Motion analysis of flexible ureteroscopic techniques by urologic surgeons

by

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Abstract

Urologic surgeons, in order to surgically remove kidney stones from patients who suffer from this painful condition, perform a common procedure known as flexible ureteroscopy. During this operation, the surgeon will utilize a 3mm-diameter flexible camera passed through the urinary tract to fragment, manipulate, and remove kidney stones. The flexible ureteroscope utilizes a non-intuitive control mechanism including a thumb-actuated lever and various wrist rotations to direct the end effector. Numerous methodologies exist to evaluate, understand, and train proper surgeon movement when operating this device, although the current literature suggests that urologists cannot sufficiently define correct or successful device interaction.

In this study, we employed infrared motion capture in combination with standard video analysis to characterize surgeon movement variables in a simulated clinical scenario. A ureteroscopic simulation box was used by 12 practicing urologists at various skill levels to perform a number of ureteroscopic tasks. Demographic, motion, and task-specific data were recorded and analyzed to delineate associations between measures of ureteroscopic efficiency and success. This project suggests that certain surgeon movement data, including measures of economy of motion and wrist rotation, trend with efficient ureteroscopic manipulation and require additional study. These variables could potentially serve as a basis for improvement in device development and urologic surgical training and evaluation.

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Leia Stirling started out as the professor of a class I decided to listen in on and has become an incomparable teacher and collaborator. Thank you so much for being willing to work with a clinical urologist who had an interest in understanding more about movement science and motion analysis. I also owe a great deal to Richard Fineman, PhD, William Woltmann, and Keegan Deppe for your assistance in study design, study execution, data analysis, and impressive MATLAB skills.

Thank you to the group of urologists who were willing to take time out of your busy clinical practices to participate in this study.

Thank you to my IDM classmates; you have reminded me how important it is to remember that life exists – and can often be more fun – outside of the medical field.

Lastly, thank you to my family. My parents and sister, who have supported me throughout my life and studies. My wife, Eugenie, who has stood by my side through many wonderful times and many, many long nights spent working on a Masters degree. And my son, Oliver, who continues to provide me with endless joy and distraction. Without you all, this would not have been possible.

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1. Introduction

1.1 Motivation

Nephrolithiasis, or the presence of kidney stones, is a very common condition, affecting approximately 1 in 11 individuals in the United States. (1) The prevalence of this disease has been increasing - nearly doubling over the last 15 years - with a multifactorial set of causes. (2) These include changing population dynamics, modification of dietary risk factors, spread of obesity and metabolic syndrome, and climate changes that affect the environment in which we live. (3) While this was typically a disease of middle-aged individuals, nephrolithiasis has also become more common in typically low-risk populations, including women, children, and elderly. (2) Studies have correlated kidney stone risk with warmer weather; as climate change increases the average ambient temperature, this risk will increase as well. (4) All told, the physical, emotional, economic, and societal burden of kidney stones is tremendous, with estimates suggesting over $5 billion in yearly direct/indirect costs of this disease. (5, 6)

Treatment of kidney stones is typically a combination of medical prevention and surgical therapy, with a variety of surgical options available depending on the clinical situation. (7-9) The most common surgical procedure currently performed for kidney stones is flexible ureteroscopy. (10) In this procedure, the patient undergoes general anesthesia and is placed in dorsal lithotomy position (on the back with legs in stirrups) such that the urethra is accessible to the surgeon. A small camera - cystoscope - is placed into the urethra and bladder and a small, compliant wire is passed up to the kidney of interest through the ureter - the conduit that drains urine from the kidney to the bladder. An approximately 3mm diameter flexible camera is then passed over this wire up into the kidney, where the surgeon can control the movement of the camera through an external control mechanism. This control mechanism typically consists of a thumb-actuated lever that directs the flexion of the camera, with wrist rotation (primarily of the dominant hand) modifying the other axes of camera rotation (Figure 1). (11)

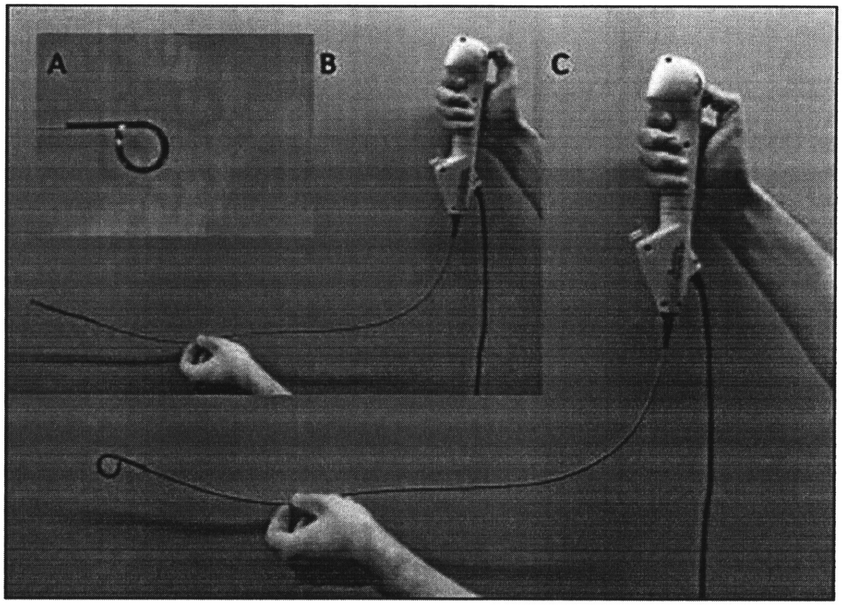


Figure 1. External view of a flexible ureteroscope; A. Flexible end effector tip at maximum deflection. B. External view of the device with dominant hand on thumb-actuated lever and non-dominant hand supporting the camera. C. External view of device with tip at maximum deflection, produced by dominant hand thumb flexion. (modified from Buttice et al(11))

Multiple types of movements can be performed by utilizing combinations of dominant hand rotation and thumb movement, although additional body movements can further modify the achievable range of motion. Furthermore, the surgeon can use slight pressure of the ureteroscope on various parts of the patient's internal anatomy to produce added flexion. From straight camera advancement to complex trajectories including retroflexion (or a complete flexion of the camera back towards the surgeon as seen in Figure 1A), the flexible ureteroscope has ample mobility to reach a majority of endoscopic targets. Once the surgeon has reached the target stone(s), various manipulators and lithotrites can be utilized to fragment and remove the kidney stones.

This procedure will typically last anywhere from 15 minutes up to – and beyond – 3 hours, depending on the complexity of the stone disease and the surrounding anatomy. It is a very common procedure that nearly all urologists perform and with which most urologic trainees become facile. (12) Some urologists, though, choose to undergo additional training specifically in the field of kidney stone treatment – endourology – and these surgeons may develop additional expertise and specialization towards this procedure. (13) Interestingly, despite the frequency of its utilization and the wide ranges of expertise seen, there is no undisputed methodology for evaluating skill or success associated with ureteroscopy. (14-18) Face-to-face observer checklists (including the URS-GRS [Appendix A], which incorporates tissue handling, instrument handling, economy of motion, and procedural knowledge) have not been sufficiently robust for understanding of surgical skill, while crowd-sourced video-based evaluations – which are commonly used for assessment in other surgical situations – appeared inadequate.(14, 19) These inadequacies seem to be secondary to a lack of understanding across the field regarding proper movement and measures of success. Similarly, although the procedure is so dependent on the understanding, utilization, and handling of the flexible ureteroscopic camera, there is no uniform and standardized methodology for teaching or familiarizing trainees with this device. (19-21)

Importantly, as urologic training becomes more focused on complicated device interaction, it becomes more critical to pinpoint methods through which we can understand current and – eventually – optimal surgical technological utilization. By exploiting the positional information embedded within a robotic-assisted laparoscopic surgical system, for example, one research group was able to correlate specific surgical movements and behaviors (increased movement efficiency and specific needle-placement gestures) with measures of success (decreased surgical time and tissue trauma). (22) While certain groups have attempted to understand the ergonomics associated with flexible ureteroscopy from the standpoint of muscle group analysis(23), direct measures of anthropometric and body kinematics data has not yet been used as a signal of – nor input variable toward – success. Anecdotally, surgeons discuss that certain movements, such as bilateral opposing wrist rotation (moving the wrists in opposite directions) and matching head roll to dominant-hand wrist rotation (tilting the head in the target direction) appear to correlate with lack of surgical experience. By developing a better understanding of the way in which urologists interact with the flexible ureteroscope and potentially use this understanding as a window into the various technical strategies utilized during this procedure, we aim to work towards a framework for improved surgical skill assessment, training, and potentially future urologic device development.

1.2 Objectives

By utilizing a ureteroscopic simulation environment, the research presented in this thesis will attempt to provide an explicit description of technically successful or efficient ureteroscope utilization. With an in-depth analysis of surgeon movements and techniques associated with success, this research will provide a scaffold upon which the interaction between urologist and ureteroscope can be further analyzed, studied, and eventually improved. This analysis will be done through several aims:

1. Record, tabulate, and describe the various movements seen during ureteroscopy simulation
2. Correlate specific movements, techniques, and strategies with several measures of ureteroscopic task success or efficiency
3. Generate behavioral or device-interface targets for future design and training methods

2. Methods

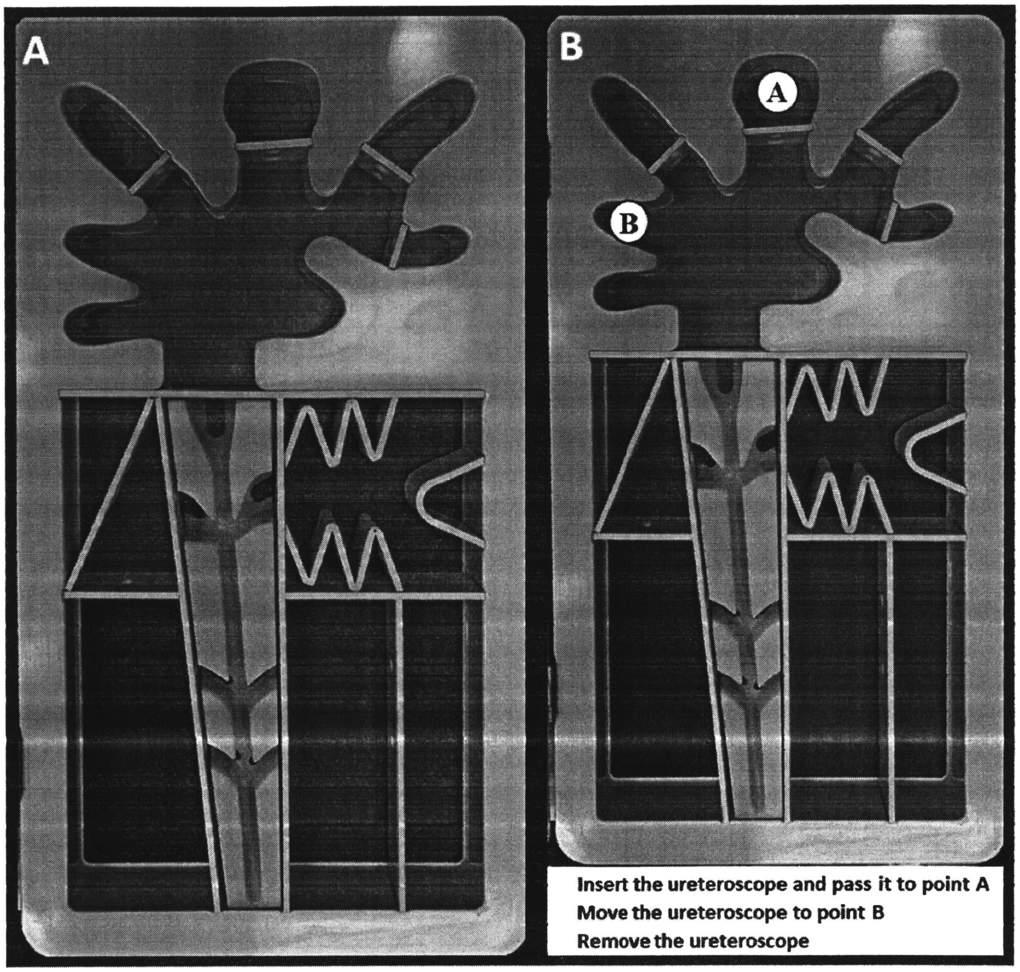
2.1 Participants

Twelve participants completed this study; participants were urologic surgeons at various levels of urologic training, from first-year resident to over 25 years of urologic practice. Inclusion criteria required that participants were healthy and currently perform ureteroscopic urologic surgery in their practice. There were no exclusion criteria. The participants gave informed written consent for their participation in the experiments, which were approved by the MIT Committee on the Use of Humans as Experimental Subjects. Participants received no monetary compensation for their participation in this study.

2.2 Experimental Protocol

2.2.1 Task

Participants were instructed to perform a series of 13 ureteroscopic simulation tasks that consisted of directing a flexible ureteroscope to a number of target stones within a simulation box as seen in Figure 2A. The tasks were performed from a standing position in a manner consistent with standard surgical practice. Participants utilized a single-use flexible ureteroscope (LithoVue, Boston Scientific, Marlborough, MA) with associated imaging tower to perform the tasks. This single-use flexible ureteroscope is lighter than a standard reusable ureteroscope, although the device layout and control mechanism is consistent between both device types. The tasks consisted of entry of the ureteroscope into the simulation box, contact with each target stone in order, and then removal of the ureteroscope from the simulation box. Each task was designed to require specific types of movement and were defined as complex or simple based upon the movements involved. A sample task can be seen in Figure 2B – each participant had continuous access to the task diagram in order to facilitate understanding of the stone locations. Time to complete each task was recorded; participants had a maximum allotted time of 2 minutes per task.



