USE OF BIOMECHANICAL MOTION ANALYSIS TO EVALUATE ENDOTRACHEAL INTUBATION SKILL IN A SIMULATED CLINICAL SETTING

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ABSTRACT

This study evaluated, using motion capture technology, the performance characteristics of novice and experienced medical personnel performing endotracheal intubation in a simulated clinical setting. Few objective measures exist that quantify the differences in intubation techniques between providers of various skill levels. These measures are inadequate for providing useful feedback towards training or performance-based research. Motion analysis may be a potential solution for the quantitative evaluation of endotracheal intubation among healthcare professionals of different skill levels. This study hypothesized that experienced personnel would exhibit movement patterns associated with higher performance and efficiency when compared to novice personnel. Twelve subjects were recruited for this study, among whom eight were novice participants and four were expert participants, based on the number of times they had performed endotracheal intubation. Each subject donned a full body 41 marker motion capture suit and performed simulated endotracheal intubation on an Airway mannequin using a Macintosh blade-fitted laryngoscope. Intubation success was defined by visible lung inflation of the mannequin. The obtained motion capture data was used to calculate path length, average path speed and use time of the laryngoscope, as well as the overall intubation time. Angular ranges of motion were calculated for the left wrist, elbow, the neck, and both knees of study subjects. Experts, when compared to novices, intubate faster and with lower overall movement (path length). One way ANOVA and two sample t-tests were conducted on all outcome variables, wherein significant p-values were obtained from the wrist abduction/adduction ($p = 0.009$) and elbow abduction/adduction ($p=0.002$) ranges of motion among novices and experts, indicating significant difference. Combined with a lower completion time and the lower overall laryngoscope movement, the lower range of motion for the wrist and the elbow in experts may indicate that experts are implementing finer, more economic maneuvers in order to achieve successful intubation. These results supports the study hypothesis that experienced personnel, compared to novice, will exhibit measurable movement patterns associated with higher performance and efficiency.

APPROVAL PAGE

The faculty listed below, appointed by the Dean of School of Computing and Engineering, have examined a thesis titled "Use of Biomechanical Motion Analysis to Evaluate Endotracheal Intubation Skill in a Simulated Clinical Setting," presented by Safeer Farrukh Siddicky, candidate for the Master of Science degree**,** and certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

INTRODUCTION

Significance of evaluating medical skill in a simulated clinical setting using biomechanical motion analysis

Medical skill is acquired through a significant amount of learning and training. Often, the application of the skills learned is a deciding factor between whether a patient continues to live, or faces an untimely expiration. The methods and efficacy of acquiring such a crucial set of skills will always have room for improvement. Traditionally, medical skill has been learned through observation of a skilled physician, practice on animal or cadaveric models, or on live patients. To our best knowledge, simulation based mastery learning has come into prominence in the field of medical education since 1969 [1] as an effective, safer alternative for learning medical skill [2], and can produce downstream results in physician training. [3]. In a similar fashion, conducting research using simulation as an investigative methodology utilizes the standardization provided by simulation to answer research questions that could not otherwise be answered feasibly, safely, ethically or in a timely fashion in clinical settings [4].

Research in medical skill typically includes few objective measures. Biomechanical motion analysis provides the opportunity to investigate medical personnel through motion data that can be analyzed to obtain objective, quantifiable kinematic variables. The evaluation of medical skill using biomechanical motion analysis may be useful in developing a more robust training protocol for novice participants who are learning medical procedures, by generating precise, objective feedback.

Thesis Content

The purpose of this study is to evaluate, using motion capture technology, the performance characteristics of novice and experienced medical personnel performing endotracheal intubation in a simulated clinical setting. We hypothesized that experienced personnel, compared to novice, will exhibit movement patterns associated with higher performance and efficiency as characterized by a variety of biomechanical variables.

This thesis is organized into four chapters as follows. Chapter 1 is a brief overview into the significance of evaluating medical skill in a simulated clinical setting using biomechanical motion analysis. Chapter 2 provides a detailed background on the significance of evaluating skill in medical procedures, the significance of performing a research study in simulated clinical settings (specifically the use of high fidelity mannequins). The bulk of the study information is contained in Chapter 3, including detailed study methodology, results obtained, and a discussion of the overall outcome. Chapter 4 presents a conclusion of the research study, including interpretation of obtained results, comparison to previous studies, implications of the findings, limitations of the current study and suggestions on future work. All illustrations and computer code in this thesis are in the Appendices.

CHAPTER 2

BACKGROUND

Significance of Evaluating Skill in Medical Procedures

Introduction to Medical Procedures Investigated

The work presented here is focused on one part of a larger study funded by a University of Missouri System Inter-disciplinary Inter-campus (IDIC) grant, which involves evaluating the performance characteristics of medical personnel while performing three simulated medical procedures: Endotracheal intubation (ETI), central venous catheterization (CVC) and laparoscopic surgery.

Endotracheal intubation (ETI) is a common emergency airway procedure used to connect the larynx and the lungs through the trachea of patients. The process is executed via a laryngoscope inserted into the mouth that helps doctors obtain a direct visualization of the glottis, through which an endotracheal tube is inserted to create an airway [5]. Often, successful and timely intubation is a life-saving procedure, while failed or delayed intubation may prove to be fatal. Additionally, a large multicenter study in 2012 among emergency department patients undergoing ETI observed that multiple intubation attempts were independently associated with adverse events (multiple forms of trauma) [6]

A central venous catheter ("central line", "CVC", "central venous line" or "central venous access catheter") is a catheter placed into a large vein in the neck (internal jugular vein), chest (subclavian vein or axillary vein) or groin (femoral vein). It is used to administer medication or fluids, obtain blood tests (specifically the "central venous oxygen saturation"), and measure central venous pressure [7]. The central venous catheterization in the broader study is conducted with the right internal jugular vein approach [8].

Laparoscopic surgery, also called minimally invasive surgery (MIS), is a modern surgical technique in which operations are performed far from their location through small incisions (usually 0.5–1.5 cm) elsewhere in the body [9]. Laparoscopic procedures are becoming increasingly popular since it is a minimally invasive procedure where patients often experience less pain, shorter recovery, lower risk of infection time and less scarring. Training programs in laparoscopy are becoming increasingly standardized and have been extensively applied in simulation based learning. In the scope of the current study, motion analysis is used to monitor procedures conducted on a Fundamentals of Laparoscopic Surgery (FLS) Trainer System [10].

This thesis focuses on evaluating endotracheal intubation skill in a simulated clinical setting.

Rationale for Evaluating Skill in Endotracheal Intubation

Proficiency both in completing a successful intubation in time and without any damage to the oral cavity of the patient is of crucial importance. In an emergency setting, unsuccessful intubation or a delay in performing the task may lead to fatal consequences, or to oxygen deprivation leading to brain damage. Additionally, a large multicenter study in 2012 among emergency department patients undergoing ETI observed that multiple intubation attempts were independently associated with adverse events (multiple forms of trauma) [6]. In spite of its critical importance, the success rate of first-attempt pre-hospital ETI among ground paramedics in the US is as low as 51%, as reported by a 2010 meta-analysis of pre-hospital airway control techniques [11]. The same study observed success rates as low as 60% for non-physicians (other EMS personnel, nurses and other allied health professionals) and as low as 85% for physicians who performed ETI in a pre-hospital setting. It is to be noted that a majority of ETI performed in these emergency pre-hospital scenarios were executed by ground paramedics and non-physicians, with physicians representing less than 1% of the pooled data.

Few objective measures exist to quantify the differences in ETI techniques between providers of various skill levels. Evaluation schemes before 2011 have only included binary success/failure methods [12] or video-based laryngoscopy analyses [13], both of which are qualitative measures. These are inadequate for providing useful feedback towards training or objectively tracking the learning curve of an intubation trainee. Since 2011, motion analysis (both marker based and marker less) has been identified by four research groups [14] [15] [16] [17] [18] [19] [20] as a potential solution for the quantitative evaluation of endotracheal intubation among healthcare professionals of different levels of skill.

Significance of Performing a Research Study in a Simulated Clinical Setting

Use of High Fidelity Medical Mannequins for Training and Research

Conducting research using simulation as an investigative methodology utilizes the standardization provided by simulation to answer research questions that could not otherwise be answered feasibly, safely, ethically or in a timely fashion in clinical settings [4]. Using simulation tools allows researchers to analyze the factors that influence patient outcomes in clinical scenarios, such as medical provider performance, without putting any actual patients at risk of injury. Mannequin-based simulation has been particularly useful in studying factors affecting human and systems performance in healthcare. Simulation based learning using high-fidelity simulators (e.g. simulators and mannequins that change and respond to the user) is an effective educational tool which improves procedural skills [21] [22] [23] [24] [25] and complements medical education in a patient care setting [26].

Use of Biomechanical Motion Analysis to Evaluate Performance

Motion Analysis Used for Skill Assessment in Other Fields

Video and marker-based motion capture has widely been used both in simulated surgical settings [27] [28] [29] [30] [31] [32] [33] and in performance-based practices such as music performance [34], industrial fabrication methods [35] and sports performance [36] to demonstrate skill level based on kinematic variables.

In discerning the movement patterns among study participants having different levels of skill, marker based motion analysis has demonstrated the ability to generate both qualitative and quantitative kinematic measures. This ability has allowed marker-based motion capture technology to become an established methodology for the biomechanical assessment of skill, and can hence be effectively translated into evaluating endotracheal intubation skill in a simulated clinical setting.

Review of Studies in Current Literature That Use Motion Analysis to Evaluate Performance in Endotracheal Intubation

Since 2011, motion analysis (both marker-based and marker-less) has been identified by four research groups as a potential solution for the quantitative evaluation of endotracheal intubation among healthcare professionals of different skill levels. These studies may be initially grouped into two main categories: marker-less and marker-based motion analysis.

To our knowledge, marker-less motion analysis to evaluate endotracheal intubation has been employed by three research groups. A short summary of each study is presented below, chronologically.

A 2011 study by Rahman et.al of the Alfred I. Dupont Hospital for Children conducted a pilot study for tracking mannequin tracheal intubation using motion analysis [14]. The study was conducted on infant Airway mannequins, and included 11 nurse anesthetists or anesthesiologists as the expert group and 11 medical students from the same academic tertiary level pediatric hospital as the novice group. Laryngoscope motion was tracked using wired receivers that utilized electromagnetic technology. During trials, intubation success was confirmed by visual or functional confirmation (e.g. achieving lung inflation during simulated bag-valve-tube ventilation). Collected data included expert vs. novice rate of success, ETI time, laryngoscope blade-tip motion path length, handle angle at intubation and motion of handle relative to mannequin. The authors state that the rate of success was greater for experts, but they had a longer path length and took longer to intubate. Movement trajectories of the handle of the laryngoscope (with respect to the mannequin) demonstrate that all subjects rotated or ‘‘rocked,’’ rather than lifted, the laryngoscope during intubation attempts. It is hypothesized that even though the mannequins impose no penalty (edema, bleeding, etc.) for intubation induced trauma, experts still recognize these risks and use maneuvers to minimize them, which may explain why experts took longer to intubate. Experts may have possibly spent more time establishing precautionary measures in the preparatory phase of intubation. Major limitations in this study included analysis of laryngoscope movement only in the sagittal plane, and the inability to confirm that the stabilization of the laryngoscope correlated to the visualization of the larynx.

DeLaveaga et al. from the University of Nebraska investigated the effect of hospital bed height on the effectiveness of ETI procedure completion on an adult Airway mannequin among novice and experienced participants [15] [16]. The study included 15 third and fourthyear medical students as the novice group and 5 expert participants from the Department of Emergency Medicine, having at least 5 years of experience. Wrist postures and muscle activity were tracked using a dual-axis goniometer, a torsiometer and a surface Electromyography (sEMG) system. During trials, intubation success was defined through visual evaluation. Collected data included ETI completion time, wrist angles and sEMG amplitude to evaluate muscle utilization. The study discussion states that task completion time and intubation errors did not vary with hospital bed height. Muscle utilization did not differ significantly between bed heights or expert and novice participants. Experts exhibited greater wrist extension and less ulnar deviation during task trials. Expert participants grasped the laryngoscope differently than novice participants, resulting in less wrist manipulation required to achieve ideal instrument positions. One of the major limitations in this study was the absence of full body kinematic quantification.

Two 2013 studies by Bartolomeo et al. and Matsuoka et al. from Waseda University in Japan focused on developing a system for the objective biomechanical evaluation and performance segmentation of doctors performing simulated ETI on an adult Airway mannequin [17][18]. The study included 5 expert and 6 novice anesthesiologists. Upper body motion of test subjects was recorded via Inertial Measurement Unit (IMU) sensors located on key locations of the upper body; whole forearm and wrist muscle activation was recorded using a sEMG system. During trials, intubation success was not explicitly defined. Collected data included angular velocity of wrist joint and elbow joint, sEMG of the upper limb, and some angles on the upper part of the body, in order to evaluate joint stiffness in the arm and posture during intubation. The study discussion states that the results presented significant differences between experts and novices in the left extensor carpi ulnaris muscle activation, its isometric contraction index (ratio of maximum voluntary contraction EMG value of a muscle with respect to the normalized angular velocity related to the joint activated by the muscle), angle of line of sight and angle of upper body. In particular, the left extensor carpi ulnaris muscle activation and its isometric contraction index can display differences while raising the tongue and inserting the tube, with both quantities being significantly higher for Expert participants. The angle of line of sight and the angle of the upper body can display great differences just before insertion of the tube, with the angle of line of sight being significantly higher for novices. A major limitation of this study involves the wired sEMG system which, as supported by complaints from study participants, may have introduced movement barriers during ETI.

