1080p footage at 240 FPS (1920x1080 pixels used in post-processing herein). The procedure in the ArUco library documentation was used to calibrate our camera and obtain intrinsic and distortion parameters [7].

The accuracy of the ArUco markers and video system was assessed in the a target workspace enclosing typical hand motion for urinary catheter insertion [Fig. 2, 3]. The “closest” configuration was roughly 270 mm away from the camera, and the displacement between the two successive configurations were

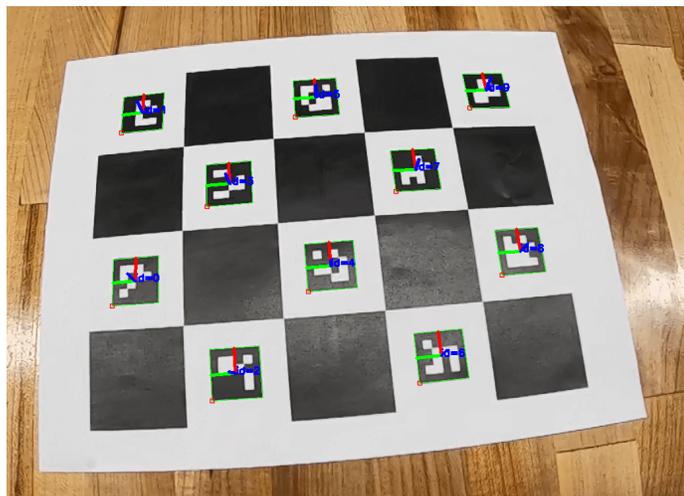


FIGURE 1: EXAMPLE POSE ESTIMATION (COLORED TRIADS) EXTRACTED USING OPENCV ARUCO MARKERS (8.5“ x 11” STANDARD U.S. PAPER SIZE)

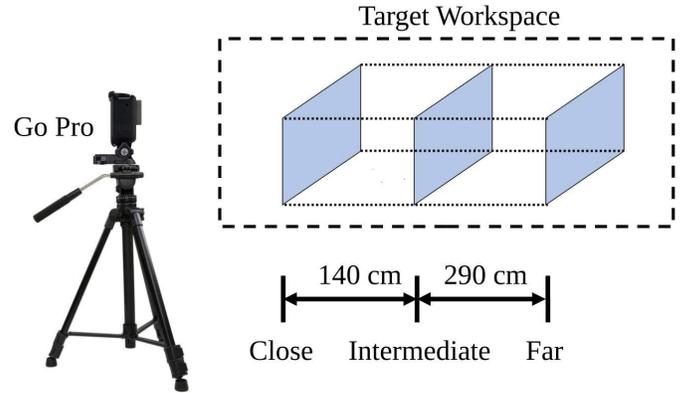


FIGURE 2: EXPERIMENTAL SETUP FOR MEASURING ARUCO MOTION CAPTURE ACCURACY WITHIN TARGET WORKSPACE OF TYPICAL CATHETER INSERTION MOTIONS. THREE REGIONS: CLOSE, INTERMEDIATE, AND FAR ARE SHOWN WITH KNOWN DISPLACEMENTS. INTERMEDIATE REPRESENTS APPROXIMATE CENTER PLANE OF WORKSPACE IN WHICH MAJORITY OF MOTIONS ARE EXPECTED TO OCCUR. THE DISTANCE FROM THE CAMERA TO THE TARGET WORKSPACE IS APPROXIMATELY 270 MM



FIGURE 3: PHOTO OF EXPERIMENTAL SETUP IN INTERMEDIATE CONFIGURATION

known to be 140 and 290 mm respectively. At each configuration, the camera was set to record an array of ArUco markers as in Figure 1 for 3 - 5 seconds. The videos were then processed by OpenCV routines and the ArUco library, and the position data imported into MATLAB.

At each frame, the centroid of all the detected ArUco mark-

ers was computed which served as a reference point. The ground truth positions in the plane of the paper (hereby referred to as the XY plane) were measured via a caliper and compared to the output of the computer vision algorithm. For details on the underlying ArUco detection and tracking algorithms see [5].

To validate our device and tracking system for feasibility in a clinically relevant setting, procedure data was collected on two non-fixed male human cadavers by coauthor MT. Access to cadavers was granted through the University of Minnesota’s Anatomy Bequest Whole Body Donation Program. The catheter insertion force assessment tool was used to place both a Foley, and Coude urinary catheter while subject to computer vision tracking [Fig. 4].