Insert the ureteroscope and pass it to point A
Move the ureteroscope to point B
Remove the ureteroscope

Figure 2. Ureteroscopic simulation box utilized for tasks; A) Internal view of simulation box – participants were unable to see the interior of the box during the tasks. B) A sample ureteroscopic simulation task with instructions as visible to participants.

2.2.2 Procedure

Participants began by filling out a questionnaire that gathered information regarding demographics, surgical training, and surgical practice. After an explanation of the planned procedure and placement of motion capture markers by the investigators (as described below in section 2.3), the participant was positioned in a neutral stance in front of the simulation box with the ureteroscope resting within the right hand. Of note, the simulation box interior was shielded from the view of the participant by utilizing a non-reflective drape. An investigator placed stones within the simulation box according to the task diagram and the participant was signaled to begin the task. At the conclusion of the task, the participant would return to a neutral position and the investigator would replace the target stones according to the next task diagram. As the order of the tasks was designed to vary the required movements and provide information regarding the progression of simple and complex tasks, each participant performed the tasks in the same sequence (Appendix B).

2.3 Data Acquisition

The kinematics were recorded utilizing a motion capture system (Bonita, Vicon Inc., Hauppauge, NY) at a capture rate of 120Hz. Forty-one reflective markers were placed on the participants' head, shoulders, cervical spine (C-spine), clavicle, sternum, scapula, anterior superior iliac spine (ASIS), posterior superior iliac spine (PSIS), bicep, elbow, forearm, wrist, hand, metacarpals, and thumb bilaterally.

In addition to the infrared motion capture system, visual movement data were captured using a GoPro camera (GoPro, Inc., San Mateo, CA) to supplement the motion capture data. A second GoPro camera was mounted inside the simulation box to allow for tracking of ureteroscope movement during each task. These video files were captured at 120Hz to allow for synchronization with the Vicon data. The arrangement of all elements of the testing procedure can be seen in Figure 3.

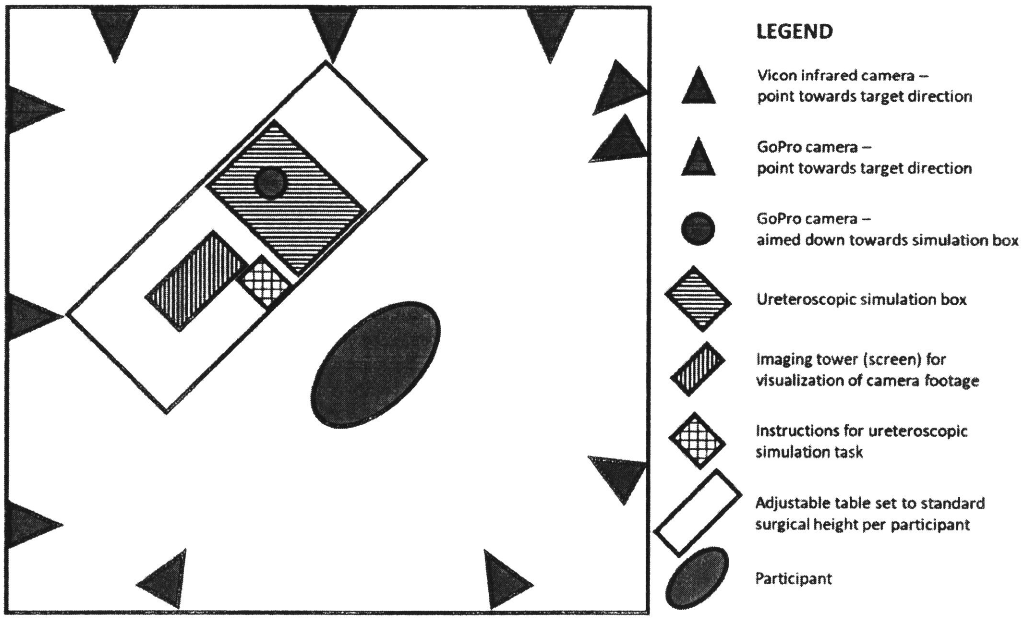


Figure 3. Ureteroscopic simulation testing schematic

2.4 Data Analysis

Demographics and surgical training/practice data were tabulated from the participant surveys. All categories of survey data can be seen in Table 1. An adjusted ratio of procedures performed:proctored was determined to better evaluate the differentiation between participants who typically performed or proctored ureteroscopic procedures in practice. This was calculated by dividing the number of procedures performed by (proctored procedures + 1) to avoid division by zero for those surgeons who did not typically proctor other trainees.

Task time was determined from the GoPro video of the participant. The time for each task was manually calculated by a single investigator from the initial placement of the ureteroscope into the simulation box through removal of the ureteroscope from the simulation box.

Utilizing a custom MATLAB script (MathWorks, Natick, MA), a *VideoReader* object was generated from the GoPro video of the ureteroscope movement. This object utilized the *ginput* function to allow an investigator to manually mark the coordinates of the ureteroscope tip on every 20th frame. The *hypot* function was utilized to calculate the distance moved between each frame and the overall ureteroscope travel distance for each task was summed.

Positional data from the motion capture acquisition were extracted using Nexus software (Vicon Inc, Hauppage, NY) and processed utilizing a variety of standard and custom MATLAB script to determine measures of participant kinematics. The markers were converted into MATLAB objects through the *ViconData* object-oriented function.(24) These objects were then used to generate the centroid of each major body segment with the following markers utilized for each segment: head [temple, crown markers], torso [C-spine, clavicle, sternum markers], and pelvis [bilateral ASIS, PSIS]. The overall task movement of the centroids was then mapped using the *delauneyTriangulation* and *convexHull* functions in order to generate a volume, defined as the "hull volume", that described the amount of body segment movement in space during each task. Example representative *convexHull* outputs can be seen in Appendix C. Utilizing the *ViconData* objects, the rotational movement (pitch, roll, yaw) of each body segment was also calculated as previously described and the variance was utilized to indicate the amount of rotational movement of each segment.(25)

Wrist angle movements were determined by calculating the angle between the vector delineated by the ulnar and radial wrist *ViconData* objects at the starting frame and this same vector at each future frame of the task. The positive/negative value of the rotation was determined by comparing this wrist vector to the vector delineated by the medial and lateral elbow *ViconData* objects. An example plot of wrist angle movements can be seen in Appendix D. Due to the anecdotal evidence discussed in the Introduction, overall correlations between bilateral wrist angles, velocities, and head roll/dominant wrist angles were calculated using the *corrcoef* function.

Due to the scope of this project, two tasks were chosen as prototypical tasks for initial pilot study analysis. Task 12 was chosen as the prototypical "simple" task as it required minimal complicated maneuvers to complete and – according to the task order – was the third time this specific task was seen by each participant. Task 9 was chosen as the prototypical "complex" task because it required intricate maneuvers (including guiding the ureteroscope into an 'S' shape for task completion), moderate need for retroflexion of the ureteroscope, and utilized a portion of the simulation box that – according to the task order – the participants had only traversed during one prior task. The task-specific data discussed above were captured and analyzed for each participant using the "simple" task and "complex" task as well as the calculated averages. All participants completed the simple and complex task within the allotted time of 120 seconds.

Descriptive statistics and graphical analysis were performed using RStudio (Version 1.2.5001, RStudio Inc). Student's paired T test was used to compare data between simple and complex tasks, while Student's independent T test was used to compare across various measures of task efficiency. For all box plots, the dark line denotes the median, the box denotes the interquartile range (IQR), the whiskers denote the minimum and maximum, and individual outliers are represented by open circles. Classification tree development was performed utilizing the *rpart* library.

3. Results

3.1 Demographics

Initial demographic and surgical practice data can be seen in Table 1. The participants in this study ranged in age from 28 to 62 years, with a mean age of 37. Half of the participants were male, and all used their right hands as the dominant surgical hand. Six of the participants were still residents in the midst of their surgical training. There was a wide variety of the number of years of surgical practice (1 - 35) with a mean of 10.2 years. One third of the participants had completed an Endourology fellowship where they received additional training in ureteroscopic techniques.

Surgeons performed and proctored a number of flexible ureteroscopic procedures during their current clinical practice. There was a mean of 9.7 cases performed per month, while a mean of 5.8 cases were proctored per month; both ranged from 0 to 30 cases per participant. Seven of the participants (58%) had previously utilized a single-use flexible ureteroscope for either simulation or clinical practice, while all participants typically use reusable ureteroscopes in practice. There was no obvious trend seen between previous single-use experience and other demographic data, including gender, history of Endourology fellowship, and resident surgeon status.

Participants had a mean of 6.6 hours of sleep the night before testing with a fatigue level of 2.5 (with 1 being least fatigued and 5 being most fatigued). Mean number of caffeinated beverages consumed per day was 1.8 and the mean number consumed on day of testing was 0.8.

Table 1: Participant Demographic, Surgical Practice, and Fatigue Data

	Overall
Age [years], mean (sd)	37.3 (10.1)
Gender (Male), N (%)	6 (50%)
Dominant hand (Right), N (%)	12 (100%)
Currently a resident surgeon (Yes), N (%)	6 (50%)
Length of surgical training/practice [years], mean (sd)	10.2 (10.7)
Completed an Endourology fellowship (Yes), N (%)	4 (33%)
Flexible ureteroscopy procedures performed [cases/month], mean (sd)	9.7 (9.4)
Flexible ureteroscopy procedures proctored [cases/month], mean (sd)	5.8 (7.6)
Previously used a single-use ureteroscope (Yes), N (%)	7 (58%)
Amount of sleep evening prior to testing [hours], mean (sd)	6.6 (1.2)
Fatigue [Likert scale], mean (sd)	2.5 (0.7)
Typical number of caffeinated beverages consumed per day, mean (sd)	1.8 (1.1)
Number of caffeinated beverages consumed day of testing, mean (sd)	0.8 (0.8)

3.2 Task-Specific Data

Task-specific data (Table 2) were compared between the simple and complex prototypical task, comparing measures of task completion and movement data. While the mean time to completion of the simple task (65.5 seconds) was less than the time needed to complete the complex task (75 seconds), this difference was not statistically significant (t(11) = -0.71, p = 0.49). Conversely, the tip of the ureteroscope moved a larger mean distance during the simple task (82.4cm) than the complex task (67.5cm), although this was also not a significant difference (t(11) = 1.28, p = 0.23).

Mean head and pelvis hull volume was larger for the complex task, while torso hull volume was larger for the simple task; none of these differences were significant. Similarly, mean head pitch and roll variance were higher for the simple task while all other rotational variances were higher for the complex task, although none of these differences were significant. Mean torso pitch variance, which was larger for the complex task, did trend near significance with t(11) = 1.89, p = 0.09.

When evaluating wrist rotational data, the bilateral wrist angle correlation was slightly higher (mean and range) for the simple task compared to the complex task, although this was not significant (t(11) = -1.11, p = 0.29). Conversely, the head roll to dominant wrist angle correlation was slightly lower for the simple task compared to the complex task, with a statistical significance of t(11) = 2.26, p = 0.05. Wrist angular velocity correlation was not different between the two task types, with t(11) = 0.70 ,p = 0.50.

Table 2: Participant Motion Data (by Task Type)

	Simple Task	Complex Task	p
Time to complete task [s], mean (sd)	65.5 (28.9)	75.0 (28.1)	0.49
Distance traveled by ureteroscope end effector during task [cm], mean (sd)	82.4 (26.3)	67.5 (21.3)	0.23
Movement of head (hull volume) [cm^3], mean (sd)	1163.5 (806.1)	1542.5 (1510.9)	0.27
Movement of torso (hull volume) [cm^3], mean (sd)	473.5 (364.8)	422.1 (373.1)	0.65
Movement of pelvis (hull volume) [cm^3], mean (sd)	285.4 (256.2)	789.9 (2088.9)	0.42
Variance of head pitch, mean (sd)	135.2 (130.5)	130.0 (99.9)	0.80
Variance of head roll, mean (sd)	151.6 (144.1)	121.8 (84.0)	0.34
Variance of head yaw, mean (sd)	45.5 (27.7)	53.9 (26.2)	0.13
Variance of torso pitch, mean (sd)	100.1 (99.0)	161.2 (120.2)	0.09
Variance of torso roll, mean (sd)	460.1 (595.0)	646.3 (893.6)	0.58
Variance of torso yaw, mean (sd)	19.6 (21.8)	21.2 (17.0)	0.84
Wrist angle correlation, mean (range)	0.03 (-0.32:0.47)	-0.09 (-0.60:0.38)	0.29
Wrist angular velocity correlation, mean (range)	0.004 (-0.02:0.06)	0.01 (-0.02:0.15)	0.50
Head roll:dominant wrist angle correlation, mean (range)	-0.19 (-0.69:0.28)	0.05 (-0.53:0.45)	0.05

Despite a lack of statistically significant differences between a majority of the means, some visual trends arise between simple and complex task-specific variables. While the overlap between the simple and complex task was substantial with regard to completion time and movement distance of the ureteroscope end effector (Figure 4), a trend was seen towards smaller hull volumes for each body segment in the complex task compared to the simple task (Figure 5).