To our knowledge, marker-based motion analysis has been employed by one research group to examine endotracheal intubation.

Two 2012 studies by Carlson et al. and Das et al. from the University of Pittsburgh and Carnegie Mellon University tested the feasibility of using marker-based motion capture to quantify variability in hand motion and laryngoscope movement among providers with various levels of experience [19], and developed a quantitative framework in order to discern the kinematic characteristics of providers with different experience levels [20]. The study included 3 providers with varying levels of experience: attending physician (experienced), Emergency Medicine resident (intermediate), and post-doctoral student with no previous ETI experience (novice). The main motion capture apparatus included retro-reflective markers and a Vicon 16-camera system. A total of 50 retro-reflective markers were placed on the upper body of the subjects, another 18 were placed on the dummy and 3 were placed on the laryngoscope handle. During trials, intubation success was defined through visual evaluation. Collected data include recorded attempt duration, path length of the left hand and the inclination of the plane of laryngoscope movement (mean square angular deviation form vertical). Inter-attempt and inter-provider variability of each measure was compared. The study demonstrated how motion capture provides high resolution information about the technique of ETI. In just four trials, the mean path that a provider makes with their left arm to achieve ETI, the duration of the ETI attempt, and the variability in the handling of the laryngoscope were quantified. Duration and laryngoscope angle were consistently different between providers with different experience levels. Intermediate and experienced providers were found to have similar patterns of laryngoscope movement that are quantitatively distinct from the novice. One of the major limitations of this study was a very small subject sample size.

CHAPTER 3

STUDY

Introduction

Proficiency both in completing a successful intubation in time and performing it without any damage to the oral cavity of the patient is of crucial importance. In an emergency setting, unsuccessful intubation or a delay in performing the task may lead to adverse, even fatal consequences. Additionally, a large multicenter study in 2012 among emergency department patients undergoing ETI observed that multiple intubation attempts were independently associated with adverse events (multiple forms of trauma) [6]. In spite of its critical importance, the success rate of first-attempt pre-hospital ETI among ground paramedics in the US is as low as 51%, as reported by a 2010 meta-analysis of pre-hospital airway control techniques [11]. The same study observed success rates as low as 60% for non-physicians (other EMS personnel, nurses and other allied health professionals) and as low as 85% for physicians who performed ETI in a pre-hospital setting. It is to be noted that a majority of ETI performed in these emergency pre-hospital scenarios were executed by ground paramedics and non-physicians, with physicians representing less than 1% of the pooled data.

There are few objective measures to quantify the differences in ETI techniques between providers of various skill levels. Evaluation schemes before 2011 have only included binary success/failure methods [12] or video laryngoscopy based analyses [13]. These are inadequate for providing useful feedback towards training or objectively tracking the learning curve of an intubation trainee.

This study utilized motion capture technology to conduct a biomechanical investigation into the performance characteristics of novice and experienced medical personnel performing Endotracheal Intubation in a simulated clinical setting.

Methods

Subjects

Subjects for this study were recruited through broad advertisement via posted paper flyers, direct email/phone contact with individuals via electronic versions of the flyer, and presentations to groups (e.g. specific UMKC departments, classes of students) via PowerPoint slides. The study recruitment flyer is available in Appendix D.

Subjects included UMKC students, employees, and clinical affiliates who are of age 18 or older, and who routinely perform endotracheal intubation as part of their regular clinical practice or curriculum. Participants were excluded if unable to comply with any task requirements, similar to those normally used in regular clinical practice, while wearing a motion capture suit. Subject recruitment methods, inclusion/exclusion criteria and study protocol have been approved as an Expedited/Full Board Application by the University of Missouri-Kansas City Institutional Review Board, under the title "Analysis of Human Performance in a Clinical Simulation Setting."

A total of 12 participants were included in evaluating the endotracheal intubation skill. Subjects included medical students, EMS students, PA program students, Master's in Anesthesiology students, medical residents, physicians, Nurses, Fellows and EMT personnel. Subject population was principally divided into two cohorts: novice and experienced subjects.

Providers who had performed Endotracheal Intubation fewer than 300 times served as the population who had limited to preliminary exposure to Intubation and were therefore representative of the "novice" demographic, based on medical skill.

Providers who had performed Endotracheal Intubation for 300 or more times served as the population who had extensive exposure to Intubation and were therefore representative of the "experienced" demographic, based on medical skill. The 300 Intubation cutoff for Novice against Expert is a replicate measure from the same classification used by Bartolomeo et al. [18].

Subject classification data is obtained through self-reporting in a confidential REDCap [37] questionnaire, filled out by each subject right before participating in the experiment. A copy of the REDCap questionnaire can be found in Appendix D.

Apparatus and Approach

Motion capture for this study is executed by a portable setup of 18 OptiTrack Flex 13 cameras [38], each mounted by a combination of two Manfrotto clamps [39][40] onto 9 On-Stage stands [41] (each stand holds 2 cameras at a 24 inch vertical separation). Figure A.1 in Appendix A demonstrates a single stand with 2 cameras mounted. The Flex 13 cameras are connected via Mini-B USB cables into 4 OptiHubs, which in turn are plugged into the study Workstation via Type-B USB cables. Details of the setup schematic can be found in Figure A.2 in Appendix A.

The captured motion data is visualized and processed through OptiTrack Motive software v1.7.4 [42], which is installed on the study Workstation. The study Workstation is a Dell Precision Workstation T3610 [43] that runs a Windows 7 Professional 64-bit operating system.

In order to participate in motion capture, each subject donned a full body motion capture suit with 41 attached retro-reflective markers, as illustrated in Figure A.3 in Appendix A.

Endotracheal intubation was conducted on a Laerdal® Airway Management Trainer [44] Airway mannequin which has 9 retro-reflective markers attached at key locations to track mannequin movement (key locations include anatomical landmarks on head, chest, lung and stomach, as shown in Figure A.11 in Appendix A). In addition to the mannequin and the bed that it is placed on, each participant is supplied with a bag-valve-mask resuscitator, an endotracheal tube and stylette, a syringe, and a medium laryngoscope handle fitted with a #4 Macintosh laryngoscope blade [45]. Figure A.4 in Appendix A demonstrates the Airway mannequin used in this study, along with the configuration of the provided equipment.

The laryngoscope is the main tracked device, and has been modified to allow for marker-based tracking of the Macintosh blade tip during the period of time between oral insertion of the blade leading to perceived laryngeal visualization and the withdrawal of the blade after the endotracheal tube has been successfully inserted into the larynx. Figure A.5 in Appendix A demonstrates the modified Laryngoscope used in this study.

Experimental Procedure

All motion capture sessions for this study were conducted in the Clinical Skills Area at the University of Missouri-Kansas City School of Medicine Clinical Training Facility. The Clinical Training Facility also provided the Airway mannequin and the intubation equipment for this study. The apparatus was set up as illustrated in Appendix A. Each study participant completed a consent form and a questionnaire in order to be included as a subject in the study. The consent form and the questionnaire can be found in Appendix D. Once consenting was completed, each participant donned a full body motion capture suit and was fitted with a 41-marker Motive motion capture setup. This setup is illustrated in Figure A.3 in Appendix A.

Inside the capture space, each participant was asked to T-pose as illustrated in Figure A.3 in Appendix A in order to initiate motion tracking in the Motive software. Once participants had verbally confirmed that all instruments required to successfully complete Endotracheal Intubation on the provided Airway mannequin were present, they were asked to adjust the height of the bed to their most comfortable, self-selected height. Participants subsequently carried out Intubation on the provided Airway mannequin and T-posed to signify the end of the procedure. Endotracheal intubation success for each trial was visually confirmed by mannequin lung inflation accompanied by no noticeable stomach inflation.

Measurements

Individual marker data is recorded by the Motive software. For each subject, relevant biometric data (height, handedness, age and gender) are collected from the REDCap questionnaire. De-identified biometric data is available in Table B.1 in Appendix B. The principal measurements taken from the motion analysis data set for each participant are the coordinates of the four markers on the modified Laryngoscope, the nine markers on the airway mannequin and the overall 41-marker data set that is exported from the Motive software in .csv format. Figure A.5 in Appendix A demonstrates the modified Laryngoscope used in this study. The laryngoscope was modified in this manner in order to virtually track the tip of the blade, since it would not be possible to track a marker on the tip of the blade when the blade went into the mannequin's oral cavity. Secondary measurements include the sampling rate of the cameras and a binary, qualitative measurement that is taken from the Motive software to track the lungs of the Airway mannequin in order to determine whether the intubation was successful or not. Lung inflation, combined with the absences of visible stomach inflation is an indicator of a successful intubation. A screenshot of this measurement is demonstrated in Figure A.6 in Appendix A.

Data Analysis

All marker based data was exported using the OptiTrack Motive software v1.7.4 [42]. Data analysis has been principally conducted with MATLAB R2013a (The Mathworks, Natick, MA, USA).

Relevant data, from here on forward, was clipped between the motion data frames corresponding to the period of time between laryngoscope pick-up and laryngoscope put-down. This frame range will be referred to as "Laryngoscope active frames". This time line includes laryngoscope pick up, oral insertion of the blade leading to perceived laryngeal visualization, withdrawal of the blade after the endotracheal tube has been successfully inserted into the larynx and the placing of the laryngoscope onto the study bed.

The four markers on the modified laryngoscope are used to identify the virtual position of the tip of the Macintosh blade that is fitted to the laryngoscope. Initially, a marker is positioned at the tip of the blade and some static and dynamic calibration data is recorded. Data from the four markers on the modified laryngoscope is used to define a local coordinate system for the laryngoscope. The calibration data is used to define a vector from this local coordinate system to the position of the Macintosh blade tip. The MATLAB code for this virtual point calculation is available in Appendix C. The correlation plots between the positioned blade marker and the calculated virtual marker is shown in Figure A.7. in Appendix A. Some laryngoscope marker data sets experienced some switching marker definitions, due to which the calculated path length would have been overestimated. In order to resolve this issue, individual low-pass Butterworth filters with cutoff frequencies between 0.5 Hz to 5 Hz were applied to the marker data sets with switching marker definitions.

The virtual tip position of the Laryngoscope is then used to calculate the path length and the average path speed of the Macintosh blade tip. Path length measures the overall movement of the blade tip over the duration of laryngoscope use, as a sum of all individual distances between the positions of the blade over time. Path length was calculated using Equation 1.

$$PL_i = PL_{i-1} + \sqrt{(m_i - m_{i-1})^2} \tag{1}$$

where PL = path length, i = time index, m = blade tip marker data

Average path speed is calculated by dividing path length by time. The laryngoscope use time is calculated by dividing the number of motion data frames included in the Laryngoscope active frames by the sampling frequency of the OptiTrack Flex 13 cameras. The MATLAB code for this calculation is available in Appendix C.

Laryngoscope use time is the time duration of the "Laryngoscope active frames", whereas intubation time is the time duration between laryngoscope pick-up and the first detected peak from successful mannequin lung inflation (recorded via a marker on each mannequin lung).

Joint angles, or segment angles, between any two body segments were calculated by first defining local coordinate systems (LCS) on each segment, and then relating the two segments via a Cardan rotation sequence. The Cardan rotation sequence XYZ is often used in biomechanics [46] to generate a 3-D rotation matrix, which is the orientation of one LCS with respect to another LCS, and is represented by three successive rotations about unique axes. This sequence is three step; first, rotation about the laterally directed X axis (α), second, rotation about the anteriorly directed Y axis (β), and third, rotation about the vertical Z axis (γ). The Cardan rotation matrix between two LCS is equivalent to the element-wise dot product of the unit vector matrices of those two LCS. This equivalency is demonstrated in Equation 2.

$$R = \begin{bmatrix} c\alpha c\beta & c\alpha s\beta s\gamma - s\alpha c\gamma & c\alpha s\beta c\gamma + s\alpha s\gamma \\ s\alpha c\beta & s\alpha s\beta s\gamma + c\alpha c\gamma & s\alpha s\beta c\gamma - c\alpha s\gamma \\ -s\beta & c\beta s\gamma & c\beta c\gamma \end{bmatrix} = \begin{bmatrix} i.I & j.I & k.I \\ i.J & j.J & k.J \\ i.K & j.K & k.K \end{bmatrix} \qquad (2)$$

where R = Cardan rotation matrix, s = sine, c = cosine, [i,j,k] = Local coordinate system for Segment 1, [I,J,K] = Local coordinate system for Segment 2.

Equating the two definitions of the rotation matrix allows the calculation of the three rotational angles, α, β, and γ. For anatomical segments, α is the flexion/extension, β is the abduction/adduction and γ is the pronation/supination (or axial rotation). Joint rotation angles calculated in this manner are Euler angles and while they are closely related to the anatomical rotation angles, they may not correlate exactly with physiological conventions. Joint angle LCS definitions are illustrated in Appendix A. For this study, the relevant joint angles calculated were the neck angle, the wrist angle, the elbow angle, the knee angle and the angle of view between the subject and the mannequin. Table B.1 through B.5. in Appendix B lists de-identified subject biometric data and calculated outcome variables for each subject.

Statistical Analysis

A between-group comparison of performance measures was conducted. The primary variable is skill level which has 2 levels, namely novice and expert. It is determined by the number of times the study participant has performed Endotracheal Intubation, with the novice level having performed less than 300 intubations and the Expert level having performed 300 or more intubations. All other outcome variables are dependent variables which were compared to these 2 levels or groups. These include biomechanical measures such as path length, joint angles, procedure times and a binary indicator indicating success or failure of the procedure.