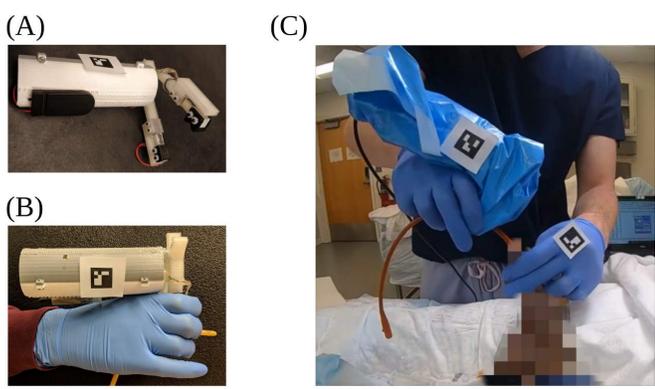


FIGURE 4: A, B) PHOTO OF CATHETER INSERTION FORCE ASSESSMENT TOOL. C) PERFORMING CATHETERIZATION ON UNFIXATED CADAVERIC DONOR WITH DEVICE AND TRACKING PLATFORM

RESULTS AND DISCUSSION

The ArUco computer vision algorithms for marker tracking are accurate, simple, and inexpensive to implement. In the XY plane, we observed a typical RMS error of 3 mm [Fig. 5]. In the z-axis (along the axis of the camera), larger errors were recorded – on the order of 10 - 25 mm depending on the distance away [Fig. 6]. Larger errors along the axis of a camera relative to in-plane errors are a well understood limitation in computer vision, reflected in the results presented here. Additionally, as expected there is a trend between increasing distance, and increasing error across both in-plane and out of plane measurements. Increasing distance between the camera and the target leads to a lower resolution capture of the marker, which leads to jitter in the detected output [8].

In the context of our application, urinary catheter insertion, the device primarily moves along a single plane. Thus proper camera positioning can mitigate the accuracy penalty incurred by motion in the z-axis. This affords us millimeter level accu-

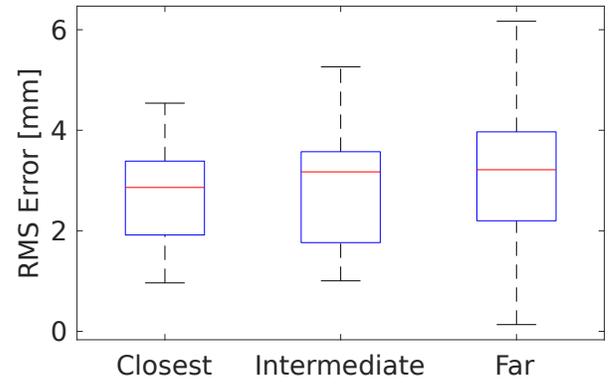


FIGURE 5: ROOT MEAN SQUARED ERROR IN THE XY PLANE FROM TRACKING EXPERIMENT IN ALL 3 CONFIGURATIONS

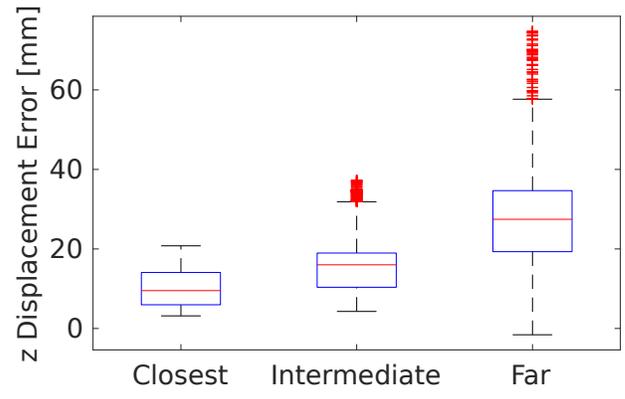


FIGURE 6: Z DISPLACEMENT ERROR FROM TRACKING EXPERIMENT IN ALL 3 CONFIGURATIONS.

racy when tracking motion during catheterizations. Admittedly, compared to the state of the art, EM based tracking, our computer vision based approach cannot deliver its sub-millimeter level accuracy. The strength of this work instead lies in its low cost and simplicity; anyone with a camera and inkjet printer can acquire catheter motion trajectories.

During the cadaver study, it was found that typical maximal urinary insertion forces were about 3 - 6 Newtons. The greater forces were often observed at the end of a “push-event” during insertion. The average speed of the catheter was 6 cm/s during the procedure. To better quantify the friction force during the insertion motion, the relationship between insertion force and velocity will be further examined in future work. Understanding the mechanical factors in urinary catheterization, such as the urethral-catheter friction are the first step in acquiring data to better inform the development of next generation simulators.