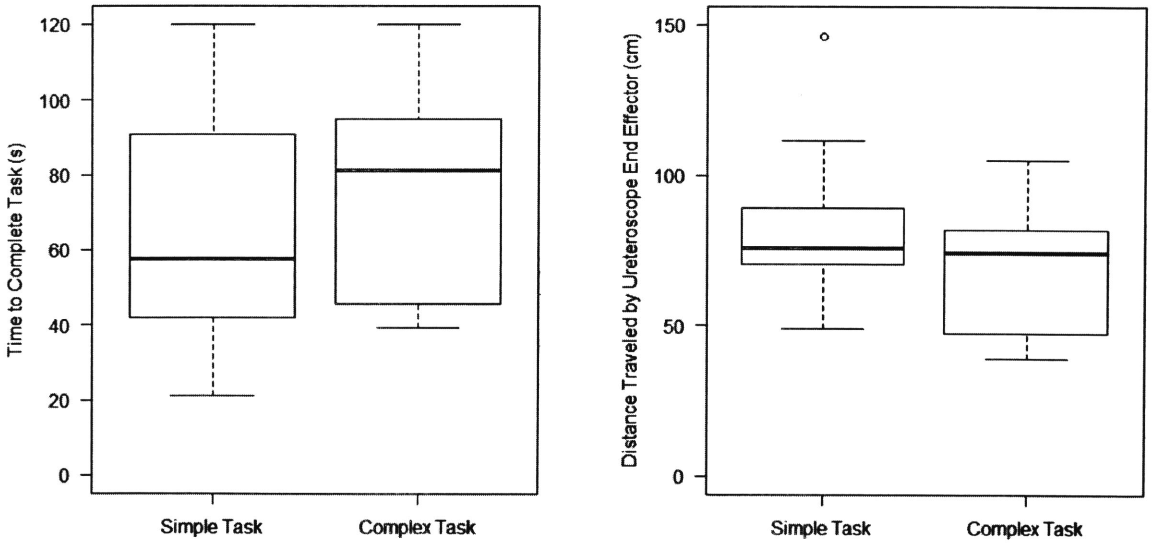


Figure 4. Measures of task completion efficiency by task complexity; Time to complete task, simple vs complex task (left); Distance traveled by ureteroscopic end effector, simple vs complex task (right)

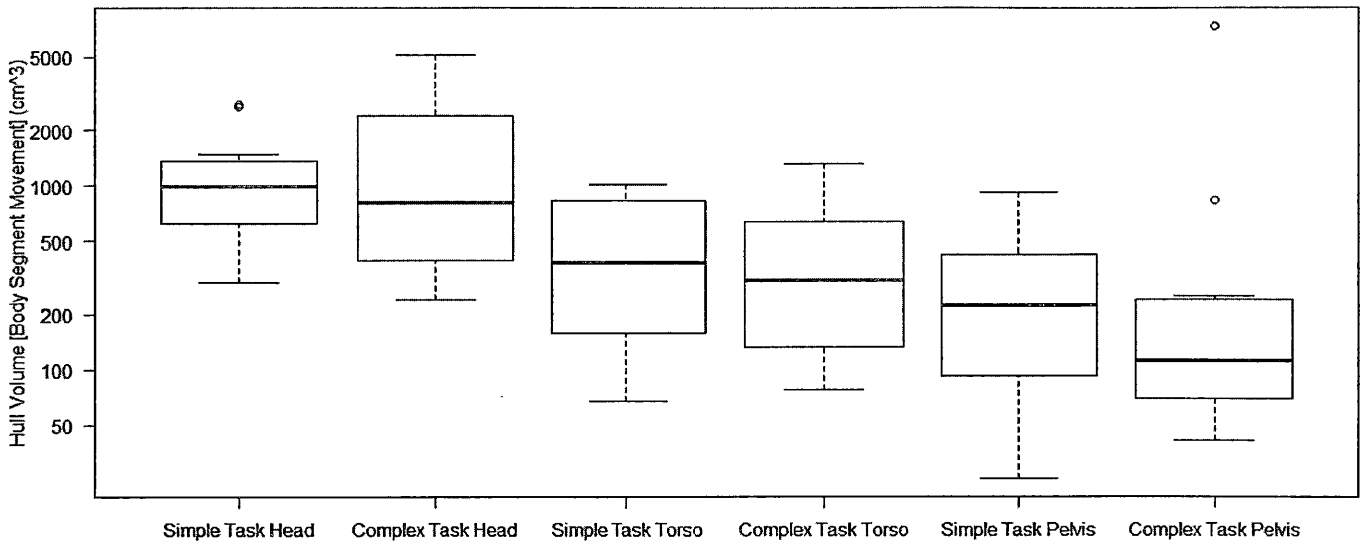


Figure 5. Hull volumes (body segment movement) comparing head/torso/pelvis across simple and complex tasks

Regarding the rotational motion of the participants' heads, the variance of pitch, roll, and yaw appeared graphically similar between the simple and complex task (Figure 6). The torso rotational motion of the complex task, though, trended towards an increased variance of pitch, roll, and yaw compared to the simple task (Figure 7).

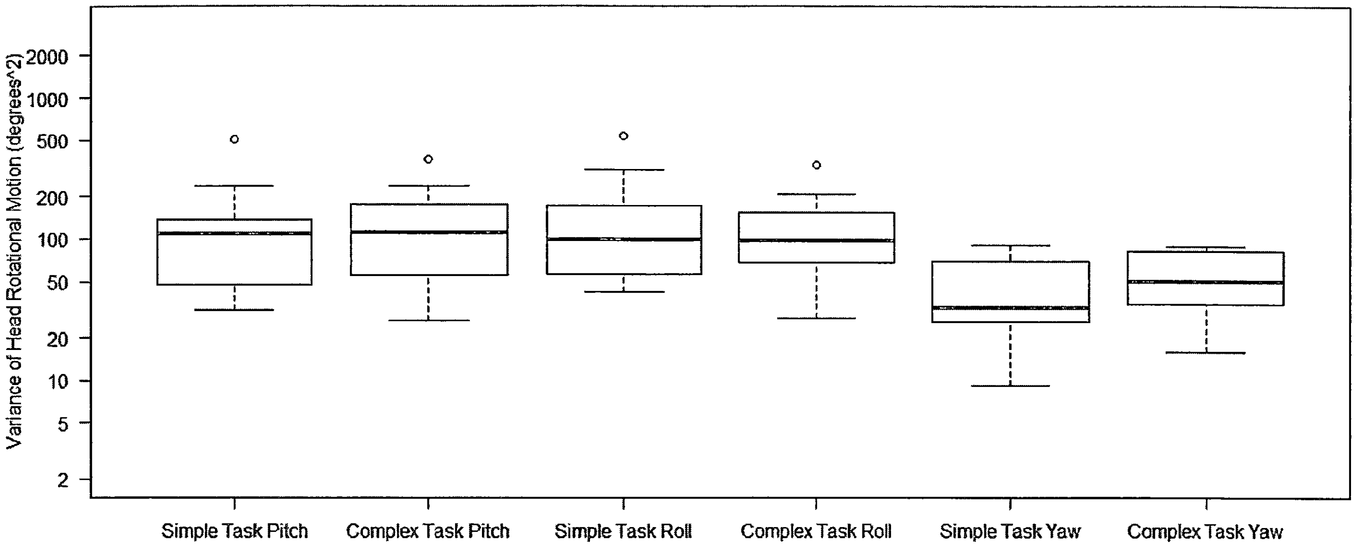


Figure 6. Variance of head rotational motion comparing pitch/roll/yaw across simple and complex tasks

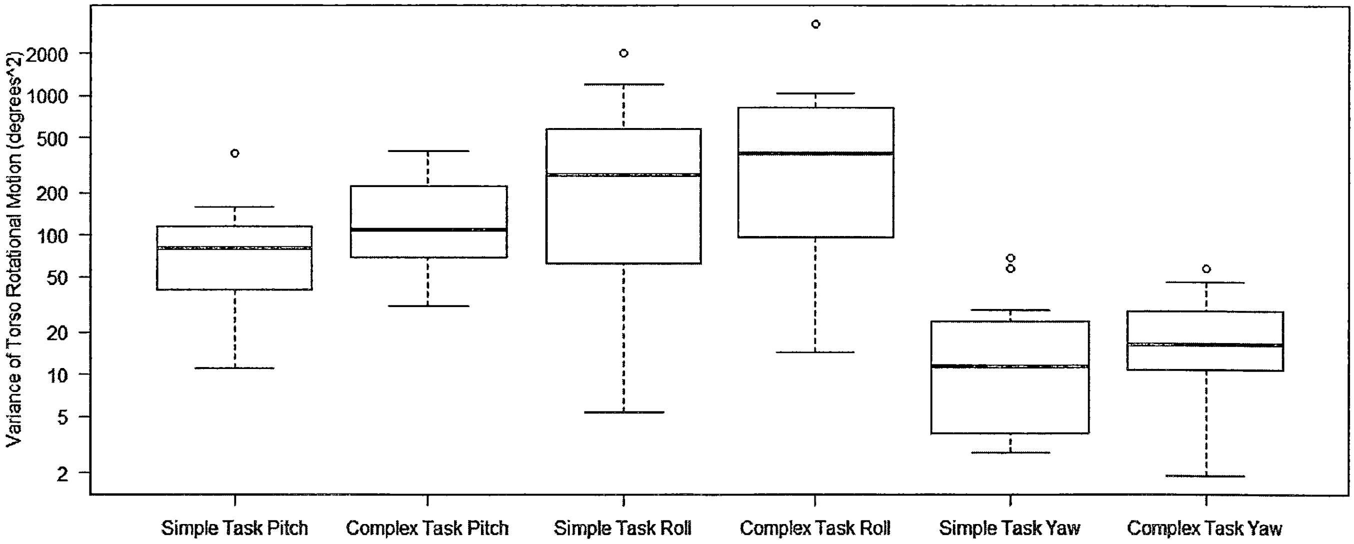


Figure 7. Variance of torso rotational motion comparing pitch/roll/yaw across simple and complex tasks

The simple and complex tasks were associated with similar wrist angle correlation, although the range of correlations was larger for the complex task. There was a positive shift to the correlation between head roll and dominant wrist angle for the complex task compared to simple task. These correlations can be seen in Figure 8.

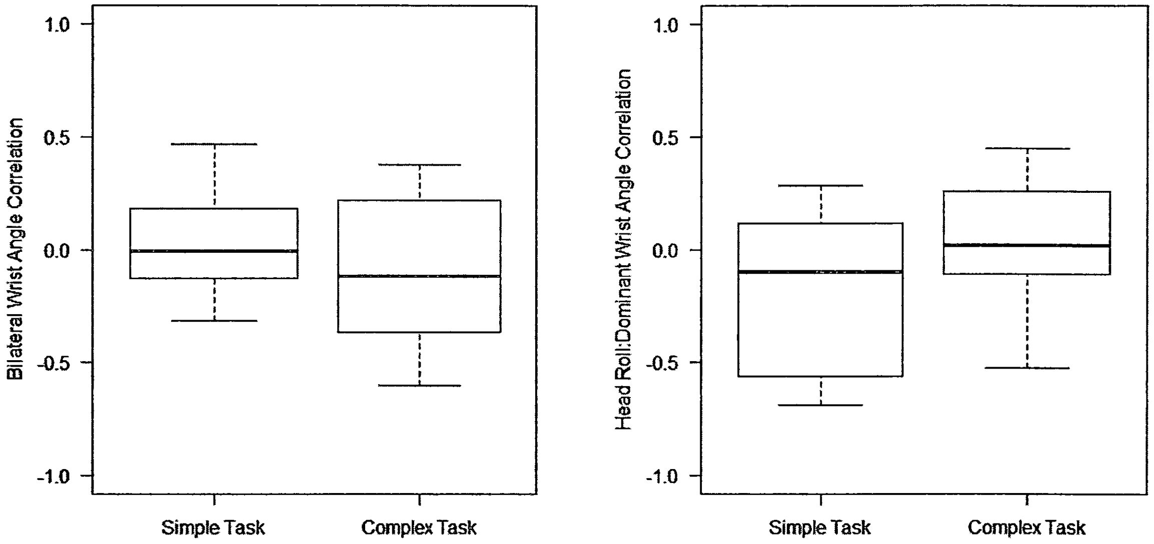


Figure 8. Wrist angle correlations by task complexity; Bilateral wrist angle correlation, simple vs complex task (left); Head roll:dominant wrist angle correlation, simple vs complex task (right, difference is statistically significant)

3.3 Correlations Between Participant Data and Measures of Task Efficiency

A quicker time to task completion was chosen as a primary endpoint of task efficiency. Similarly, a smaller distance traveled by the ureteroscope end effector to complete the task was also considered more efficient, as the participant would have required less non-essential ureteroscope movement to achieve success. A number of graphical comparisons were made between the demographic and task-specific data described above to delineate trends seen between input variables and these indicators of task efficiency. While many of these comparisons did not produce any correlation, there were some notable graphical findings which are discussed in the following section.

Evaluating demographic data, female gender and completion of an Endourology fellowship were associated with a slower average completion time in this study group, although these associations were not statistically significant (t(8.7) = -1.84, p = 0.10 for gender, t(9.4) = 1.61, p = 0.14 for Endourology fellowship). Resident surgeons, compared to those who had completed residency, had a longer and more varied task completion time specifically on the simple task (Figure 9), although this was similarly not statistically significant (t(9.0) = 1.09, p = 0.30). Regarding movement data, hull volumes (head, torso, and pelvis) correlated directly with task completion time in the complex task alone across all body segments (R^2 = 0.39 for head, R^2 = 0.49 for torso, R^2 = 0.29 for pelvis), while this correlation was not seen with the simple task (Figure 10).