Initially, an ANOVA F-test was conducted to find the critical F-value based on sample size of the two groups. One way ANOVA was then conducted with the Factor being skill level (Group) and the response being each calculated outcome variable. If significant results were observed from the one way ANOVA, a two sample t-test was conducted on those variables to confirm that a significant two-tailed p-value was generated. The null hypothesis for this comparison states that level of experience does not affect performance measures. Since one way ANOVA is conducted on the special case of two groups, it is expected that its results will be identical to those from a t-test.

Results

Table 1 displays the means and standard deviations of calculated variables among Novice and Experienced study populations.

Table 1. Calculated variables

Variable (means ± 1 S.D)	Novice	Experienced
Path Length (m)	5.17 ± 2.86	3.58 ± 0.82
Average path speed (m/s)	0.21 ± 0.14	0.20 ± 0.03
Laryngoscope Use time (s)	27.34 ± 9.37	18.45 ± 6.45
Intubation Time (s)	48.05 ± 11.97	37.25 ± 12.92
Left Wrist α ROM (deg)	50.48 ± 16.44	43.56 ± 2.49
Left Wrist β ROM (deg) *	47.45 ± 11.90	26.13 ± 6.11
Left Wrist γ ROM (deg)	71.60 ± 27.00	72.12 ± 22.77
Left Elbow α ROM (deg)	49.67 ± 9.58	37.88 ± 10.53
Left Elbow β ROM (deg) *	31.40 ± 6.45	17.16 ± 3.06
Left Elbow γ ROM (deg)	33.34 ± 9.96	25.58 ± 11.12

Variable (means ± 1 S.D)	Novice	Experienced
Head α ROM (deg)	41.75 ± 7.38	49.82 ± 9.88
Head β ROM (deg)	32.10 ± 8.37	24.28 ± 7.56
Head γ ROM (deg)	41.73 ± 8.49	28.67 ± 11.24
View α ROM (deg)	37.91 ± 16.90	55.66 ± 8.64
View β ROM (deg)	36.69 ± 13.66	27.03 ± 8.17
View γ ROM (deg)	33.47 ± 14.40	26.06 ± 5.42
Left Knee α ROM (deg)	39.90 ± 18.415	42.35 ± 17.120
Left Knee β ROM (deg)	21.87 ± 11.624	25.64 ± 9.276
Left Knee γ ROM (deg)	31.53 ± 37.133	30.03 ± 2.753
Right Knee α ROM (deg)	33.54 ± 16.494	32.79 ± 6.709
Right Knee β ROM (deg)	25.19 ± 11.114	26.99 ± 4.647
Right Knee γ ROM (deg)	13.47 ± 7.293	18.36 ± 7.410

For the joint angles, the means were taken of the total range of motion of each joint so as to effectively compare overall joint movement. As mentioned previously, the joint angles calculated do not necessarily correspond exactly with physiological conventions.

These results are displayed in bar graph format in Appendix A, under Figure A.12. Results indicate Novices, when compared to experts, have a greater Laryngoscope path length, a greater Laryngoscope average path speed, a greater Laryngoscope use time and Intubation completion time, greater wrist flexion/extension and abduction/adduction range of motion, lower wrist pronation/supination range of motion, greater elbow flexion/extension, abduction/adduction and pronation/supination range of motion, lower neck flexion/extension range of motion, greater neck abduction/adduction and pronation/supination range of motion, lower flexion/extension head rotation range of motion with respect to the airway mannequin and greater abduction/adduction and pronation/supination head rotation range of motion with respect to the airway mannequin. Novices also exhibit lower left knee flexion/extension and abduction/adduction range of motion, higher left knee pronation/supination range of motion, higher right knee flexion/extension range of motion and lower right knee abduction/adduction and pronation/supination range of motion.

MINITAB output from statistical analysis is presented in Appendix A. It is observed that significant p-values are obtained from the wrist abduction/adduction ($p = 0.009$) and elbow abduction/adduction ($p=0.002$) ranges of motion among novices and experts, indicating significant difference.

Discussion

Our results indicate that novices use the laryngoscope for a greater time and take longer to intubate than experts. The higher intubation time of novices maybe attributed to inexperience and low familiarity with the equipment and/or with the procedure itself. Novices demonstrate a greater mean path length and have a high standard deviation in this measure, which may be an indicator for greater movement variability. These path length characteristics are supported by the study by Carlson et al. [19].

The lower wrist range of motion among experts, especially in the abduction/adduction rotation angle may indicate finer, more economic maneuvers in achieving successful intubation. The characteristics of the wrist angles also correlates to the elbow rotation angles, with a lower abduction/adduction range among experts. Statistical significance is seen in this difference between the two groups, an observation which is supported for the wrist angle by a study by Matsuoka et. al. [18]

Among experts, the higher flexion/extension range of motion of the neck, combined with the lower neck abduction/adduction and pronation/supination range of motion may indicate that experts visualize the vocal cord of the mannequin in a more “straight-on” manner, resulting in higher movement of the neck about the medial-lateral axis, and lower movement in the other two axes. In comparison, novices may be attaining visualization of the vocal cords through increased neck movements around the anterior posterior and superior inferior axes. These characteristics are also observed in the rotational movement of the neck in relation to the head of the mannequin. A similar observation (related to neck flexion/extension) was made in the study by Matsuoka et al. [18] where the angle between line of sight (provider eye to vocal cord) and line perpendicular to face plane was relatively smaller for experts than that for novices.

CHAPTER 4

CONCLUSION

Interpretation of Results

While further analysis is recommended on the outcome variables, current results indicate that, on average, an expert participant (someone who has performed endotracheal intubation 300 or more times) intubates faster and with less overall movement when compared to a Novice participant (someone who has performed Endotracheal Intubation less than 300 times). We also observed that an expert has significantly lower range of motion for wrist abduction/adduction and elbow abduction/adduction.

Combined with a lower completion time and the lower overall laryngoscope movement, the lower range of motion for the wrist and the elbow in experts may indicate that experts are implementing finer, more economic maneuvers in order to achieve successful intubation. These results support the study hypothesis that experienced personnel, compared to novice, exhibit movement patterns associated with higher performance and efficiency.

Comparison to Previous Studies

Rahman et al. [14] showed that experienced providers required greater time and greater overall movement to successfully intubate. Our findings were not consistent with this. It is to be noted that the study by Rahman et al. was conducted on infant airway mannequins. The study speculates that experts may have taken a longer time and exhibited greater movement due to unfamiliarity with the mannequin and due to the fact that even though these mannequins impose no penalty for trauma, experts still recognize these risks and use techniques to minimize them, hence spending a greater time in the preparatory stages to adjust the mannequin position.

Carlson et al. [19] showed that the mean path lengths increased from experienced providers to novice providers, but did not reach statistically significant levels. This result is replicated in the current study, but with statistical significance. Related studies that use motion analysis to investigate other medical procedures, such as intraocular surgery and laparoscopic surgery, also indicate results where the experienced provider performs the task in less time with fewer movements and/or lower overall movements [27][28][30].

Matsuoka et. al [18] showed that the average wrist angular velocity profile for novices shows statistically significant difference during the lifting of the mannequin tongue. Our study shows statistical significance between novices and experts in the wrist abduction/adduction and elbow abduction/adduction range of motion during the overall procedure, and so a more discrete, segmented investigation of the procedure may display replicate results amongst our subject population.

Implication of Findings

Endotracheal Intubation is highly challenging skill, the application of which is almost always a matter of life and death. Due to its crucial importance, adequate training is absolutely essential for all physicians.

Current findings indicate that there are significant differences in wrist and elbow movement between the two provider groups – novice and expert. Other non-significant differences are observed on the other biomechanical movements that have been quantified. Since these movements are overall calculated movements of the procedure, current findings lay the groundwork for a more discrete, granular and segmented investigation of the procedure to determine whether finer adjustments to technique maybe observed among the two groups. For example, the difference in the overall movement characteristics in the wrist and neck of providers suggests a more detailed study of the wrist and neck angle profiles of experts. This detailed study may lead to the observation of finer wrist adjustments and unique vocal cord viewing techniques among experts during endotracheal intubation, which can help accelerate the learning curve of intubation trainees by providing them with specific suggestions on how to potentially replicate and implement the finer adjustments made by experts.

Since this study finds that experienced participants exhibit movement patterns associated with higher performance and efficiency during performing endotracheal intubation, data from this and future motion analysis studies may be useful in developing a more robust training protocol for novice participants who are learning endotracheal intubation by generating precise, objective feedback.

Overall, this study provided the construct validity of using a portable, marker-based, biomechanical motion capture system towards evaluating skill in simulated medical procedures. The portability of the motion capture system used in this study provides a unique opportunity to evaluate the movement characteristics of medical personnel in varying simulated medical scenarios. In investigating endotracheal intubation, this work utilized some unique quantification methods, especially the use of additive markers on the laryngoscope to virtually track the movement of the laryngoscope blade tip and the use of mannequin lung markers combined with a peak finder algorithm [47] to more accurately signify successful lung inflation. The latter helped represent the end point of successful intubation in a more discrete fashion.

Limitations and Future Work

The current subject sample size, especially on the expert spectrum, maybe small. An increase in the sample size may more clearly exhibit significant differences in biomechanical outcome variables among providers.

Some laryngoscope marker data sets experienced some switching marker definitions, due to which the calculated path length would have been overestimated. While we temporarily resolved the issue by applying low-pass Butterworth filters, in the future this phenomenon can be avoided by not defining the Laryngoscope markers as a “Rigid Body” within the OptiTrack Motive software.

In various observations of the outcome variables calculated (such as path length), novices exhibited a high variance. Possibly, the definition of the novice cohort in this study may have been too broadly defined, which may mask some findings at either end of the spectrum. The novice personnel who had the lowest number of self-reported intubations only had 5 whereas the novice personnel with the highest number of self-reported intubations had 200. It is very likely that there is a steeper learning curve between, say, the first 100 intubations of a trainee than between 100 and 200 intubations. To resolve this broad definition, it may be beneficial to define an “intermediate” cohort among the subject population.

The study currently has some unevaluated data such as handedness, knee angles, provider training models (MD, EMT, RN, etc.). Complementing this data with the current calculated outcomes may lead to unique observations.

A key limitation, from the motion capture perspective, was the inability to measure activity at the digit (finger) level. While our motion capture setup does have the ability to track digit level marker data, our initial subjects reported discomfort with the finger markers. Loss of data in the software was also observed due to frequent finger marker occlusion while tracking the medical procedures investigated. Our research collaborators at the Immersive Visualization Lab at the University Of Missouri Department Of Architectural Studies are working on implementing marker-less data gloves into the motion capture setup so as to resolve the digit level tracking issue. They are also developing architectural models of our capture space in order to incorporate our subject motion data into an immersive virtual medical environment.

While Airway mannequins are useful for practicing simulated intubation, they do not provide varying anatomical structures of airways, or high fidelity feedback such as imposing penalties (edema, bleeding, etc.) for intubation induced trauma. Future work may involve either conducting motion analysis trials on higher fidelity mannequins [48] or cadaver models.

This study focuses on overall movements. Some finer movements and specific movement patterns may have been overlooked in the process of calculating overall trajectories of the laryngoscope blade. Future work may involve a principal component analysis on the hand markers and the laryngoscope blade tip movement to investigate whether experienced participants exhibit fewer modes of movement in the overall procedure.

A majority of the data collected is kinematic in nature. Collection of electromyographic (EMG) data from key muscles in the wrist and forearm may provide complimentary data to help strengthen conclusions reached in discerning movement patterns of expert participants.

Additionally, muscle memory studies have been conducted in other fields, and they may be applicable for expert participants in similar motion capture studies.

APPENDIX A

Equipment Photographs and Layout Schematics

Figure A.1. Setup of Two Flex 13 Cameras Mounted Onto an On Stage Stand

Motion Capture Equipment Layout Schematic in the Clinical Skills Area
Clinical Training Facility
University of Missouri-Kansas City School of Medicine