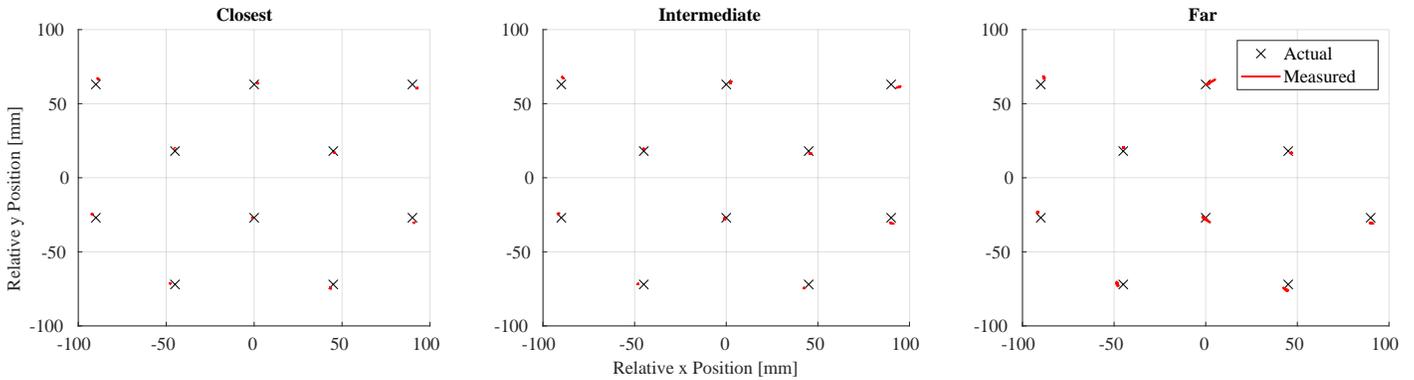


FIGURE 7: DEPICTS THE RELATIVE ACCURACY IN THE XY PLANE RELATIVE TO THE ARUCO GRID. THE GROUND TRUTH (X) IS COMPARED WITH THE MEASURED OUTPUT FROM THE COMPUTER VISION ALGORITHM. THIS IS SHOWN FOR ALL 3 CONFIGURATIONS

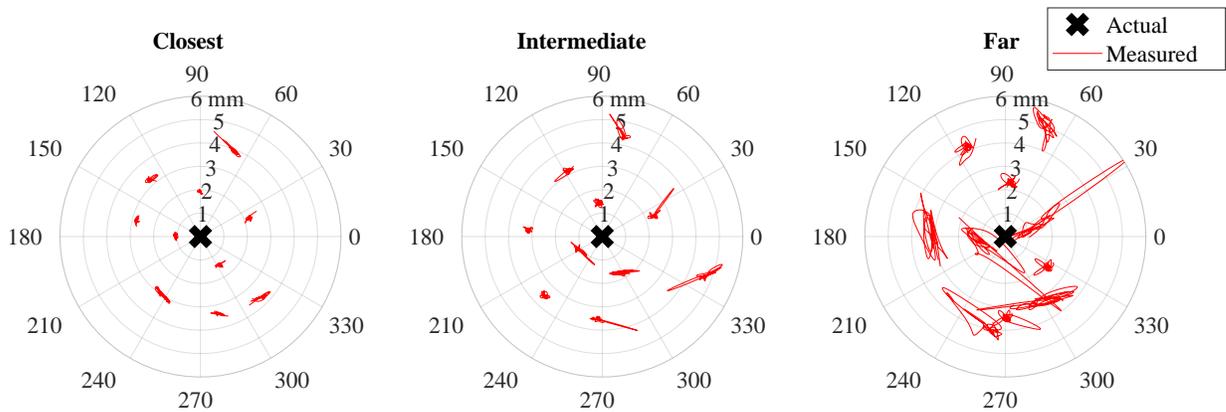


FIGURE 8: A MAGNIFIED VIEW OF FIG. 7 WITH ALL GROUND TRUTH POINTS ALIGNED AT THE ORIGIN.

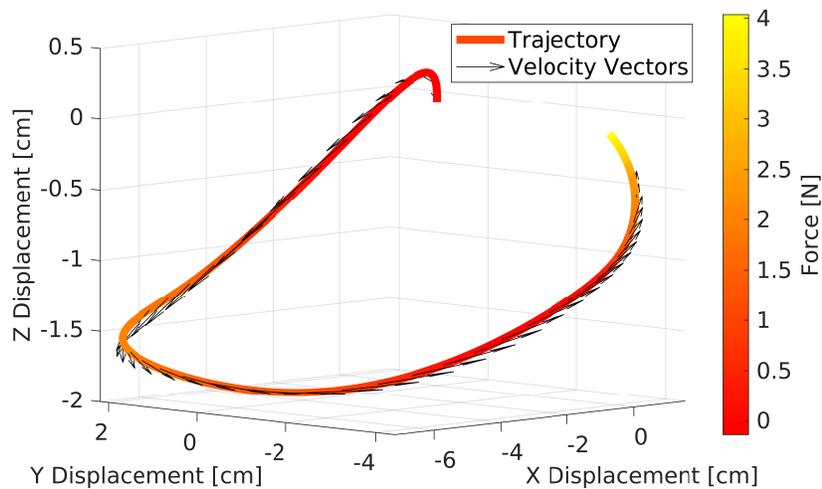


FIGURE 9: 3D TRAJECTORY CAPTURED DURING THE CADAVERIC STUDY. REPRESENTS MOTION AND DYNAMICS OF CATHETER INSERTION FORCE ASSESSMENT TOOL OVER A 2 SECOND PERIOD.

CONCLUSION

This work demonstrates successful, practical motion and insertion force collection on urinary catheter placement in clinically realistic settings. Future work will seek in-vivo data from consenting patients.

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