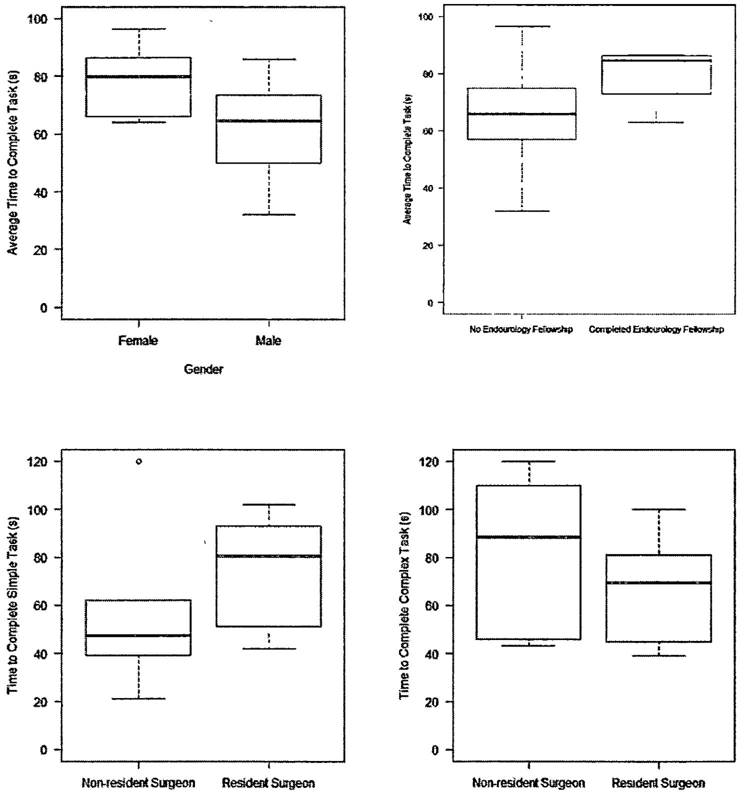


Figure 9. Task completion time trends seen across demographic data, all differences not statistically significant; Average time to complete task, by gender (top left), and completion of Endourology fellowship (top right); Time to complete simple task, by resident status (bottom left); Time to complete complex task, by resident status (bottom right)

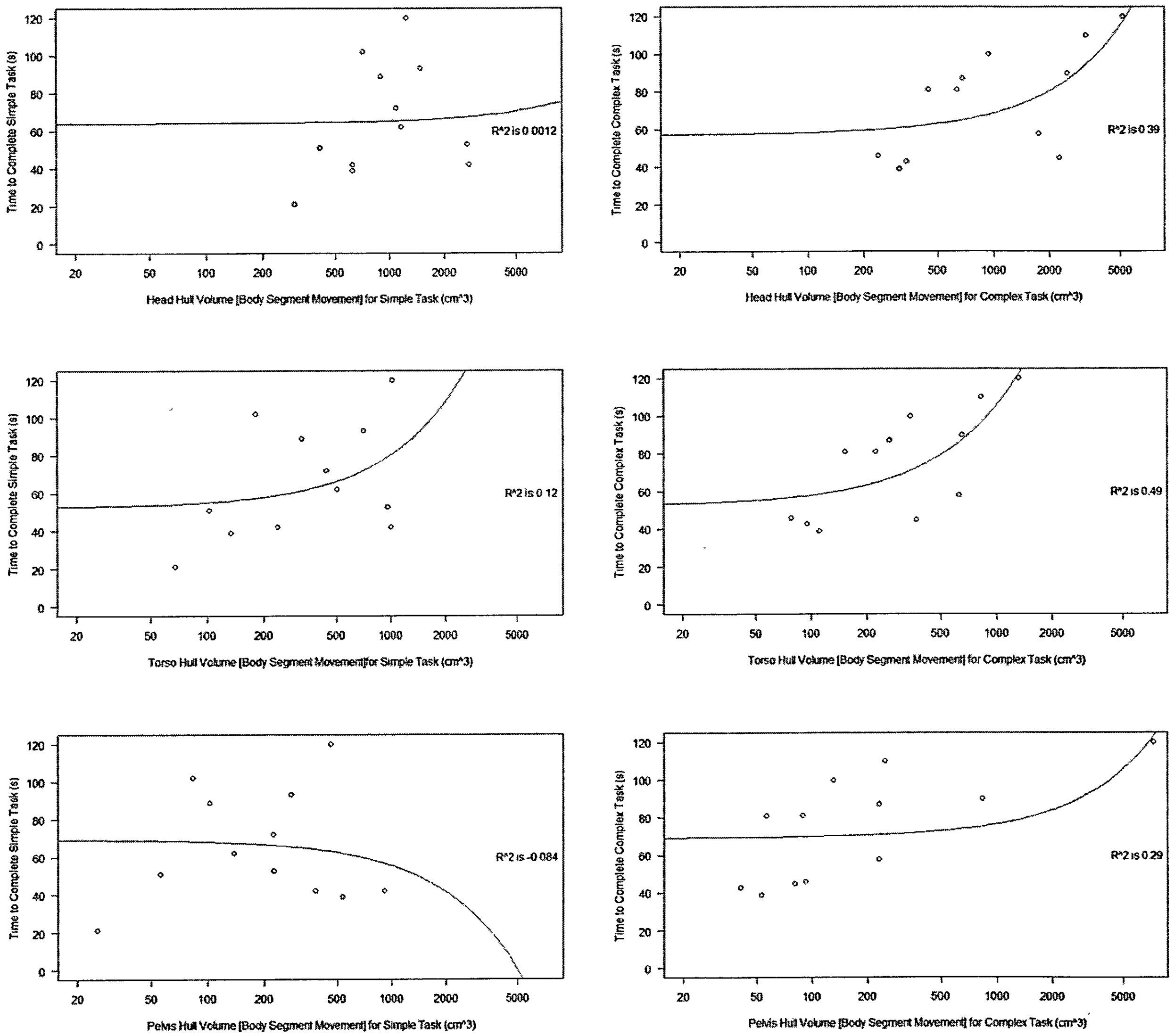


Figure 10. Time to complete simple task compared across simple task hull volumes (head – top left, torso – mid left, pelvis – bottom left); Time to complete complex task compared across complex task hull volumes (head – top right, torso – mid right, pelvis – bottom right); x axis plotted as log scale

When comparing demographic data to ureteroscope tip travel distance, female gender, completion of an Endourology fellowship, and non-resident surgeon status trended in this study group with a larger ureteroscope movement (Figure 11). Only the difference between distance traveled based on Endourology fellowship was statistically significant (t(9.4) = -1.55, p = 0.15 for gender, t(9.5) = 2.92, p = 0.02 for Endourology fellowship, and t(6.9) = -0.71, p = 0.50 for resident status). Similarly, larger hull volumes (head, torso, and pelvis) appeared to trend with increased ureteroscope tip movement, although these correlations were not robust ($R^2 \leq 0.16$) across either task type (Figure 12).

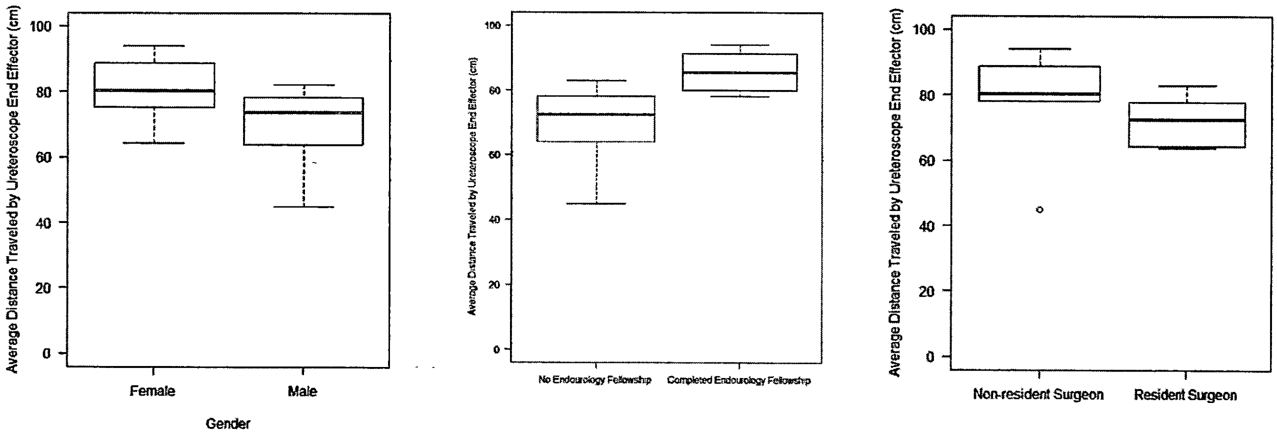


Figure 11. Ureteroscope distance travel trends seen across demographic data; Average ureteroscope end effector travel distance, by gender (left), completion of Endourology fellowship (center, difference is statistically significant), and resident surgeon status (right)

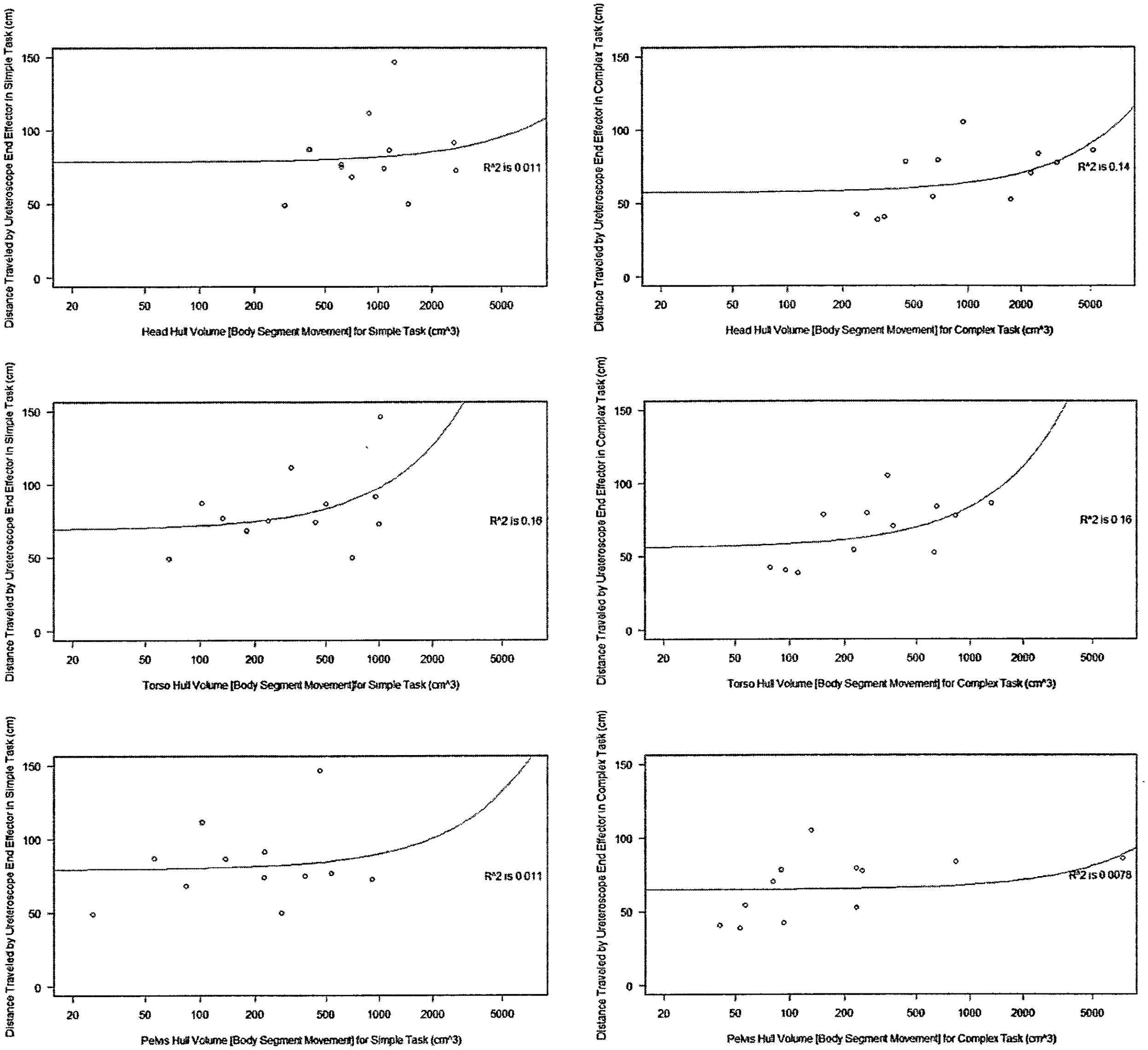


Figure 12. Ureteroscope distance travel trends across simple task hull volumes (head - top left, torso - mid left, pelvis - bottom left); Ureteroscope distance travel trends across complex task hull volumes (head - top right, torso - mid right, pelvis - bottom right); x axis plotted as log scale

Given that task completion time nor ureteroscope end effector travel distance completely describe the efficiencies of camera manipulation when considered individually, a graphical comparison between these two variables was performed. This comparison showed a reasonable correlation, which appeared strongest when assessing the data from the complex task (with an R^2 of 0.61, compared to 0.20 for the simple task and 0.50 for the average of both tasks). As such, this graph (as seen in Figure 13) was used to divide the study group into six high efficiency performers and six low efficiency performers.