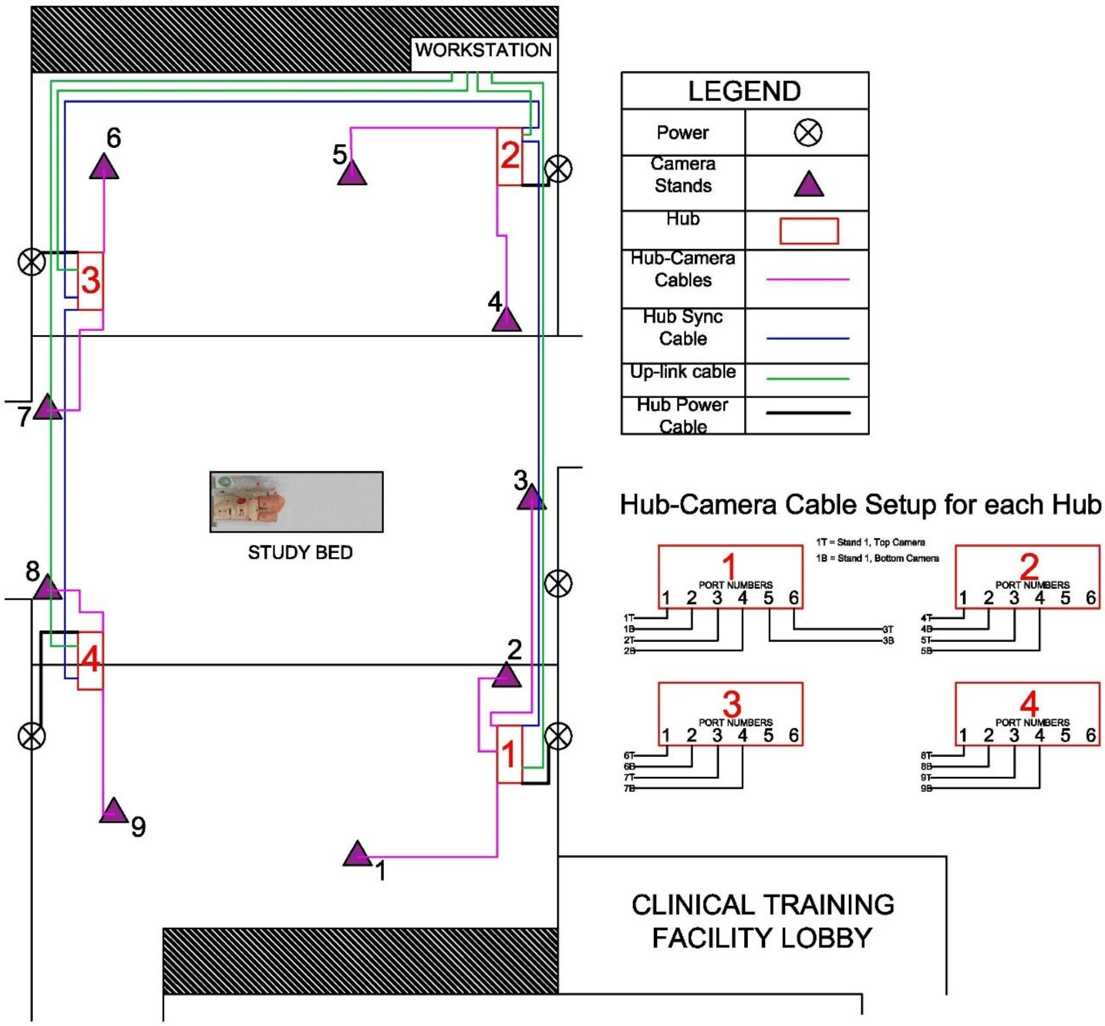


Figure A.2. Equipment Layout Schematic for Motion Capture Study

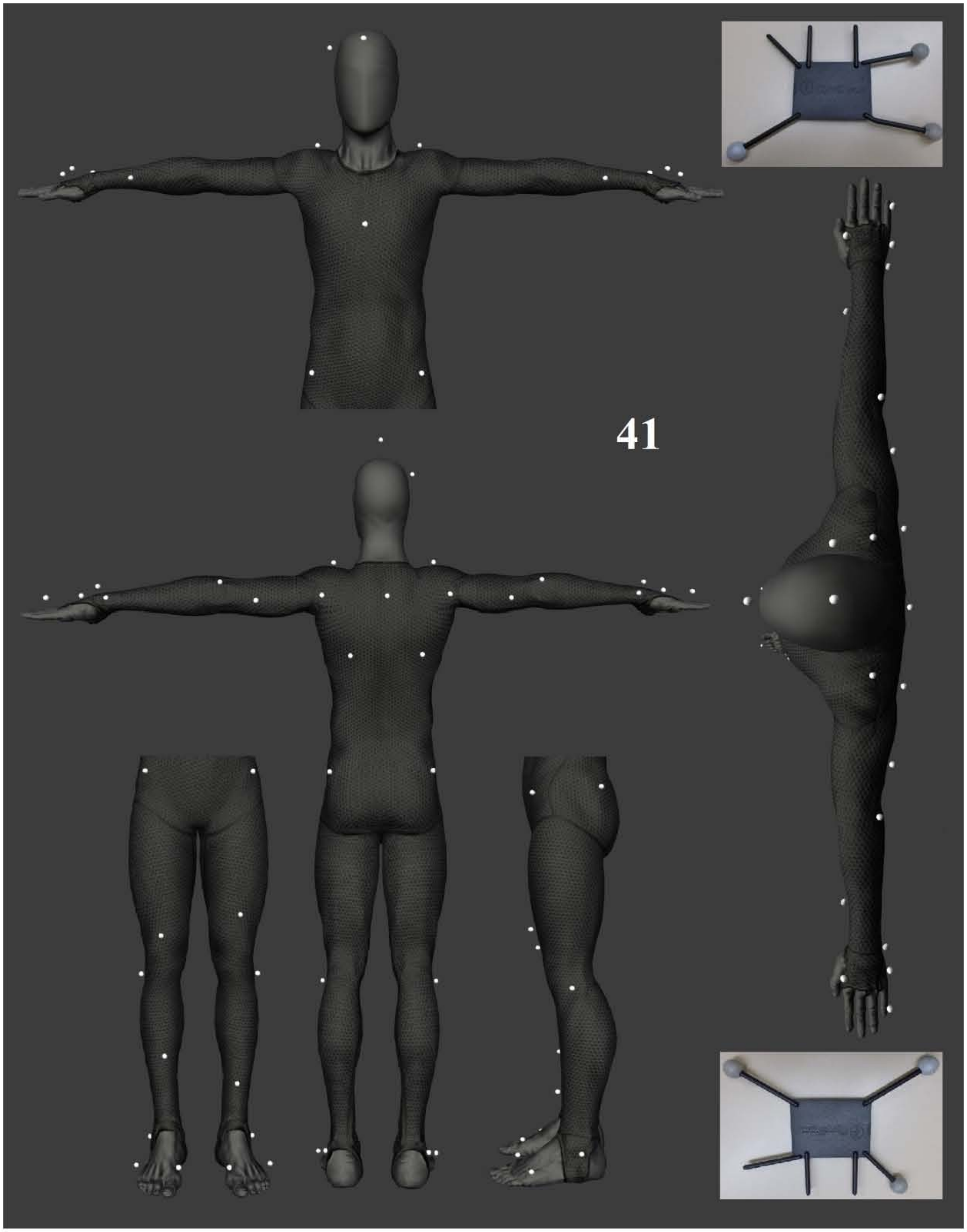


Figure A.3. Marker Setup Illustration for a 41 Marker Motion Capture Model

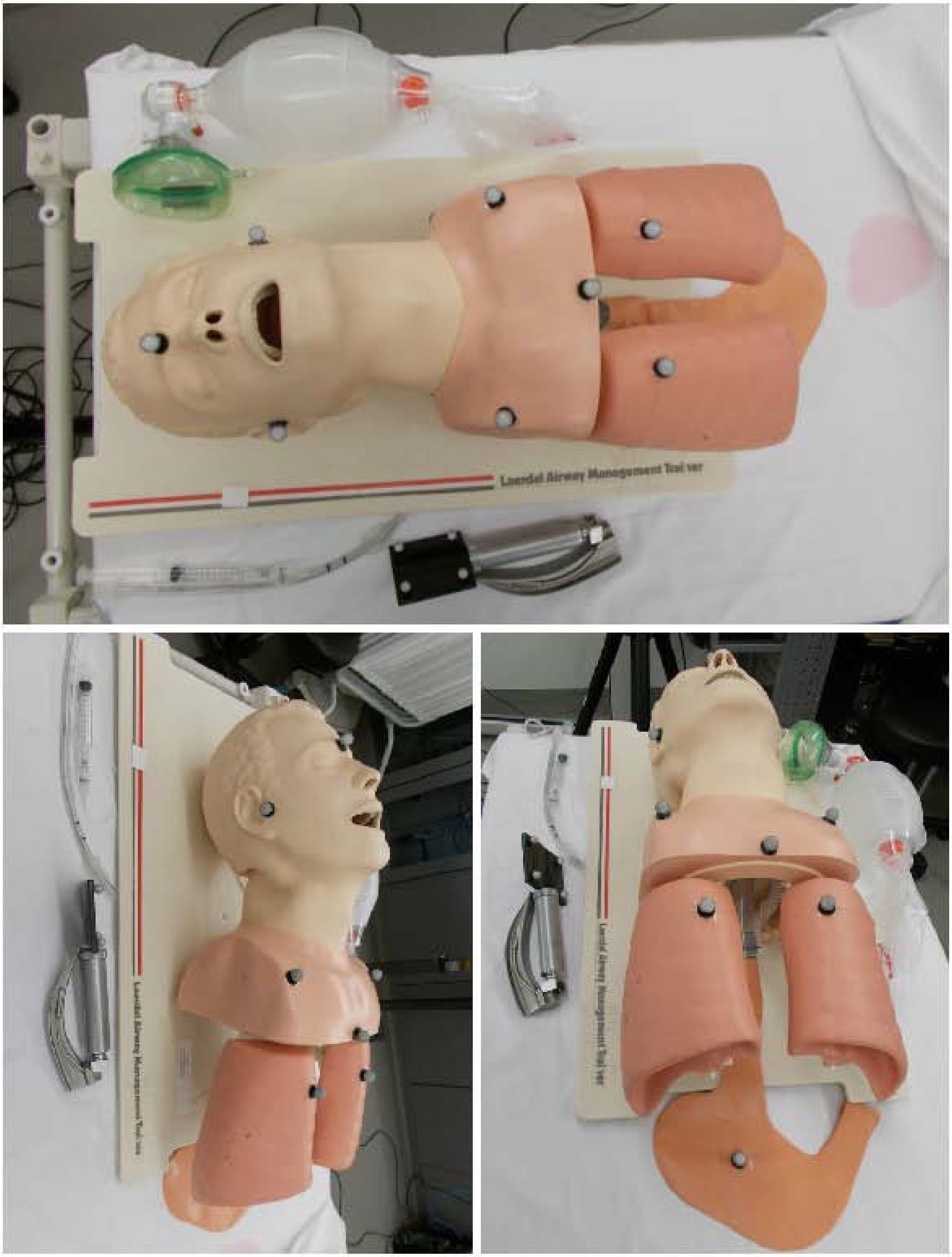


Figure A.4. Laerdal® Airway Management Trainer (With Added Markers) and General Layout of Endotracheal Intubation Instruments

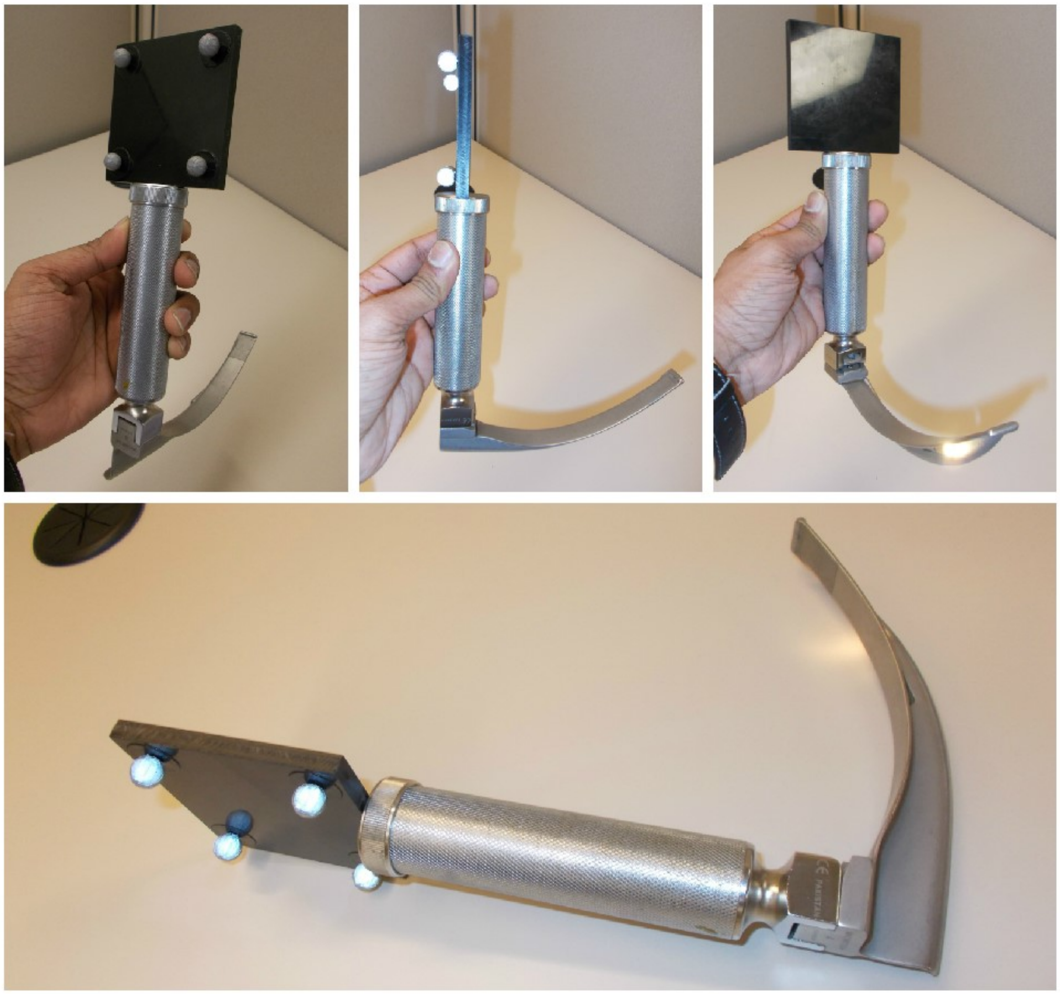


Figure A.5. Modified Laryngoscope with Reflective Markers

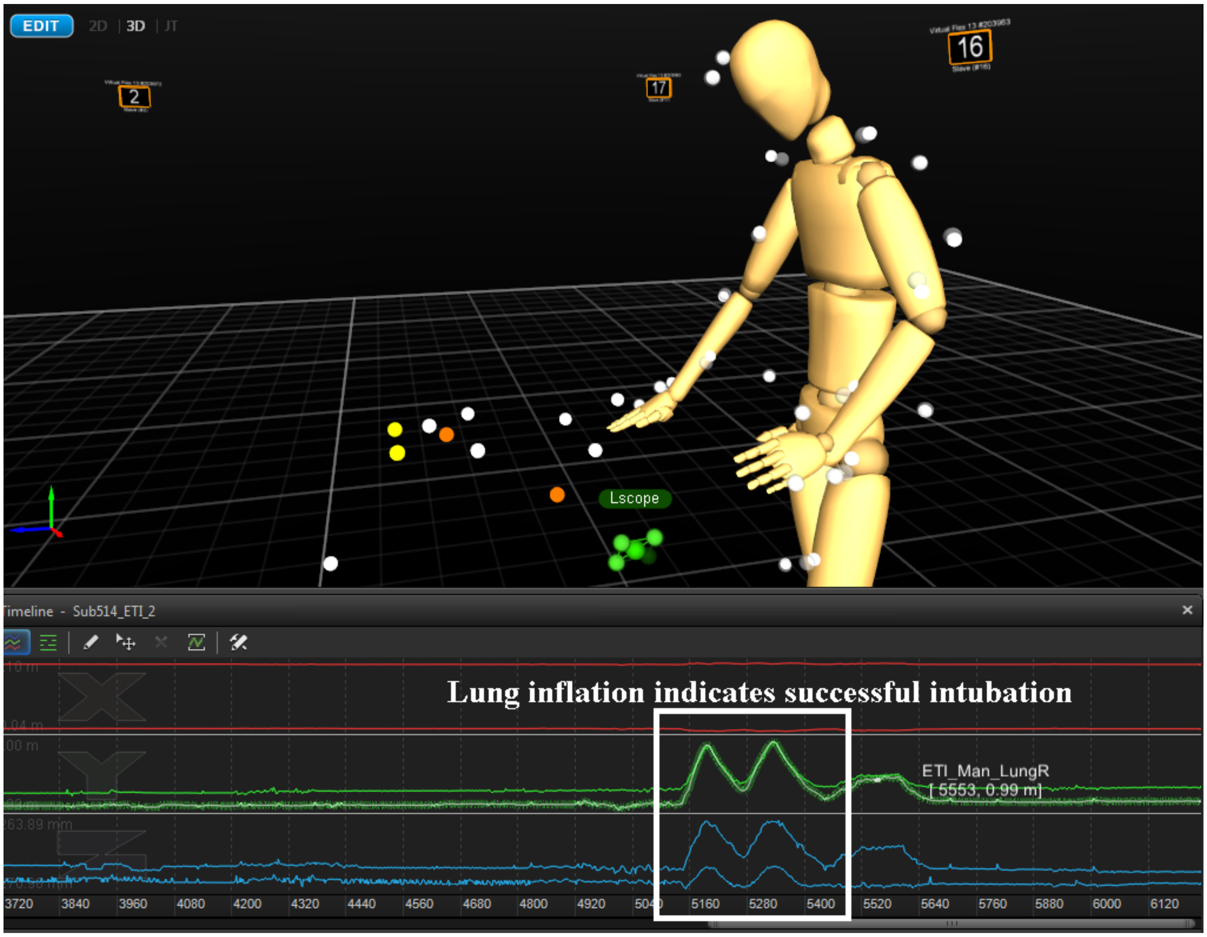


Figure A.6. Screenshot of Intubation Success Indicator

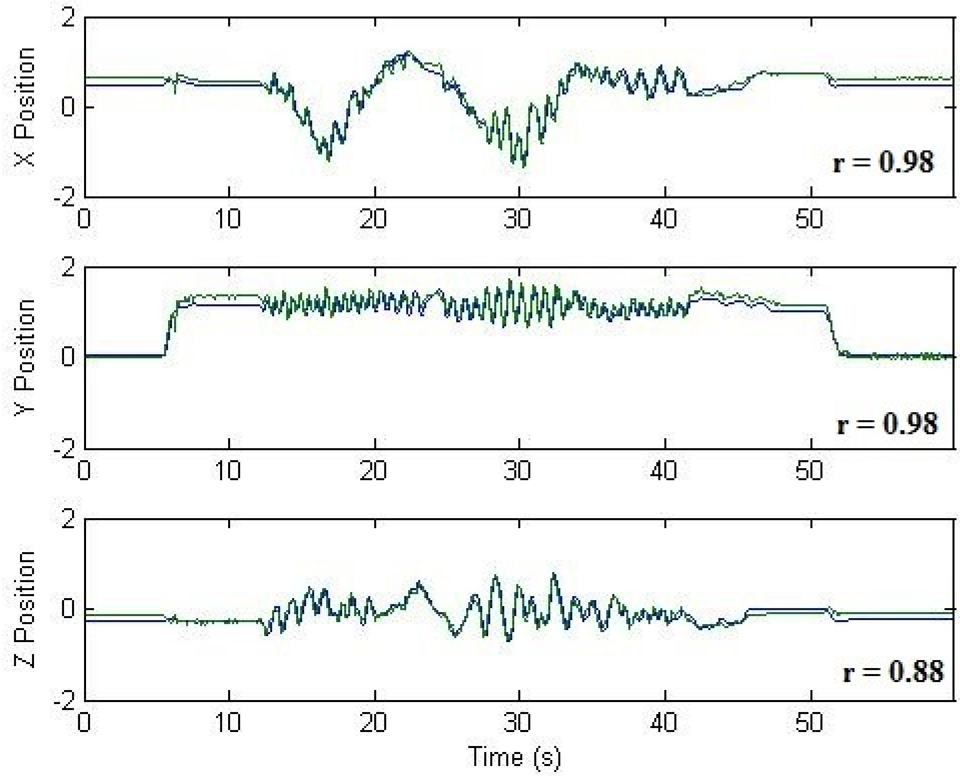


Figure A.7. Correlation plots between placed blade tip marker and virtual blade tip marker