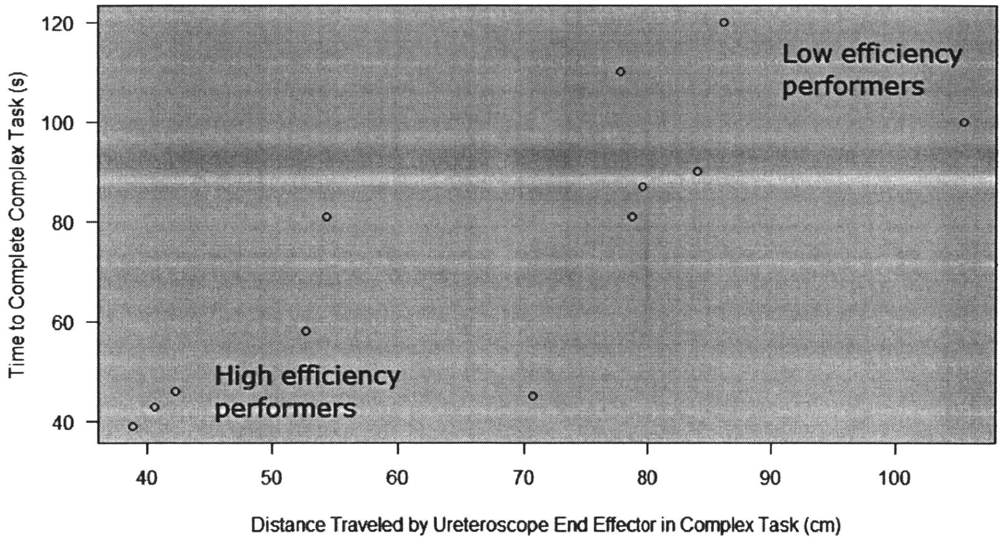


Figure 13. Time to complete complex task vs distance traveled by end effector in complex task – participants in the lower left were considered high efficiency performers and participants in the upper right were considered low efficiency performers

3.4 Examination of High Efficiency and Low Efficiency Performers

Upon dividing the study sample into high and low efficiency performers, graphical evaluation demonstrated trends across the two groups. Regarding the demographic data, the high efficiency performers tended to have a shorter length of clinical practice (mean, 6 vs 14 years) as well as perform and proctor fewer ureteroscopic surgeries (mean, 7.7 vs 11.7 and 1.0 vs 10.7, respectively). The adjusted ratio of performed:proctored cases, though, was higher in the high efficiency group (mean, 7.4 vs 5.6, Figure 14). These differences were not statistically significant, except for number of cases proctored (t(9.7) = -1.27, p = 0.23 for practice length, t(9.9) = -0.72, p = 0.49 for cases performed, t(5.9) = -2.78, p = 0.03 for cases proctored, and t(9.5) = 0.29, p = 0.78 for adjusted case ratio).

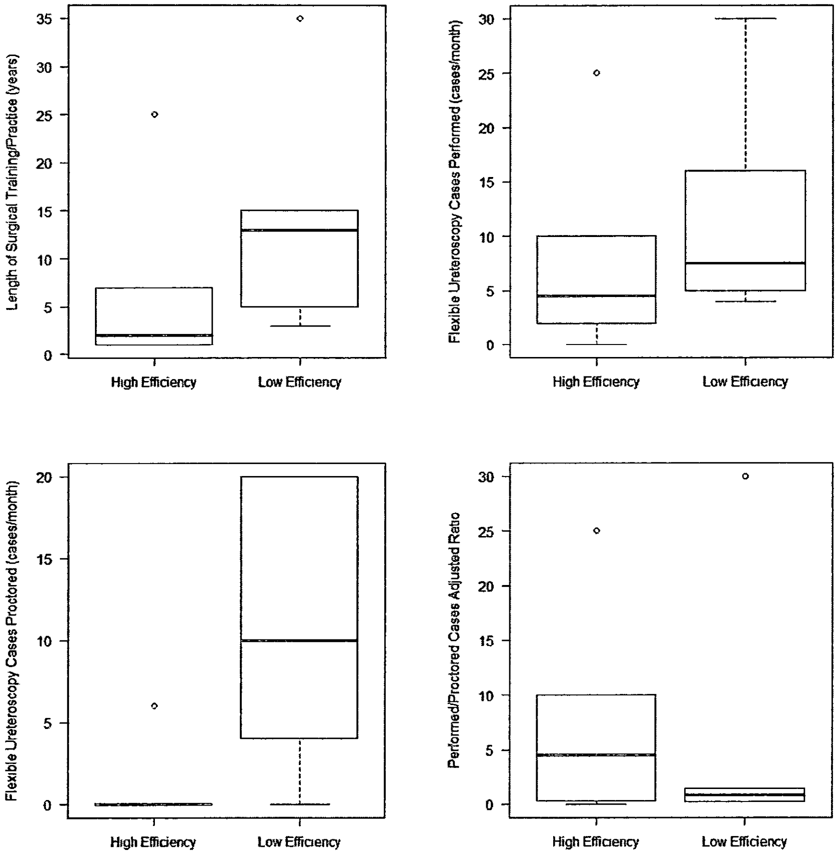


Figure 14. Demographic trends between high and low efficiency groups; Length of surgical training/practice (top left), flexible ureteroscopy cases performed, proctored (statistically significant difference), and modified ratio (top right, bottom right/left)

Graphical and statistical comparison of high and low efficiency performers also presented contrasts in participant motion data. High efficiency performers tended to have smaller hull volumes (and thereby move their head, torso, and pelvis less) than the low efficiency performers (mean, 867.1 vs 1838.9cm^3, 314.4 vs 581.2cm^3, 152.8 vs 922.4cm^3, respectively). This can be seen in Figure 15. These comparisons were not statistically significant (t(6.0) = -1.70, p = 0.14 for head, t(6.8) = -1.56, p = 0.16 for torso, and t(5.1) = -1.30, p = 0.25 for pelvis). Rotational data was neither statistically nor showed visual trends between groups (p > 0.45 for all comparisons).

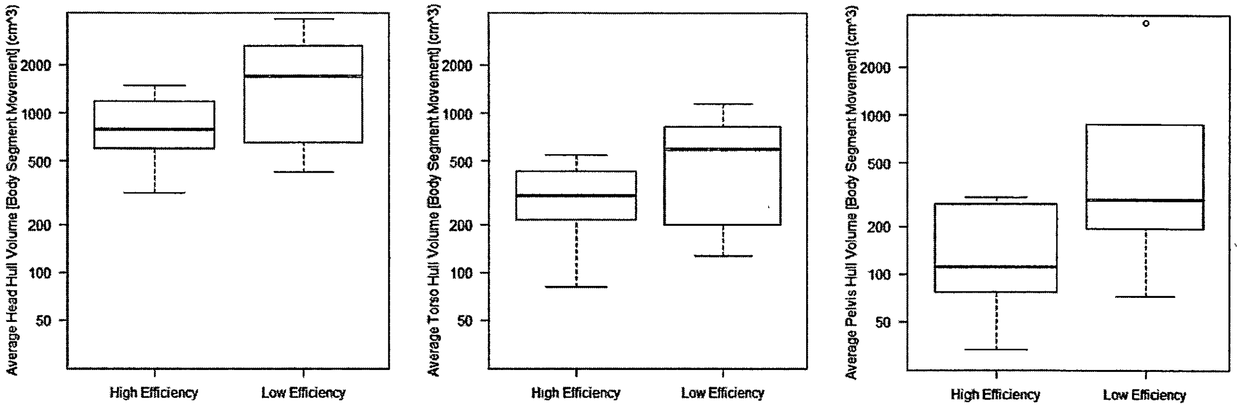


Figure 15. Hull volume (body segment movement) trends between high and low efficiency groups; head (left), torso (middle), pelvis (right)

A trend was also noted regarding wrist movement correlation between high and low efficiency performers, with the high efficiency group tending to have a more positive correlation in bilateral wrist rotational movement (mean, 0.03 vs -0.09). The high efficiency group also tended to have a correlation closer to zero between head roll and the dominant wrist rotation than the low efficiency group, whose range of correlations was farther from zero. Mean (-0.07 vs -0.07) and median (seen in Figure 16) of these two groups were similar, but the range appeared to vary by efficiency.

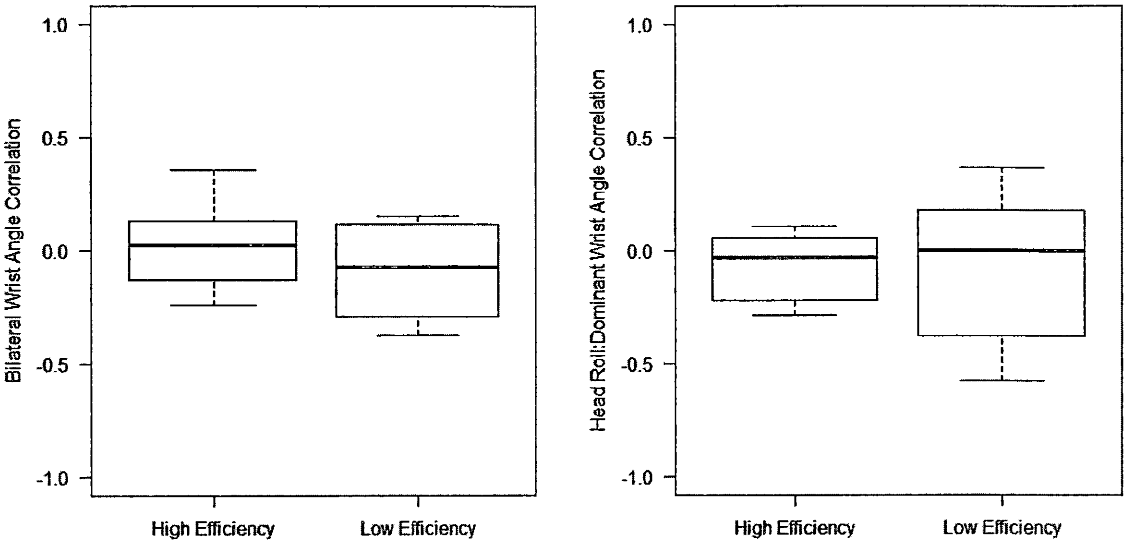


Figure 16. Task average wrist angle correlation trends between high and low efficiency groups; Bilateral wrist angle correlation (left); Head roll:dominant wrist angle correlation (right)

3.5 Generation of Pilot Classification Tree from Average Motion Data

To further understand the motion variables that influence the efficiency of the participants in this pilot study and potentially inform further future analyses, a simple classification tree was developed utilizing this data set. The tree, which can be seen in Figure 17, focuses solely on the average motion variables captured during this study and classifies the participants into high and low efficiency groups. The classification function suggested the four most important variables as follows: Average Torso Yaw Variance, Average Head Hull Volume, Average Pelvis Hull Volume, and Average Wrist Angle Correlation.

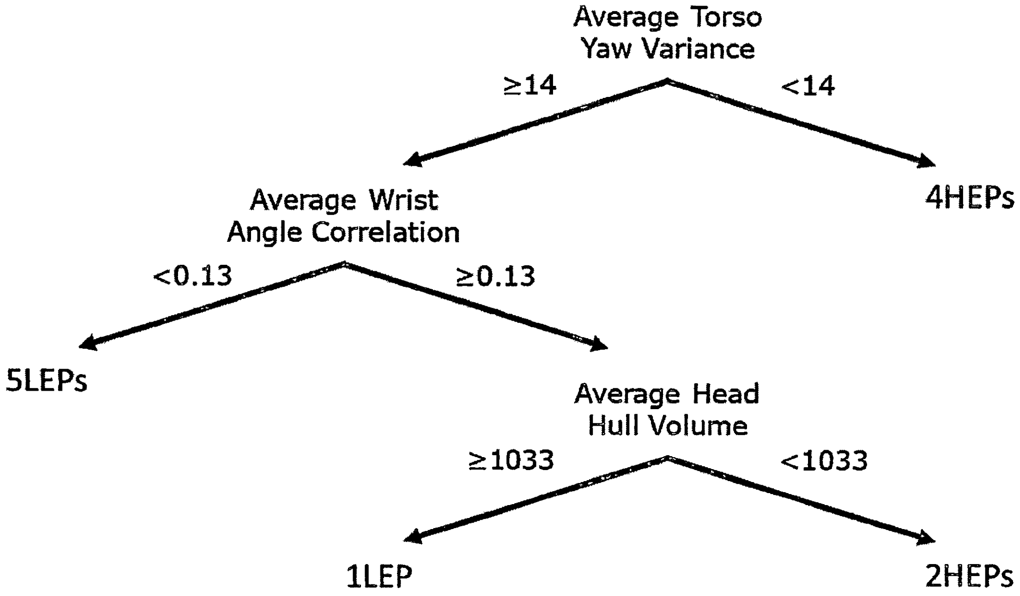


Figure 17. Pilot classification tree utilizing average movement data and classification results from study dataset (HEP = high efficiency performer, LEP = low efficiency performer)

4. Discussion

By assessing the motion data generated by urologic surgeons performing ureteroscopic simulation tasks, this study characterized surgeon motion and interaction with this endoscopic surgical device. This characterization was performed by comparing simple and complex ureteroscopic tasks, as well as classifying participants as high and low efficiency performers. The correlations and conclusions discussed herein will inform further study, improve endoscopic device design, and eventually improve surgeon training and evaluation.

While no movement data (including body segment motion, rotation, and wrist angle correlations) were significantly different between simple and complex tasks, there existed notable trends in the data. The complex task, in general, took longer for participants to complete; this is not unexpected, as it was designed to require more complicated ureteroscope movement. Interestingly, though, participants required less ureteroscope movement to complete the complex task. This is likely due to the nature of the tasks, since the simple task required movement between disparate areas of the simulation box, while the complex task utilized a more focal area despite requiring more complicated movements. (Appendix B) This reasoning could also explain the decreased hull volumes seen in the complex task compared to the simple task; the simple task required more movement around the simulation box and so may require more motion of the head, torso, and pelvis to complete the task. Certain rotational movements of the ureteroscope may require additional body movement for improved range of motion, and a wider area of ureteroscope travel in the simple task may influence the need for more body mobility. It is possible, though, that more complex tasks in general may require slow and careful movements, producing a longer time but shorter, more measured pathway of the ureteroscope and motion of the major body segments.

Higher hull volumes were seen in the cranial body segments as the caudal body segments likely remained more stationary – this suggests surgeons held a relatively set stance during the tasks. The body acted as an inverted pendulum, where the head had the largest freedom of movement and the pelvis remained more fixed.