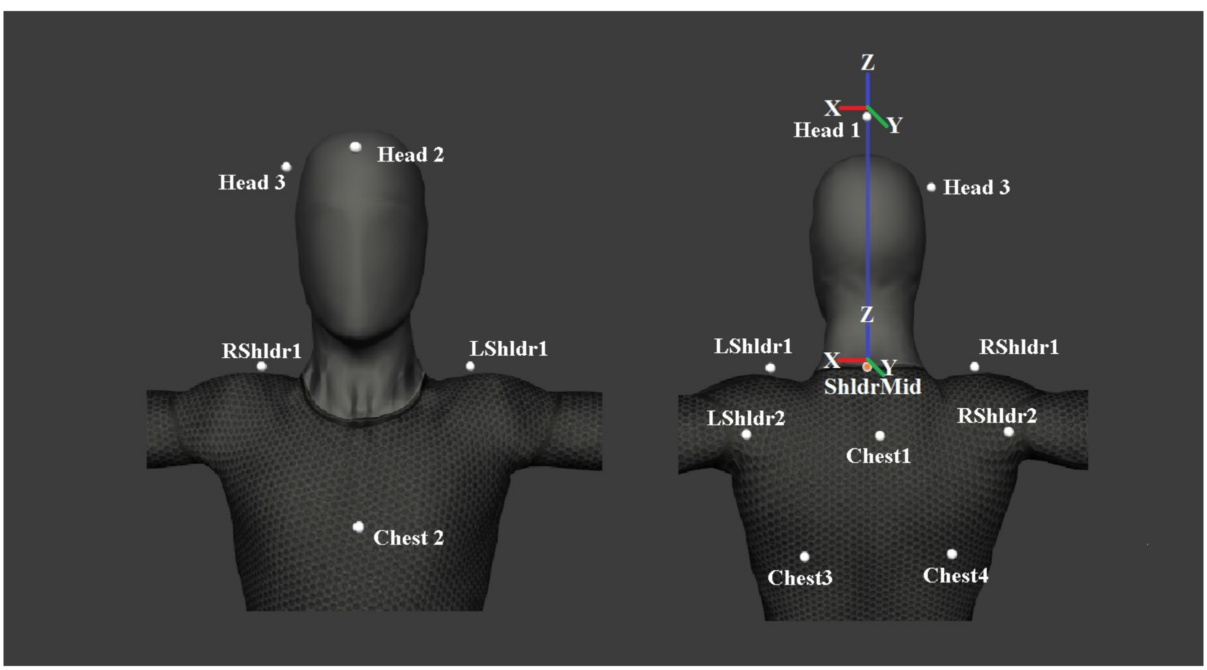


Figure A.8. Head and torso markers and Local Coordinate Systems

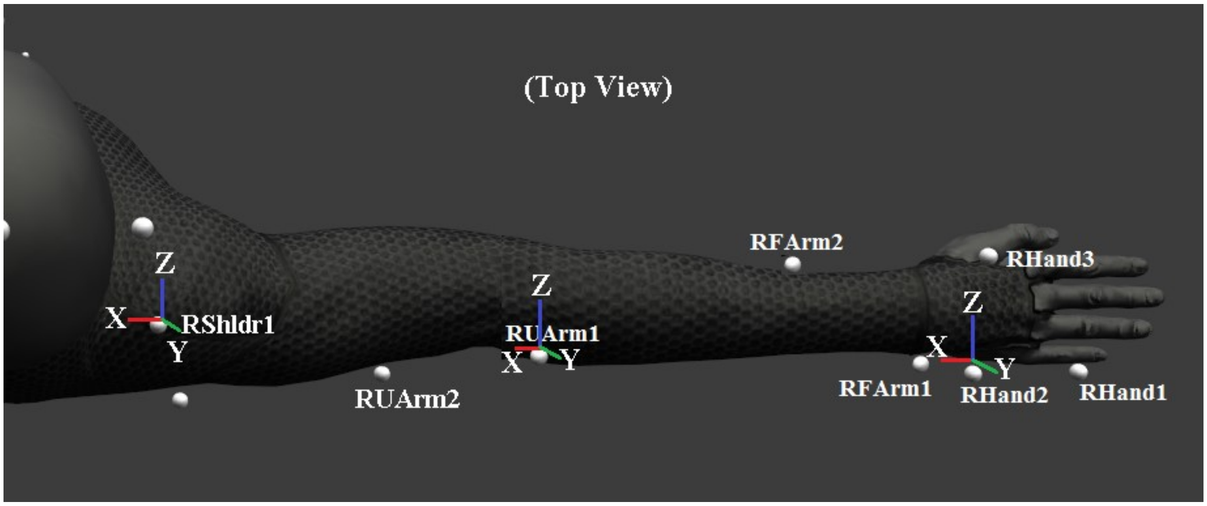


Figure A.9. Wrist, Elbow and Shoulder markers and Local Coordinate Systems

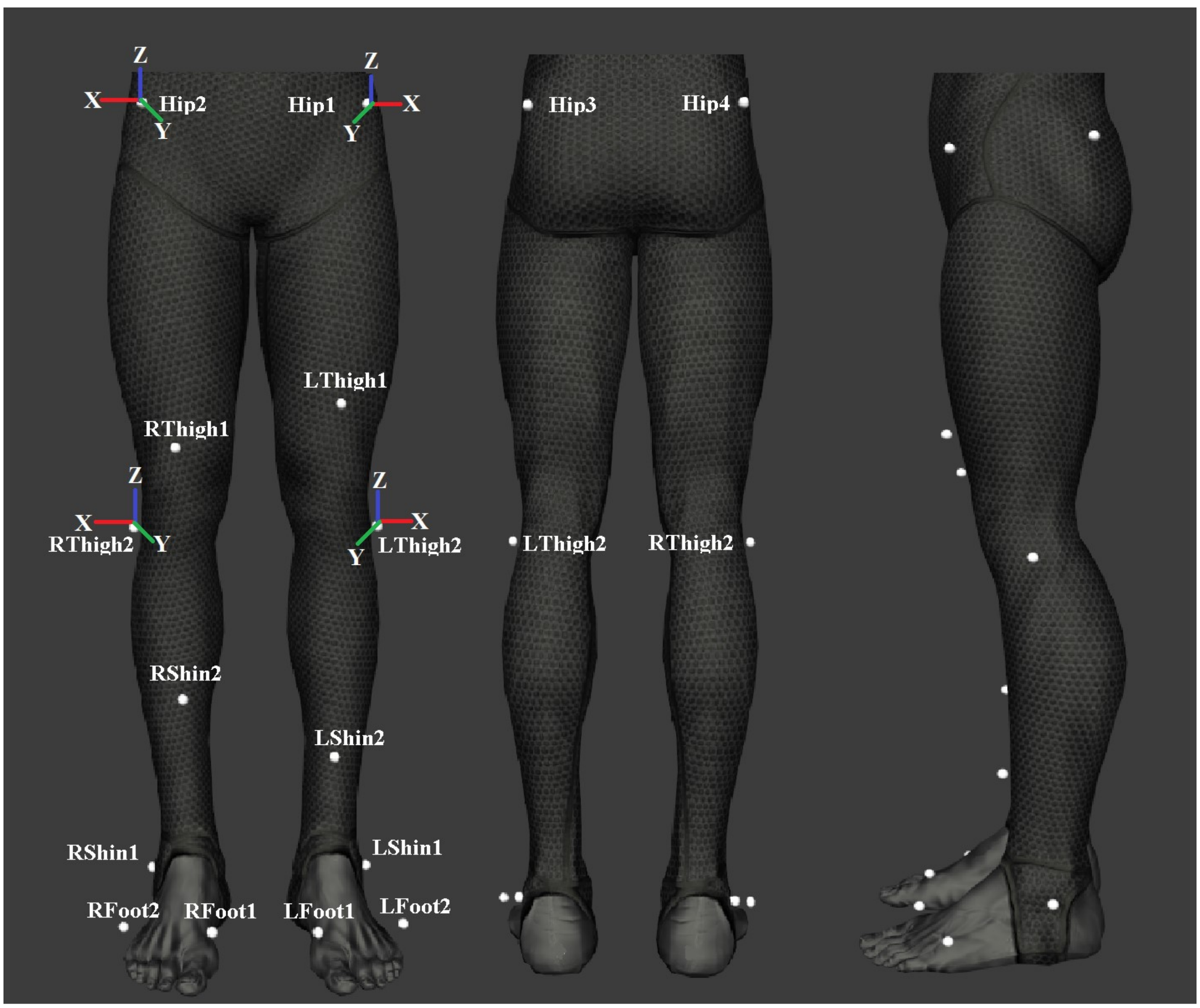


Figure A.10. Knee markers and Local Coordinate Systems

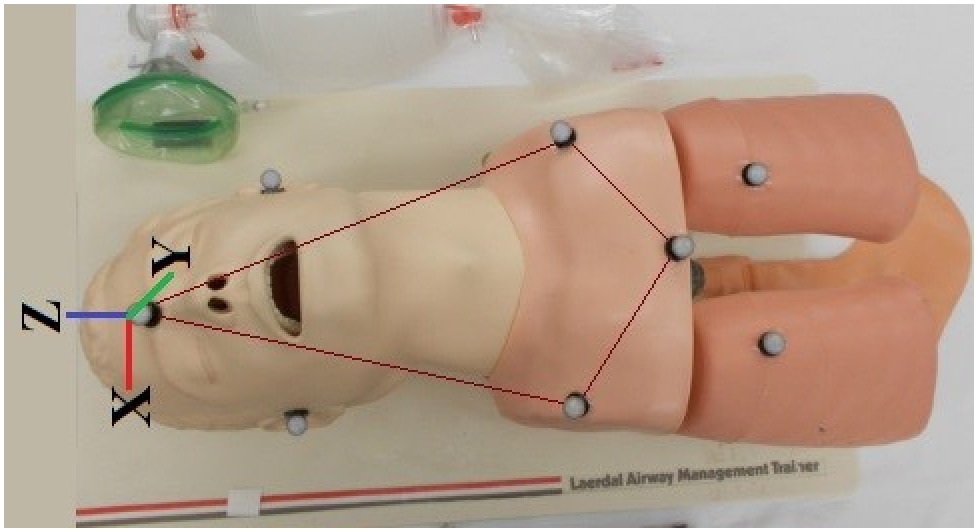
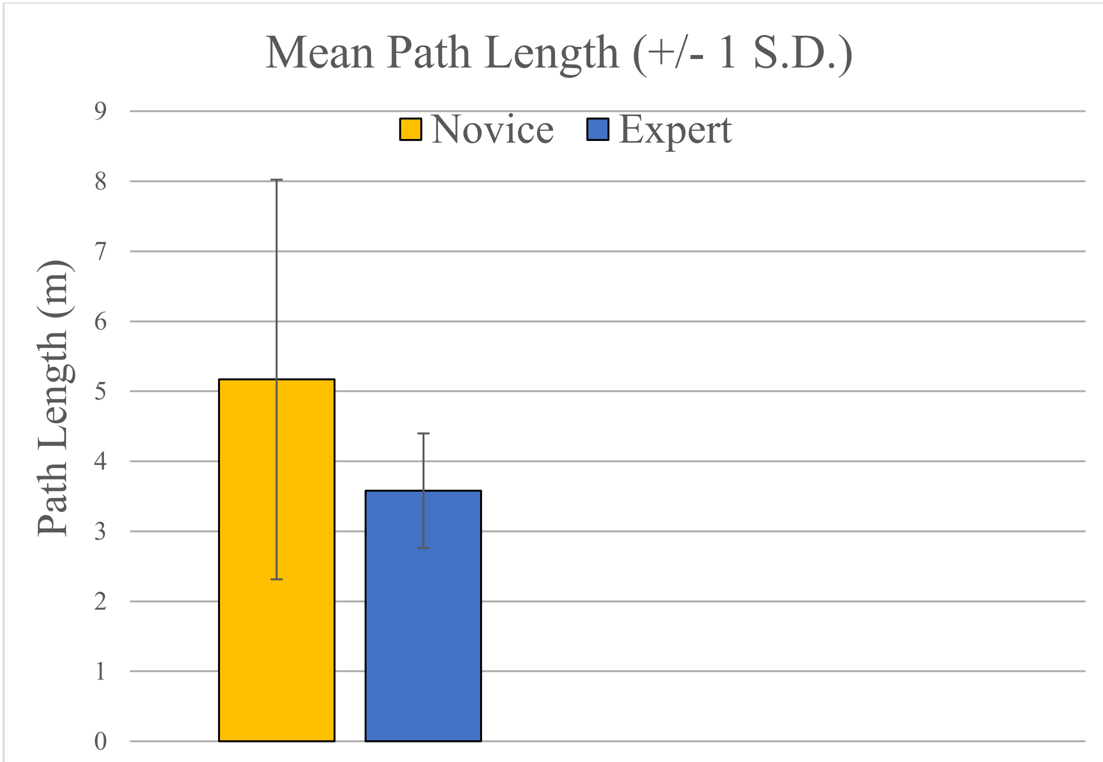
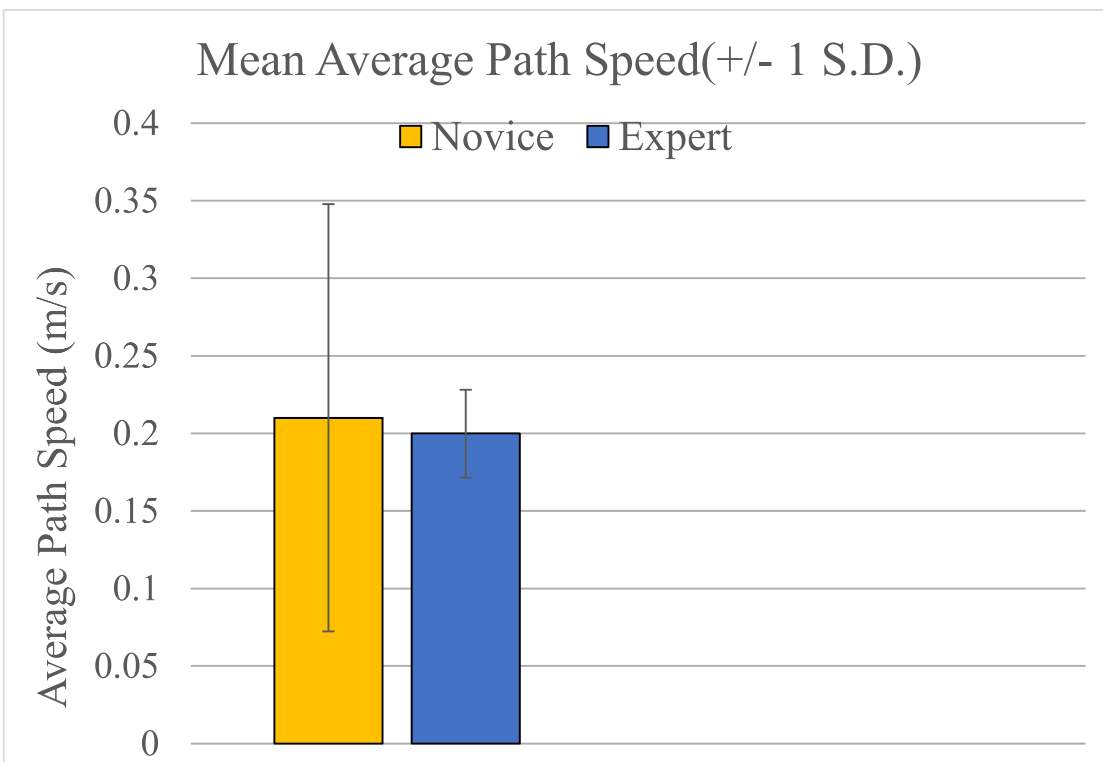
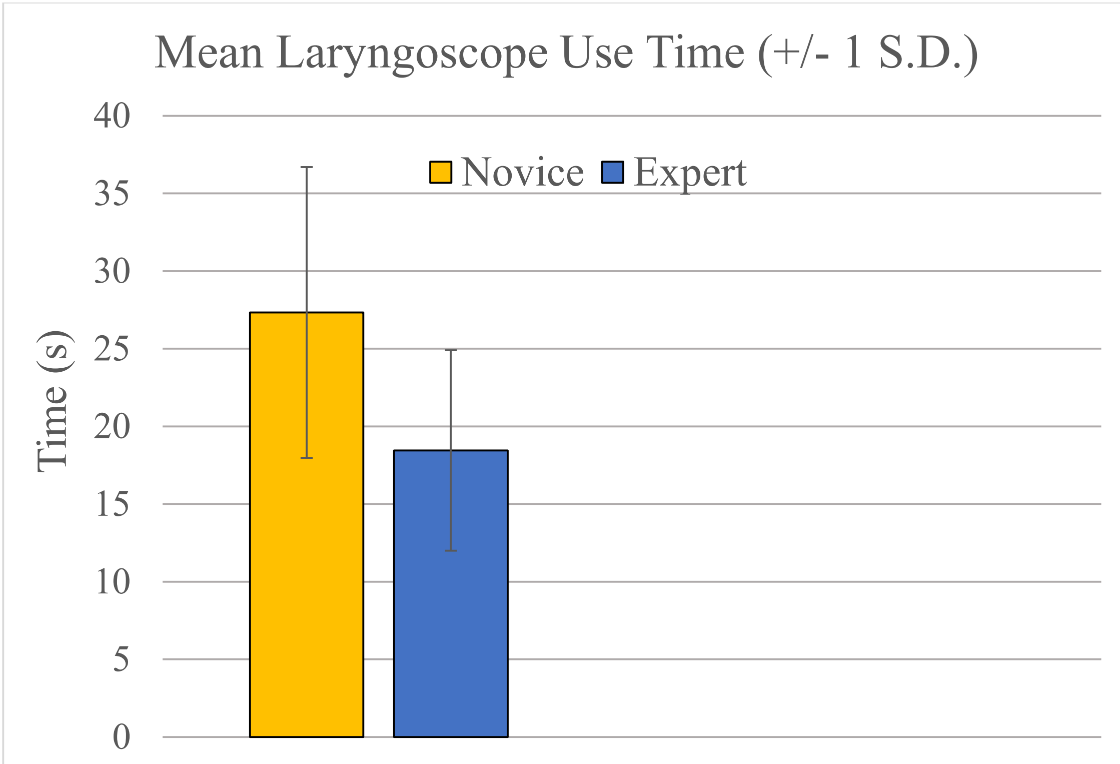


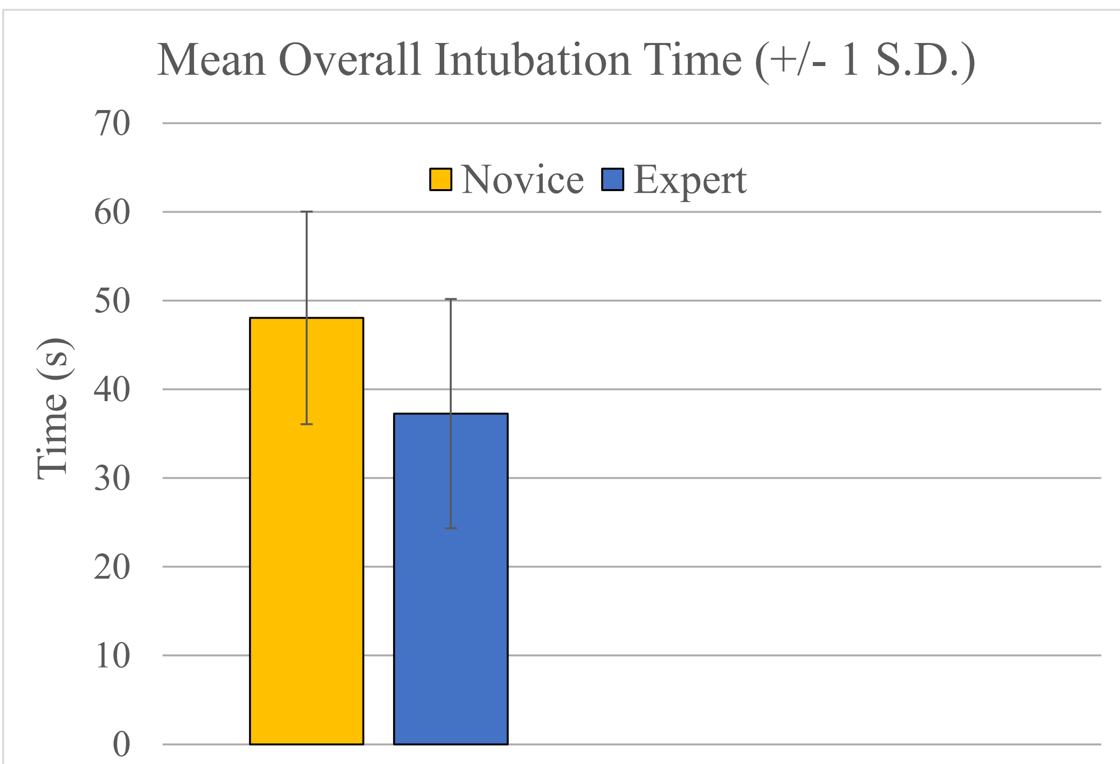
Figure A.11. Airway mannequin markers and Local Coordinate Systems

Figure A.12. Bar Graphs for Results: Calculated Variables among Novice and Expert study populations

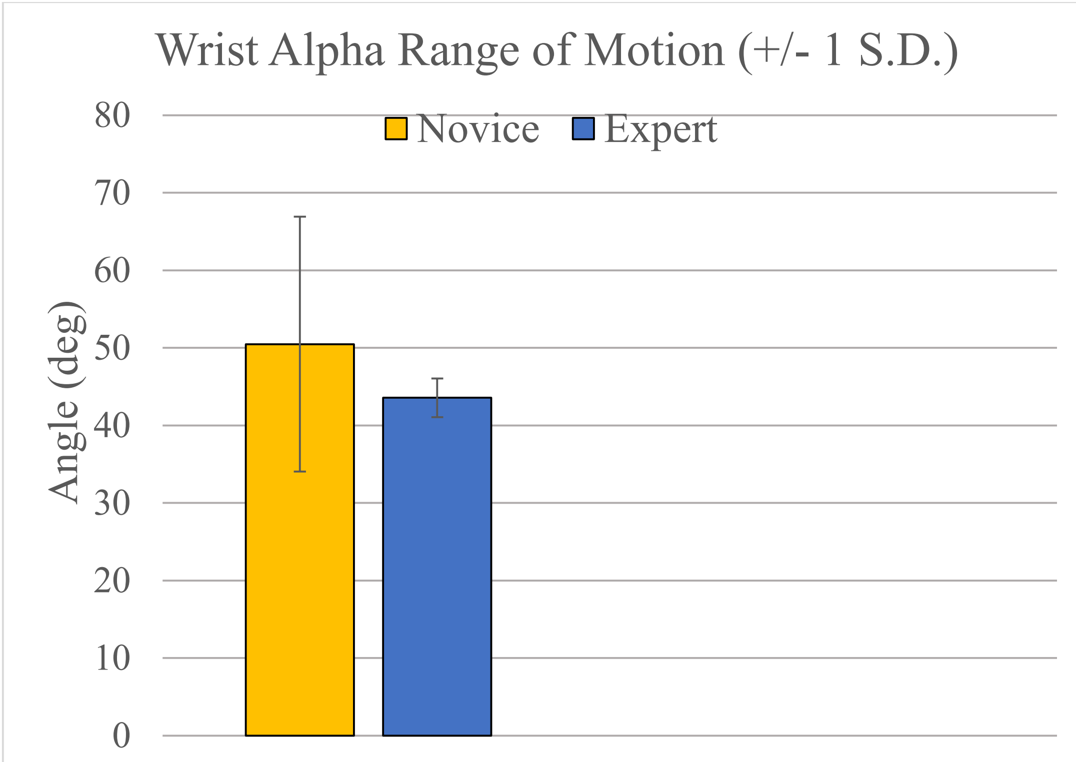


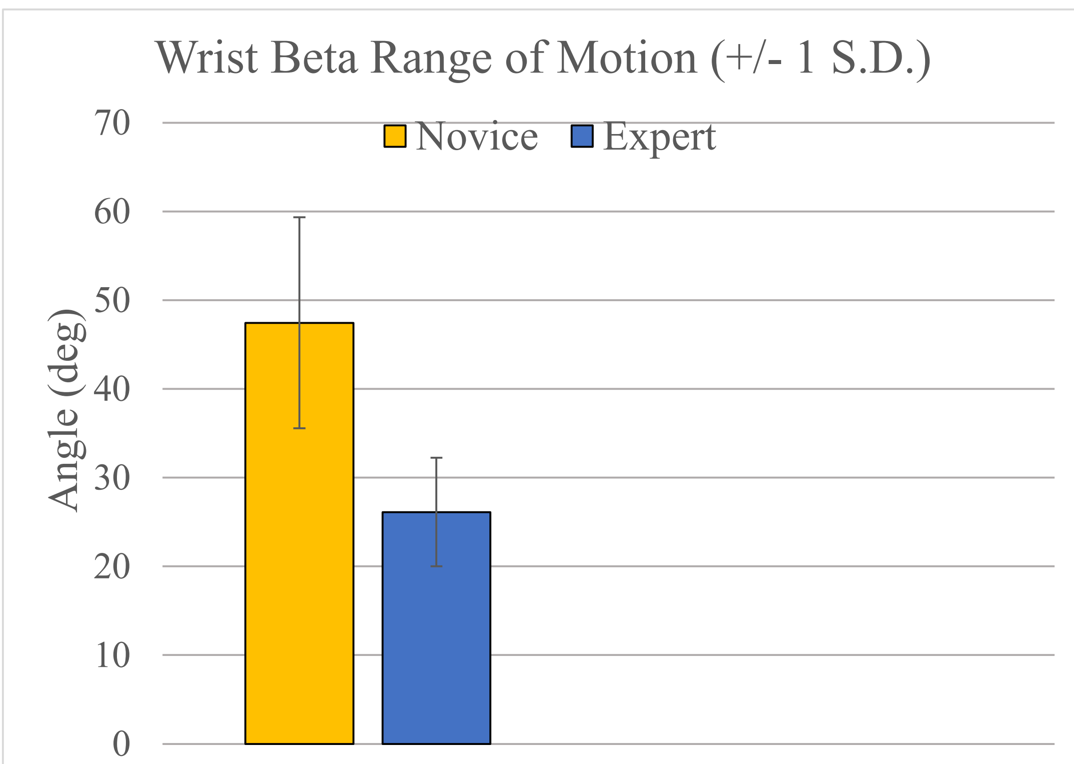


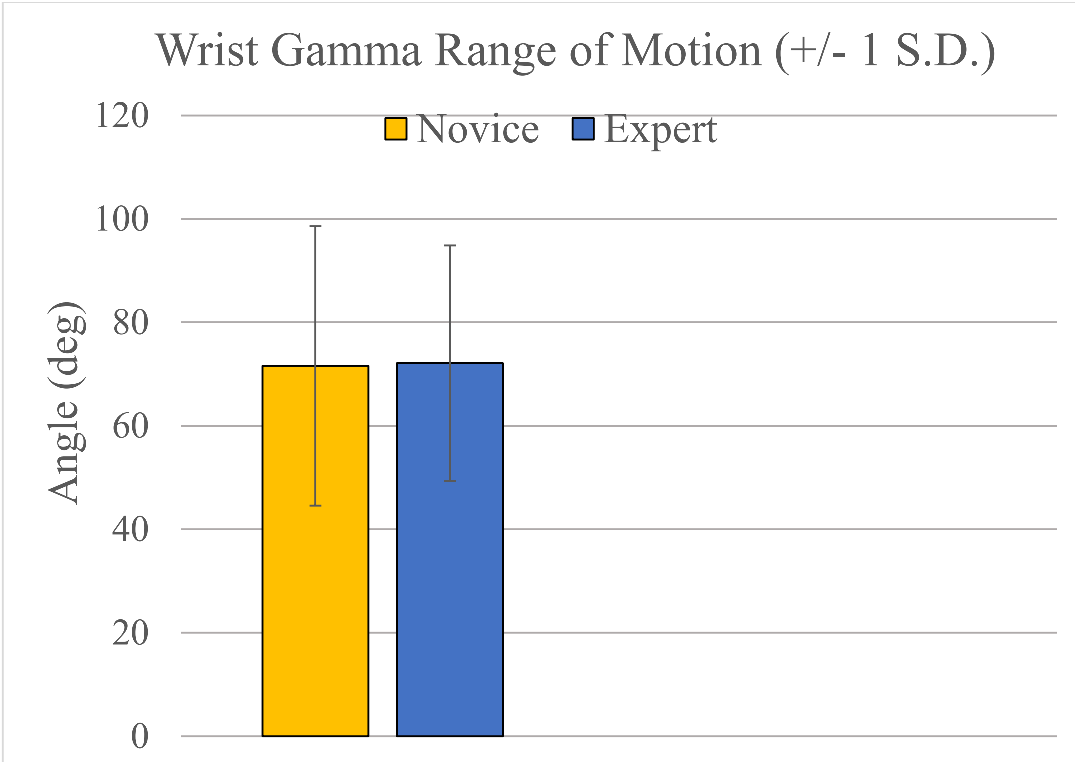

Mean Laryngoscope Use Time (+/- 1 S.D.)
Time (s)
40
35
30
25
20
15
10
5
0
Novice
Expert

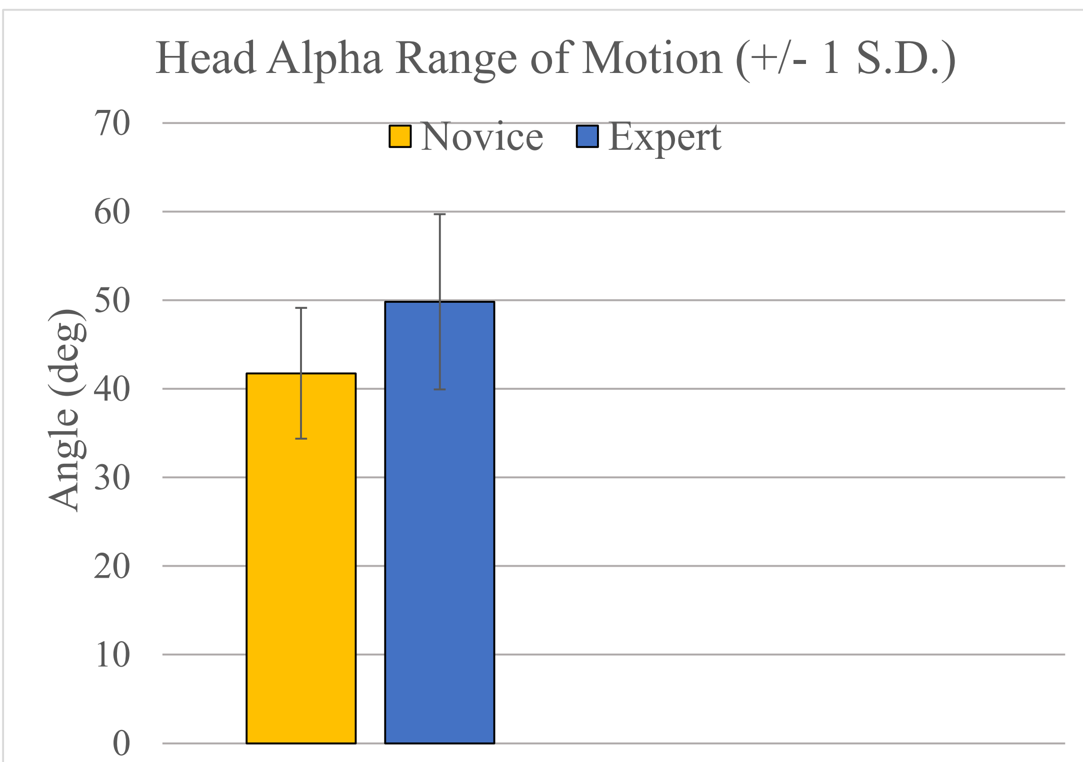

Mean Overall Intubation Time (+/- 1 S.D.)
Time (s)
70
60
50
40
30
20
10
0
Novice
Expert

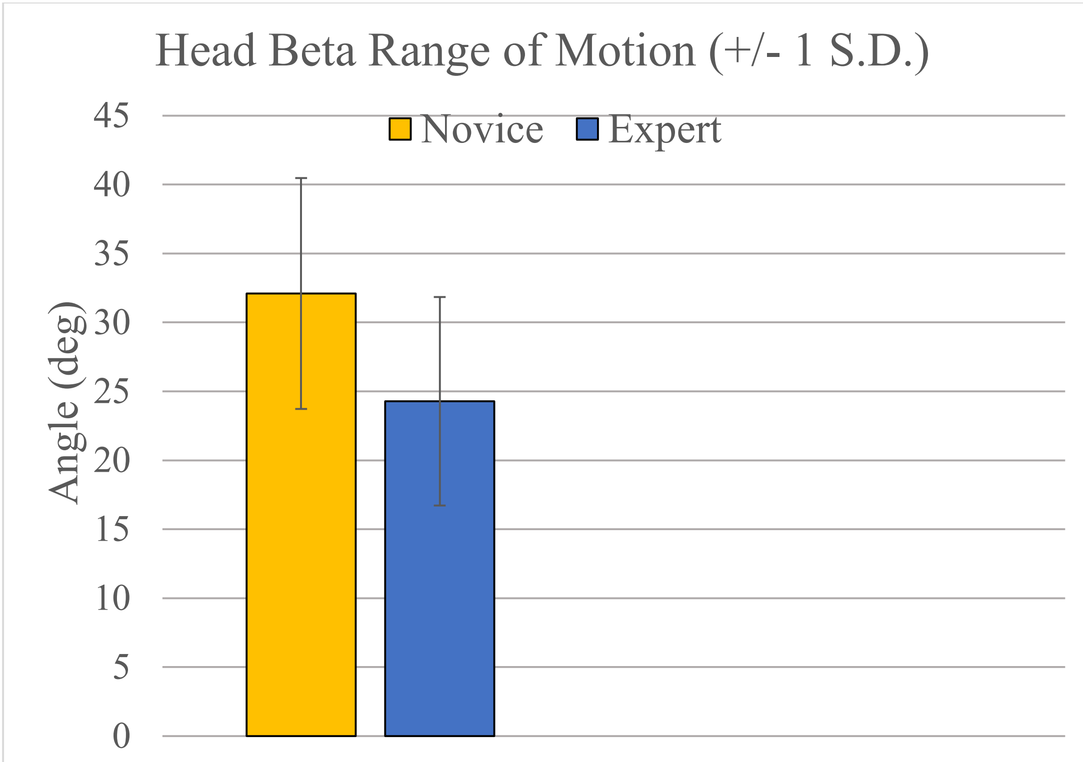
Alpha – Flexion/Extension, Beta- Abduction/Adduction, Gamma – Pronation/Supination