Of note, hull volume analysis was performed utilizing the log values of body segment movement; this was done due to the visual and numerical spread of the data. Future work should consider the log relationship of body segment movement to measures of efficiency in addition to direct relationships.

When evaluating variance of the rotational motion of the head and torso, there appeared to be no association between head pitch, roll, or yaw and task complexity. Torso rotational variance measures (pitch, roll, and yaw), though, were greater for the complex task, suggesting that participants utilized more torso rotation to achieve the complex maneuvers required for this task. Retroflexion and other intricate ureteroscope motions can be performed using dominant hand movements alone, although rotation of the torso allows for additional range of motion of the hand and endoscope. This result suggests that participants utilized torso rotation to improve maneuverability in the setting of the complex task, which may define a difference in technique between simple and complex tasks.

Coordinated wrist movements were hypothesized to represent efficient and successful technique, as the majority of ureteroscope motion is controlled by the rotation of the dominant wrist while the contralateral hand simply supports the camera. By moving the contralateral hand in a counterproductive manner to the wrist movement of the dominant hand, the endoscope can be twisted on itself and damaged, and a portion of the surgeon movement is wasted. Coordinated wrist movements appeared more common in the simple task, as the correlation coefficients of bilateral wrist movement were more positive for the simple task. This suggests that the increased difficulty of the complex task may have led to less efficient surgeon wrist movement. It is important to note, though, that for each participant, the bilateral wrist correlations were not not strong, suggesting that overall there may be limited concurrent wrist rotation. It is also feasible that the measure of wrist correlation was improperly defined in this study as the correlation between pronation and supination; surgeons may utilize wrist flexion/extension (which was not explicitly compared) or passively allow the camera to spin within the non-dominant hand, decreasing the utility of wrist correlation analysis.

Anecdotally, inexperienced surgeons tend to unconsciously "mirror" the direction of interest by rotating their head in the intended direction instead of simply rotating the dominant wrist. Thus, it was hypothesized that high correlation between head roll and dominant wrist angle would signify a less polished mental model of ureteroscope use and a decreased efficiency of surgeon movement. It can be seen that the complex task led to a higher direct head roll:dominant wrist angle correlation, suggesting once again that the increased difficulty of the complex task may have brought about less efficient movement. Interestingly, the head roll:dominant wrist angle correlation seen in the simple task was overall a stronger correlation, although this was a negative correlation, suggesting countermovement between the head roll and dominant wrist. It is possible that, in this situation, the head movement is not due to the same "mirroring" effect and may actually be a subconscious attempt to maintain a neutral head position by countering the dominant wrist movement with a reciprocal head roll.

When utilizing time to task completion or ureteroscope tip travel distance as markers of efficient endoscopic movement, few demographic data had meaningful differences. Female surgeons and those who completed an Endourology fellowship trended towards slightly longer task times, suggesting either less efficient movement or more measured speed of ureteroscope travel (which could potentially be of some utility if tissue injury can be avoided). These possibilities cannot be differentiated from these data. Interestingly, resident surgeons had longer and more varied task completion times compared to non-trainees for the simple task alone. As surgeons continue to practice, they become more familiar with standard anatomy and standard surgical situations; simple surgical tasks may become more consistent over time. Resident surgeons, though, are still developing surgical technique consistency and may treat every task as a novel situation and, as such, may select from a larger variety of strategies for a simple task. This would be compatible with the larger variability seen across this sample of resident surgeons.

Complex task completion time also correlated with head, torso, and pelvis hull volume, indicating that increased body movement was associated with less efficient task completion in a complex situation. This correlation was not observed in the setting of the simple task, suggesting that, specifically during the complex ureteroscopic task, surgeon economy of motion was associated with a decreased time to task completion. These findings were similar when using ureteroscope end effector travel distance as the measure of efficiency, although the R^2 values were less substantial.

By combining time to task completion and ureteroscope tip travel distance as a combined marker of surgeon motion efficiency, the participant sample was divided into a low efficiency group and high efficiency group. The high efficiency group tended to have surgeons with shorter length of practice and higher ratio of ureteroscopic cases performed:proctored. These factors both suggest a common technique-focused truism – practice makes perfect. Flexible ureteroscopic surgery is typically a procedure performed by surgeons in the early stages of their training; as surgeons move further along in their training and practice, they often move towards proctoring such "junior-level" cases and become more hands off in the operating room. It is reasonable that, while the understanding of various surgical situations and mental models of ureteroscopic device control may not be solidified at an early stage of training, the novice surgeons are the ones who perform these procedures more commonly. As such, frequent performance of flexible ureteroscopy may be the most important demographic input towards efficiency.

Mirroring the correlations seen between task completion time and hull volumes, participants in the high efficiency group tended to have smaller body segment hull volumes. As discussed above, economy of body motion trended towards an association with ureteroscopic task efficiency, although this was not statistically significant. The possibility of a relationship between economy of body motion and task efficiency is not surprising, as large movements of the head, torso, and pelvis are unlikely to improve the mobility of the ureteroscope and likely suggest a tendency towards inefficient motion or techniques. It is important to note, though, that the hull volumes were not normalized by body height (not captured during this study), and this could theoretically serve as a confounder in this setting if all participants in one subgroup were markedly taller.

Wrist correlations, as discussed previously, were hypothesized as markers of ureteroscopic efficiency. The high efficiency group in this study tended to have slightly higher bilateral wrist correlations than the low efficiency group. Head roll:dominant wrist correlation had a larger positive or negative value for the low efficiency group, compared to the high efficiency group who had correlations closer to zero. These results suggest that, despite low correlations across bilateral wrists and head roll for a majority of participants, higher bilateral wrist correlation and lower (direct or indirect) correlation between head roll and dominant wrist angle warrant further study regarding their association with efficient endoscopic surgery. Remarkably, while all participants were right-hand dominant for surgery, all but one of the participants utilized their non-dominant hand in a supine position. Despite the difference in technique by the single surgeon who utilized a prone non-dominant hand, this participant was not an outlier in the measures assessed, although he/she was categorized into the less efficient group. Importantly, variations in technique such as this should be documented, analyzed, and understood since the standard practice may not be the most efficient or effective.

Using solely the average motion variables analyzed, a classification tree was generated to explain the results seen in this pilot study. While this classification tree does not likely tell the complete story, it is noteworthy in its identification of markers of ureteroscopic efficiency. The tree utilizes movement variables from head, wrist, and torso, suggesting the importance of analyzing the entire body to understand efficient and effective surgical motion. By focusing on participants with low torso yaw variance (those who maintained a relatively stable torso orientation, likely towards the simulation box), high bilateral wrist correlation, and low head hull volume (those who kept their head in one place), the classification tree categorizes the study participants by efficiency group. The predictive utility of this classification scheme will require external participant data for validation. These data, as well as others collected and analyzed here, will be useful for further study to understand efficient techniques in endoscopic surgery.

There are a number of limitations of this study, although as a pilot study it does support the feasibility of utilizing motion capture data to understand surgical movement in a simulation setting. Firstly, the participants do not perform actual ureteroscopic surgery in this study; the simulation setting merely attempts to recreate the necessary variables for realistic procedures. This specific simulation box was used for this study due to each participants' unfamiliarity with its layout; this was done to remove the strategic anatomic understanding that could serve as an advantage to more senior surgeons. Despite this reasoning, the use of a non-anatomic simulation box does decrease the surgical realism of the simulation. Additionally, there were 12 participants in this study, all of whom were practicing urologic surgeons. A larger number of participants would increase the utility of the results. Lastly, important movement data, such as the mobility and pressure generated by the dominant thumb on the ureteroscope control mechanism, was unable to be captured. Initial study design included acquisition of these data, but was found to be unfeasible given the available technology.

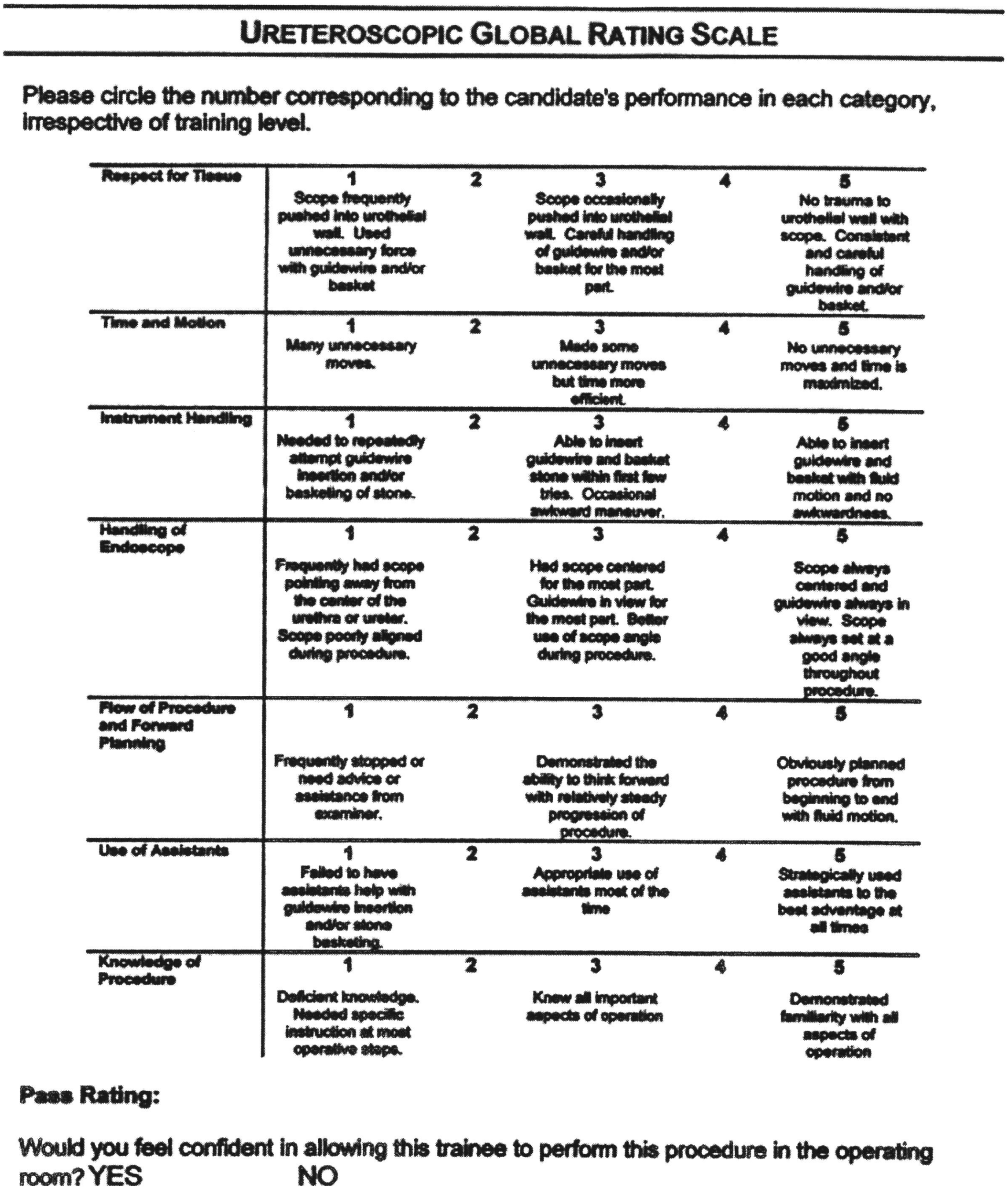
Future studies will focus on the additional tasks performed as a part of this study that, due to the scope of the project, could not be analyzed for this thesis. Additionally, detailed evaluation of the ureteroscope flexion methods used to complete each task would give improved understanding of end effector movement. By utilizing the wider variety of tasks and more granular information regarding ureteroscope motion, specific strategies employed by participants could be isolated. These strategies could be used to inform future device design and teaching methodologies, especially as part of a larger-scale data collection.

5. Conclusion

Urologic surgeon movement is an important variable that factors into ureteroscopic surgical efficiency, which can be defined as a combination of shorter task time and less endoscopic end effector movement required for task completion. Specifically, economy of surgeon body motion, correlation of bilateral wrist rotation, and lack of head:wrist rotational mirroring were variables of interest that require further study regarding their potential association with efficient task completion. By utilizing these data and motion-analysis techniques discussed within this study, future surgeons and endoscopic devices can be evaluated, improved, and leveraged to eventually advance clinical care in surgical management of nephrolithiasis.

Appendix A

Ureteroscopic Global Rating Scale (URS-GRS)



URETEROSCOPIC GLOBAL RATING SCALE

Please circle the number corresponding to the candidate's performance in each category, irrespective of training level.

Respect for Tissue	**1** Scope frequently pushed into urothelial wall. Used unnecessary force with guidewire and/or basket	**2**	**3** Scope occasionally pushed into urothelial wall. Careful handling of guidewire and/or basket for the most part.	**4**	**5** No trauma to urothelial wall with scope. Consistent and careful handling of guidewire and/or basket.
Time and Motion	**1** Many unnecessary moves.	**2**	**3** Made some unnecessary moves but time more efficient.	**4**	**5** No unnecessary moves and time is maximized.
Instrument Handling	**1** Needed to repeatedly attempt guidewire insertion and/or basketing of stone.	**2**	**3** Able to insert guidewire and basket stone within first few tries. Occasional awkward maneuver.	**4**	**5** Able to insert guidewire and basket with fluid motion and no awkwardness.
Handling of Endoscope	**1** Frequently had scope pointing away from the center of the urethra or ureter. Scope poorly aligned during procedure.	**2**	**3** Had scope centered for the most part. Guidewire in view for the most part. Better use of scope angle during procedure.	**4**	**5** Scope always centered and guidewire always in view. Scope always set at a good angle throughout procedure.
Flow of Procedure and Forward Planning	**1** Frequently stopped or need advice or assistance from examiner.	**2**	**3** Demonstrated the ability to think forward with relatively steady progression of procedure.	**4**	**5** Obviously planned procedure from beginning to end with fluid motion.
Use of Assistants	**1** Failed to have assistants help with guidewire insertion and/or stone basketing.	**2**	**3** Appropriate use of assistants most of the time	**4**	**5** Strategically used assistants to the best advantage at all times
Knowledge of Procedure	**1** Deficient knowledge. Needed specific instruction at most operative steps.	**2**	**3** Knew all important aspects of operation	**4**	**5** Demonstrated familiarity with all aspects of operation

Pass Rating:

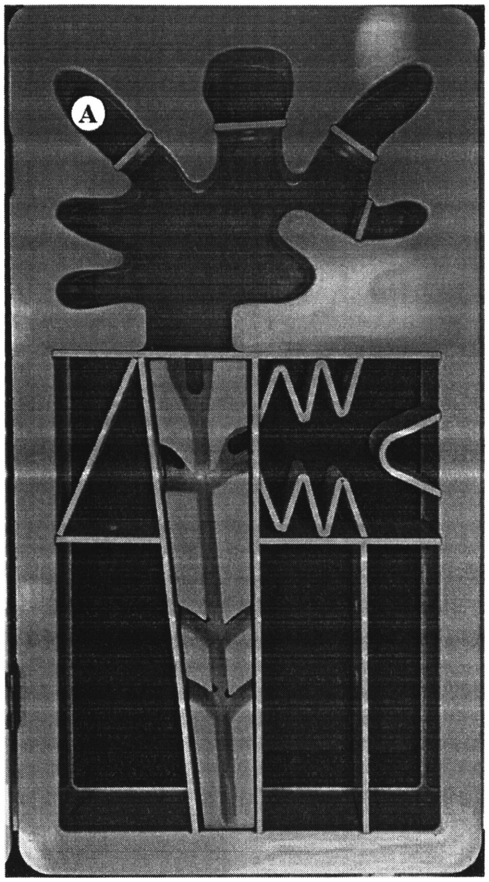
Would you feel confident in allowing this trainee to perform this procedure in the operating room? YES NO

Appendix B

Ureteroscopic Simulation Task Diagrams with Instructions Given to Participants

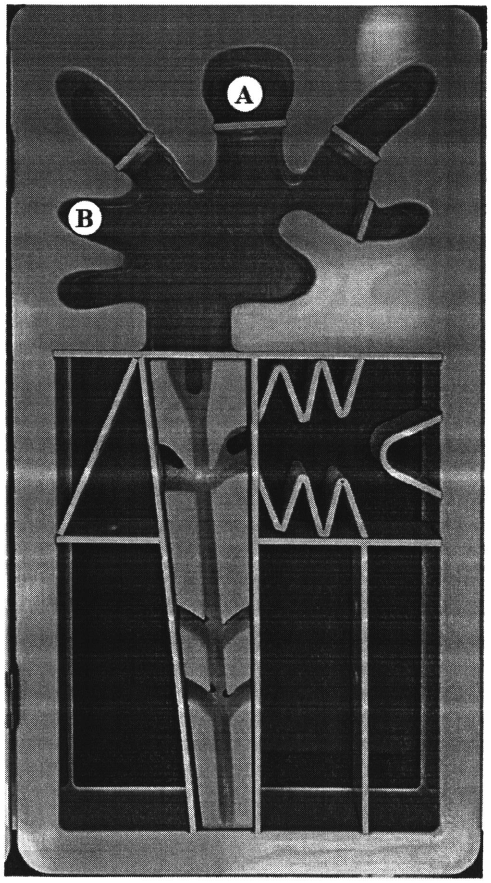
Task 1:

- **Insert the ureteroscope and pass it to point A**
- **Remove the ureteroscope**



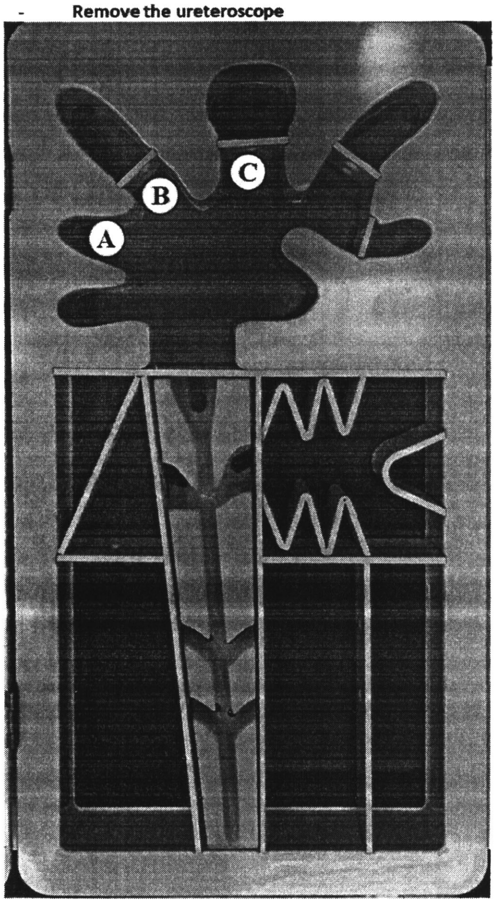
Task 2:

- **Insert the ureteroscope and pass it to point A**
- **Move the ureteroscope to point B**
- **Remove the ureteroscope**



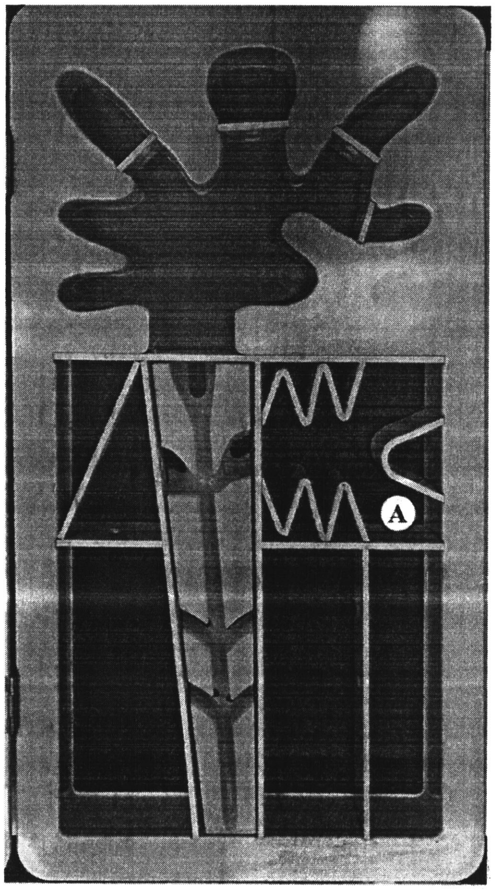
Task 3:

- **Insert the ureteroscope and pass it to point A**
- **Move the ureteroscope to point B**
- **Move the ureteroscope to point C**
- **Remove the ureteroscope**



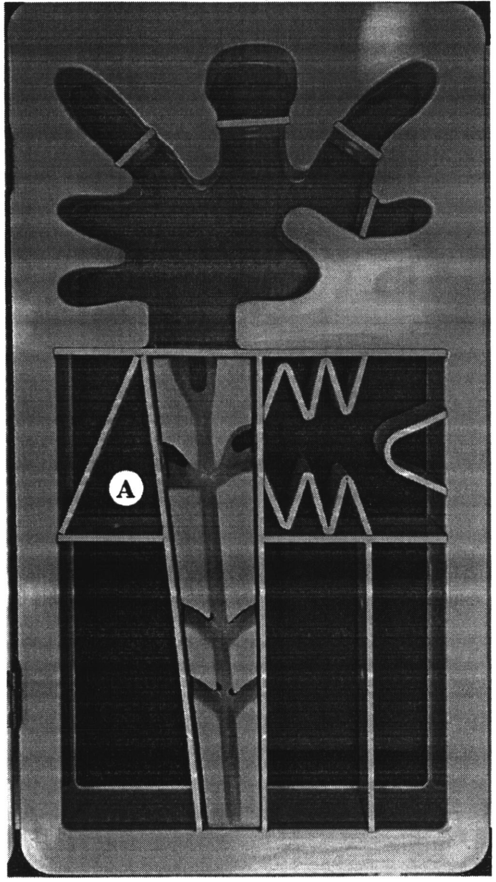
Task 4:

- **Insert the ureteroscope and pass it to point A**
- **Move the ureteroscope to point B**
- **Remove the ureteroscope**



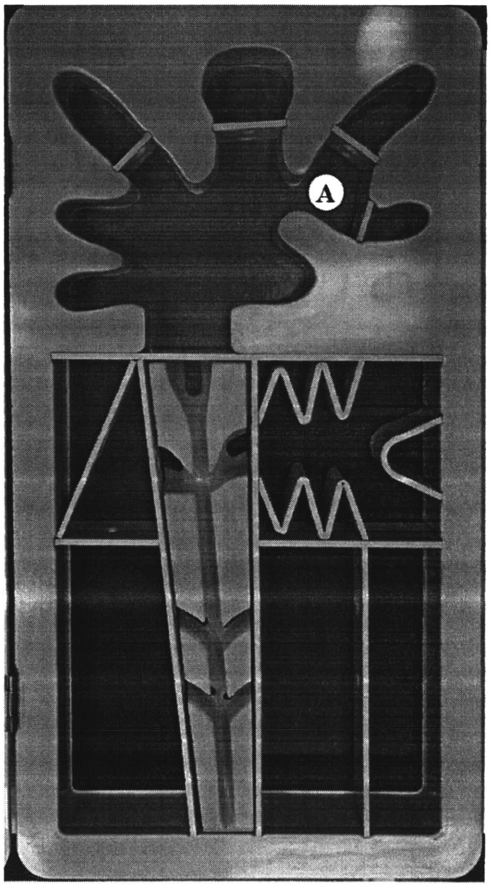
Task 5:

- Insert the ureteroscope and pass it to point A
- Move the ureteroscope to view the blue area through the hole
- Remove the ureteroscope



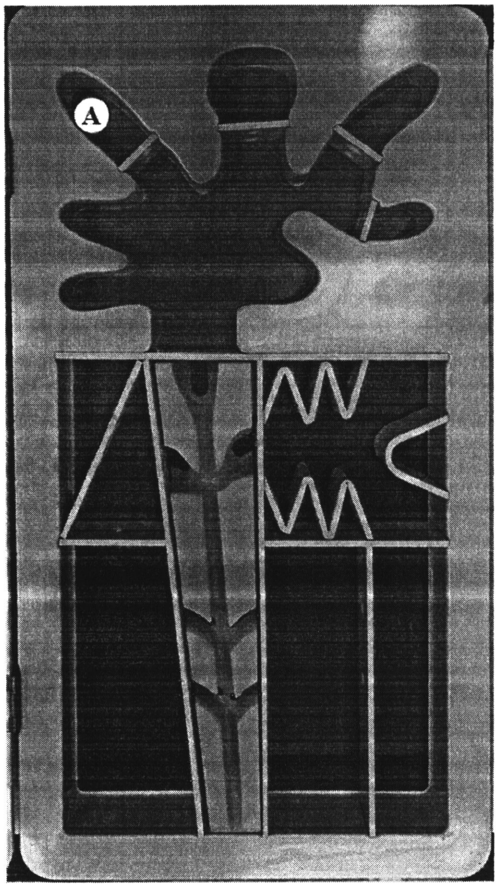
Task 6:

- Insert the ureteroscope and pass it to point A
- Remove the ureteroscope



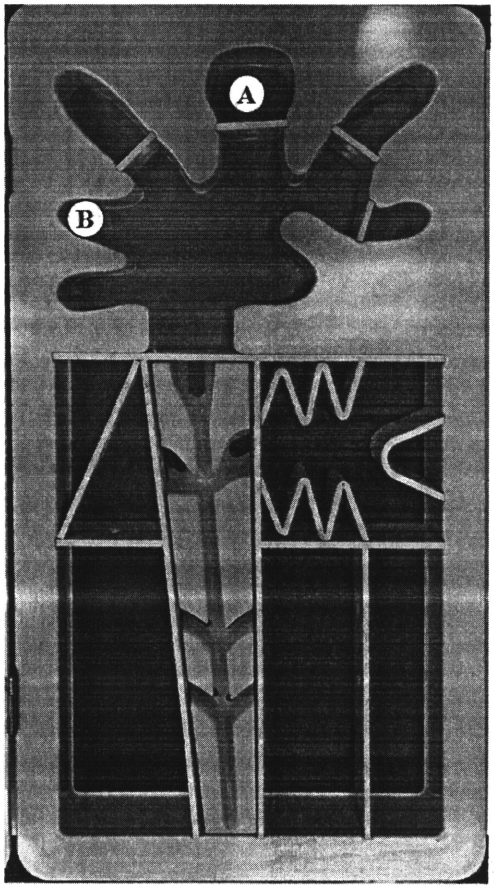
Task 7:

- Insert the ureteroscope and pass it to point A
- Remove the ureteroscope



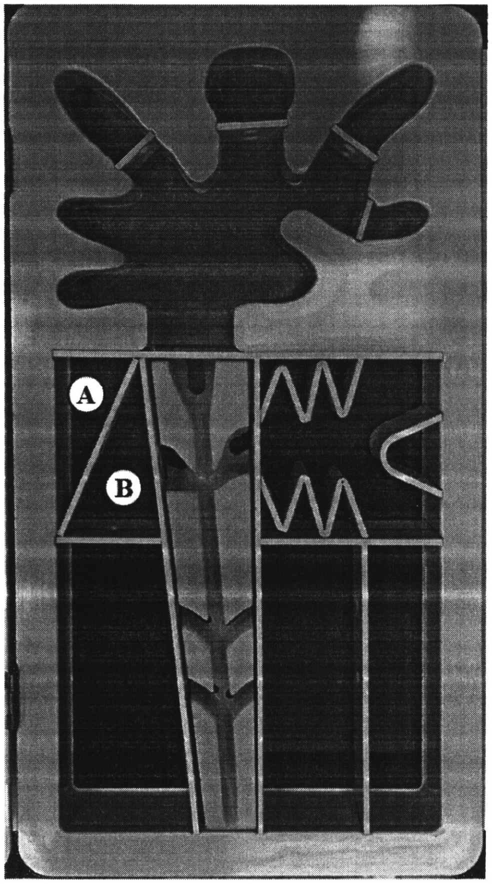
Task 8:

- Insert the ureteroscope and pass it to point A
- Move the ureteroscope to point B
- Remove the ureteroscope



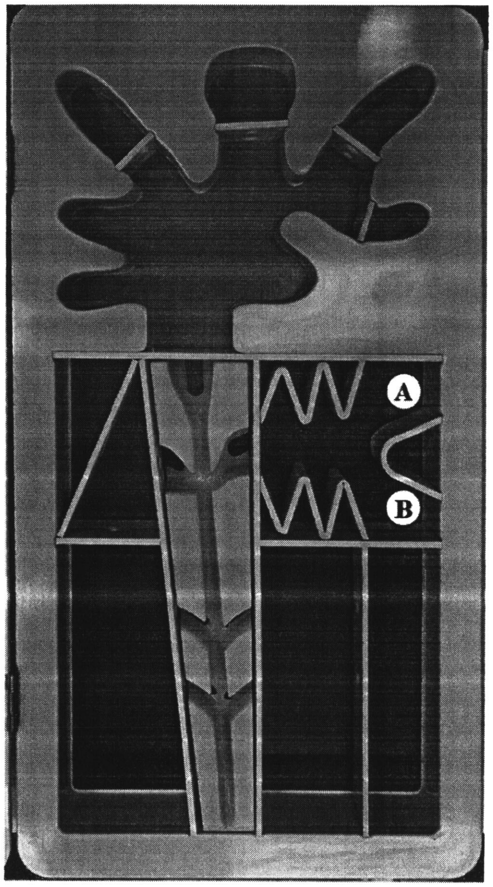
Task 9:

- **Insert the ureteroscope and pass it to point A**
- **Move the ureteroscope to point B**
- **Remove the ureteroscope**



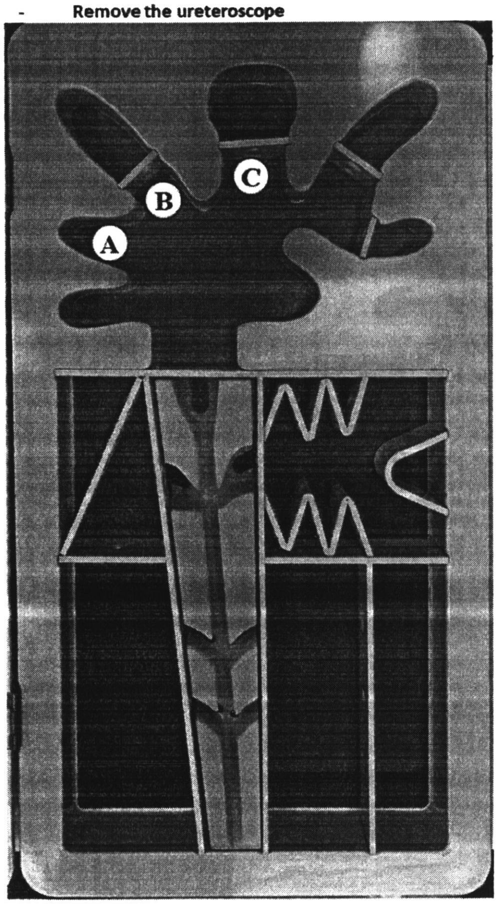
Task 10:

- **Insert the ureteroscope and pass it to point A**
- **Move the ureteroscope to point B**
- **Remove the ureteroscope**



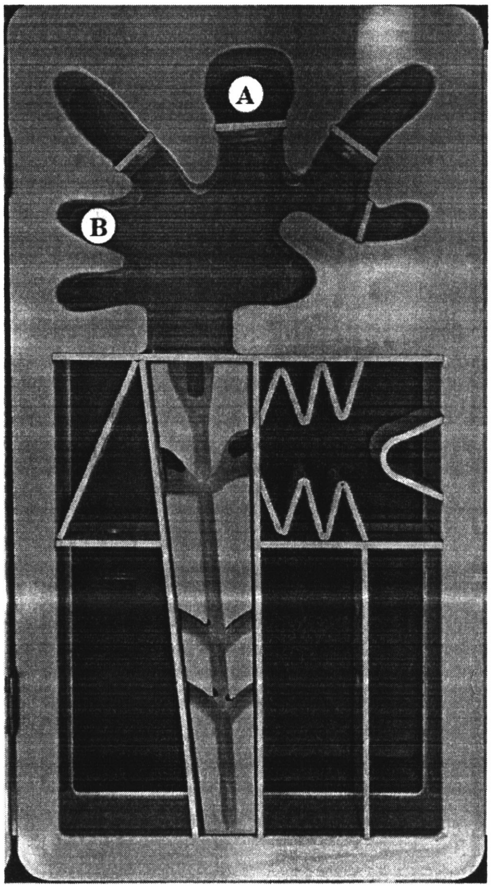
Task 11:

- **Insert the ureteroscope and pass it to point A**
- **Move the ureteroscope to point B**
- **Move the ureteroscope to point C**
- **Remove the ureteroscope**



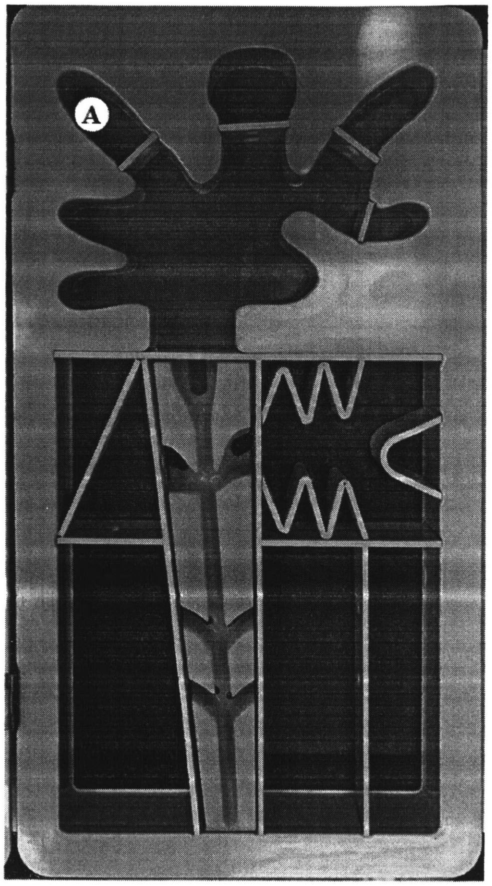
Task 12:

- **Insert the ureteroscope and pass it to point A**
- **Move the ureteroscope to point B**
- **Remove the ureteroscope**



Task 13:

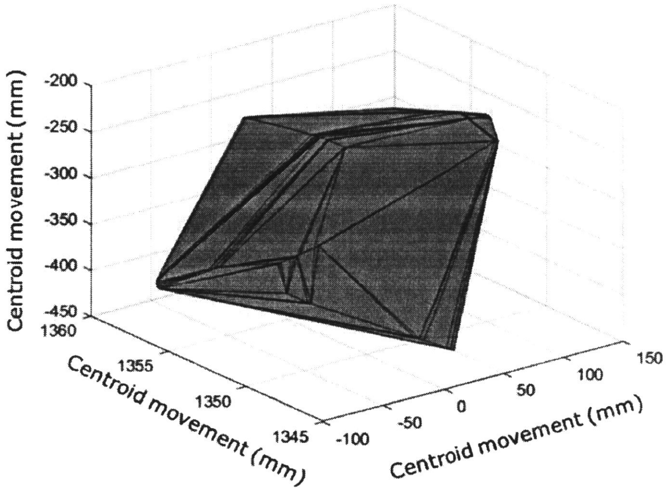
- **Insert the ureteroscope and pass it to point A**
- **Remove the ureteroscope**

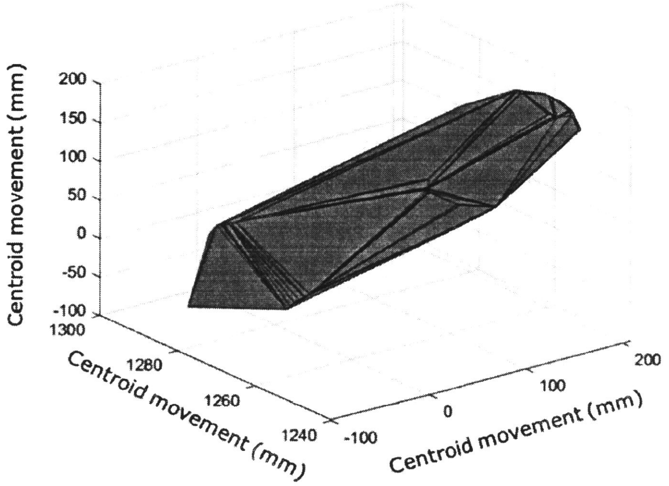


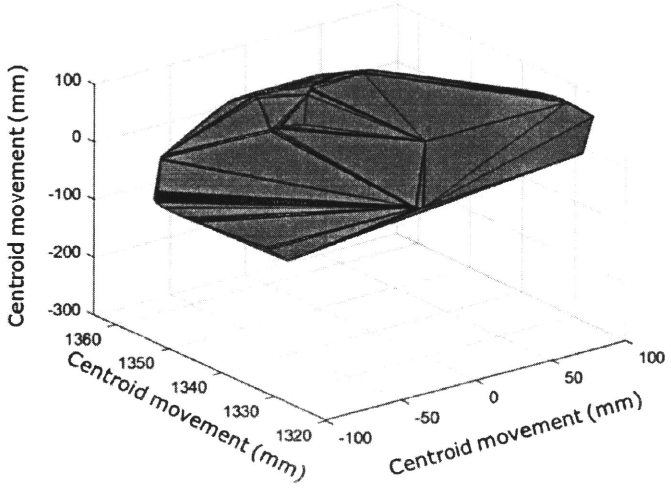
Appendix C

Representative Example *convexHull* Outputs Utilized to Generate Hull Volumes

[all examples are torso-generated hulls]

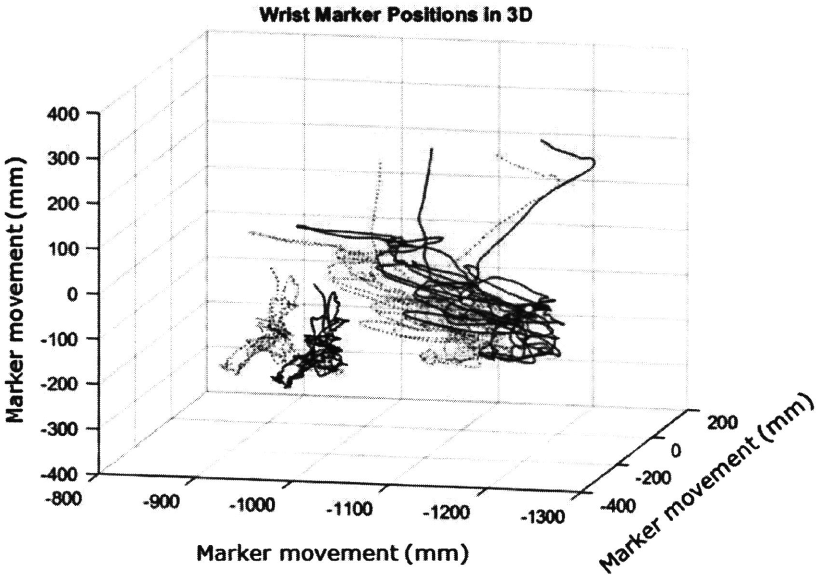


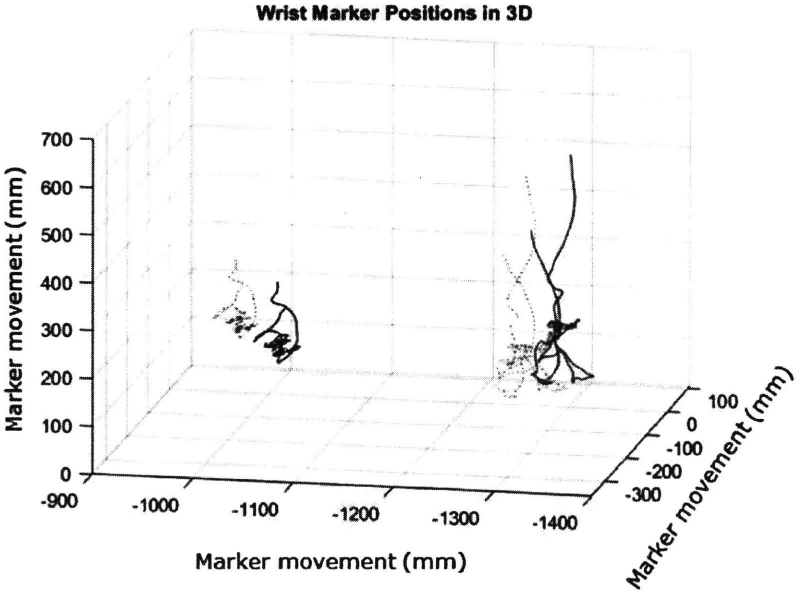




Appendix D

Representative Example Wrist Motion Plots





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