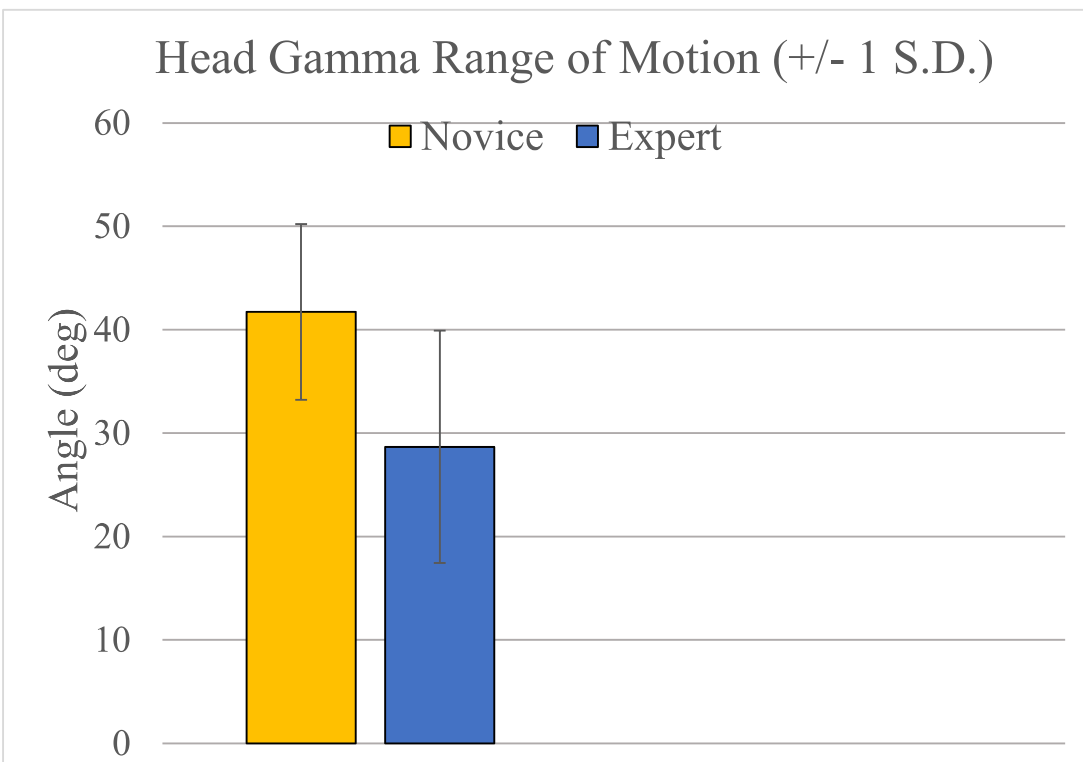


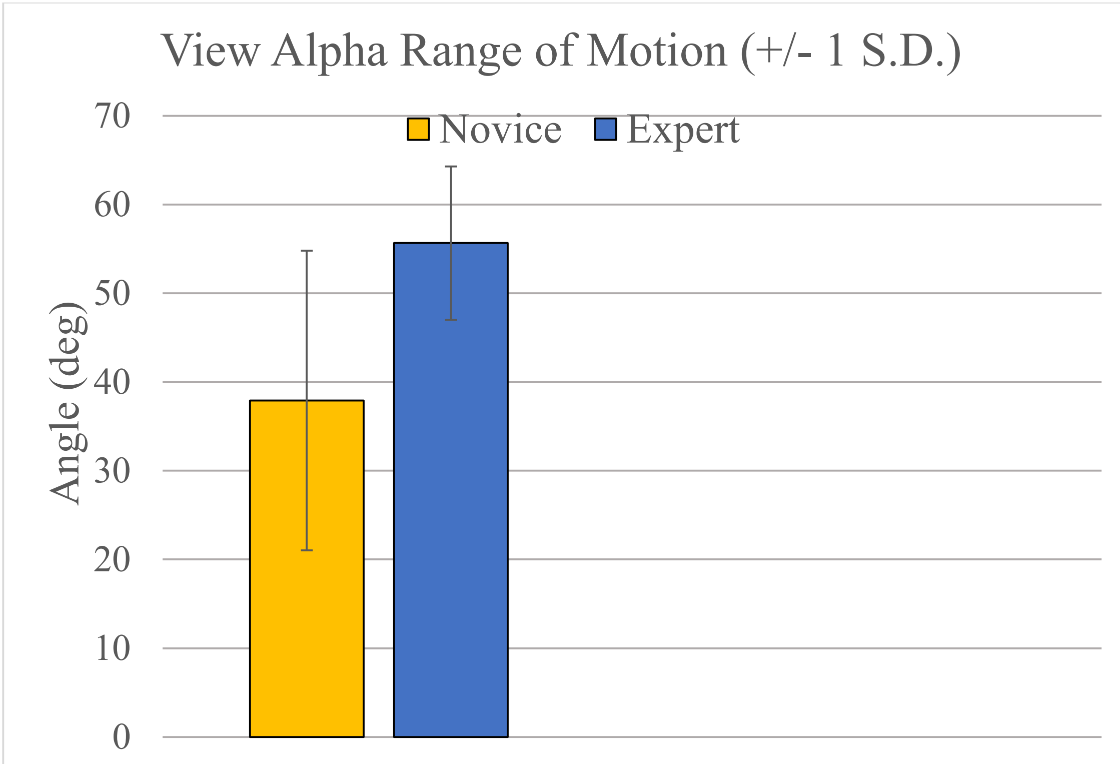


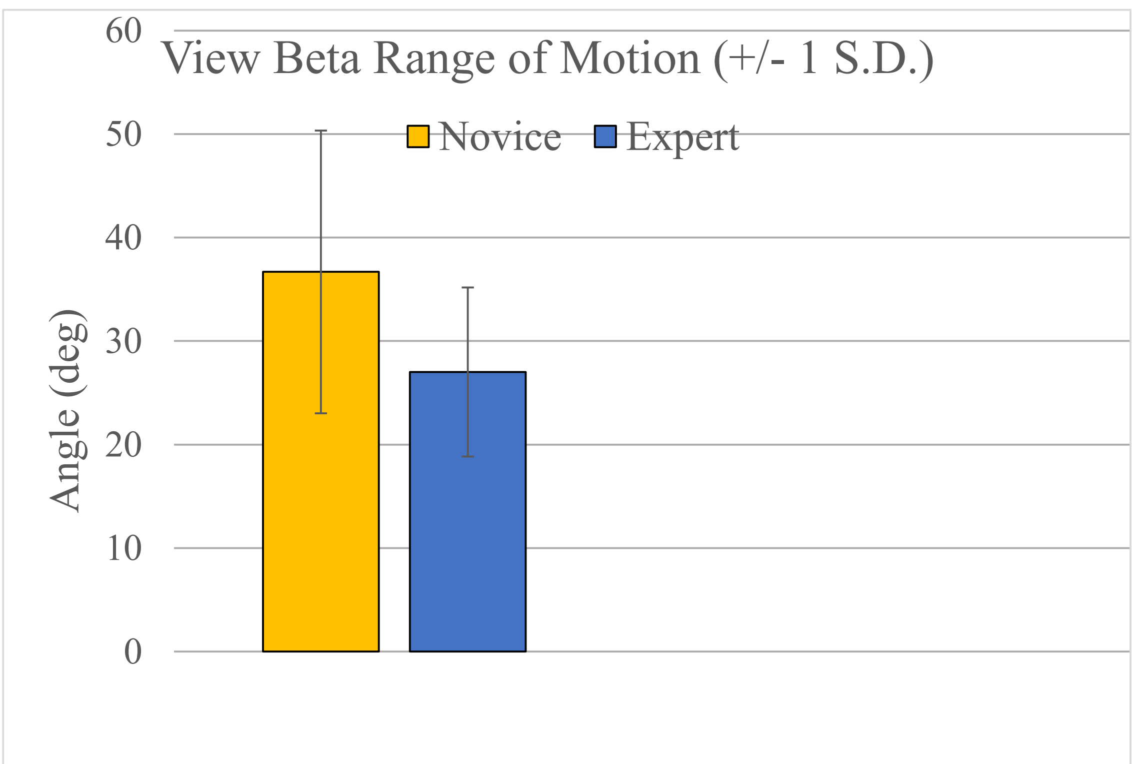

Wrist Gamma Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
120
100
80
60
40
20
0

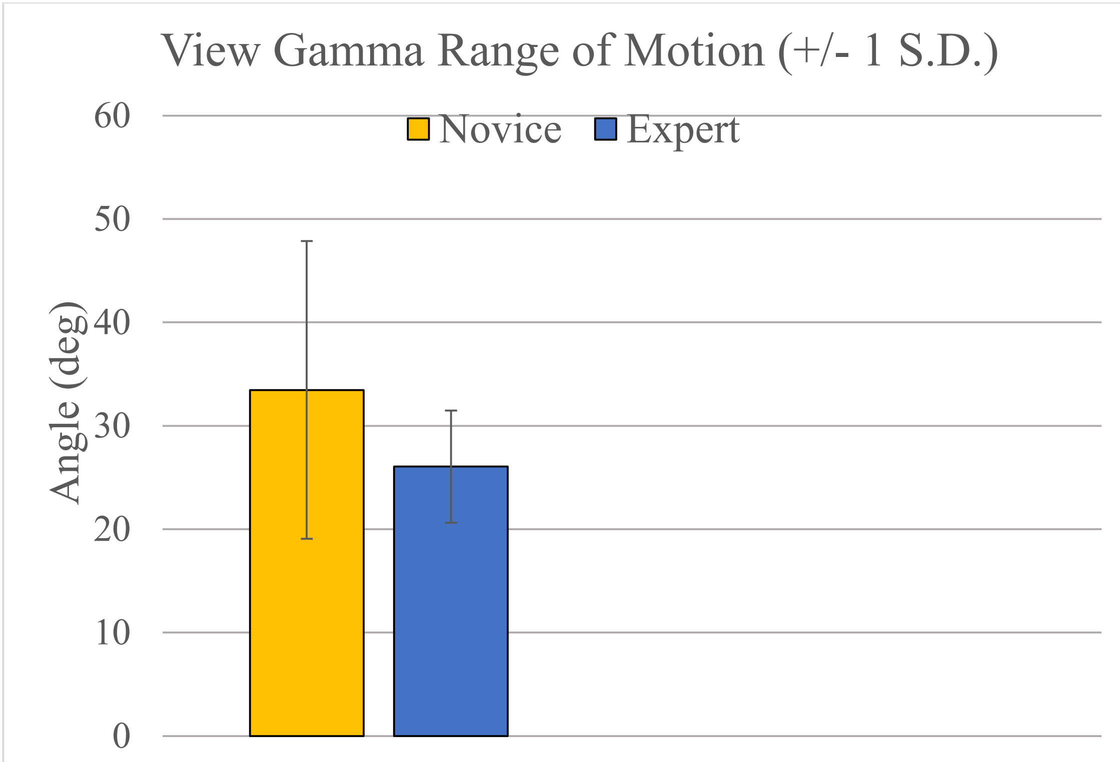

Head Alpha Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
70
60
50
40
30
20
10
0

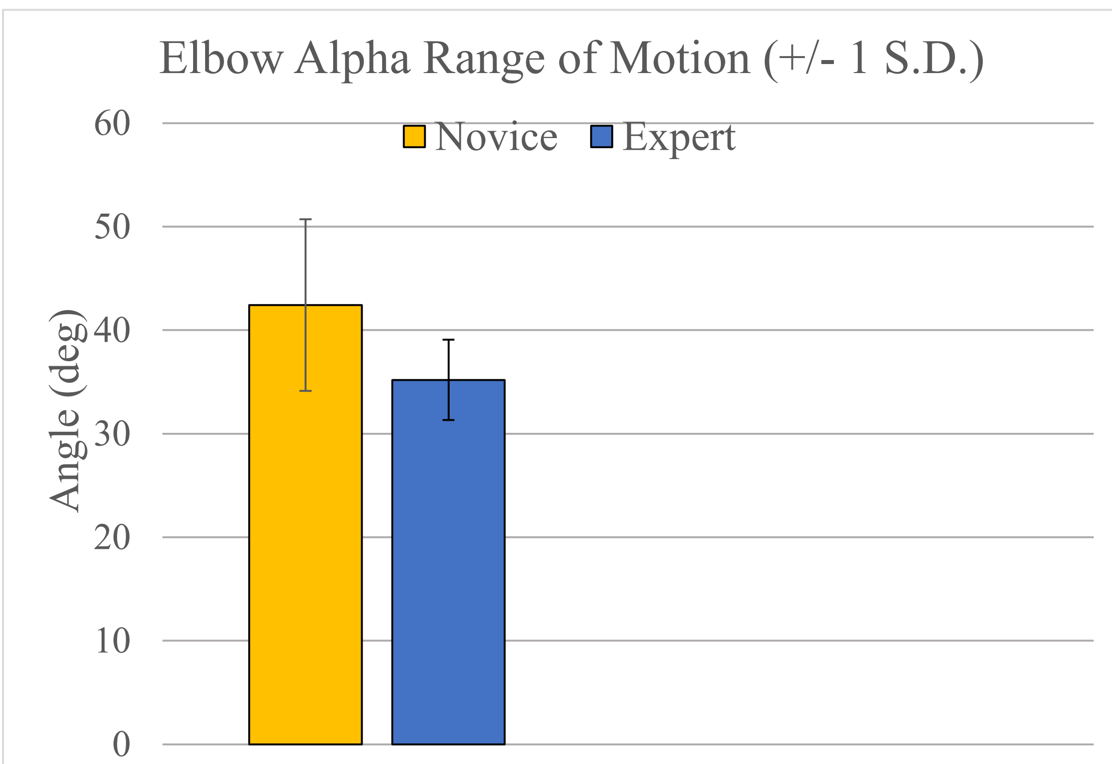

Head Beta Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
0
5
10
15
20
25
30
35
40
45

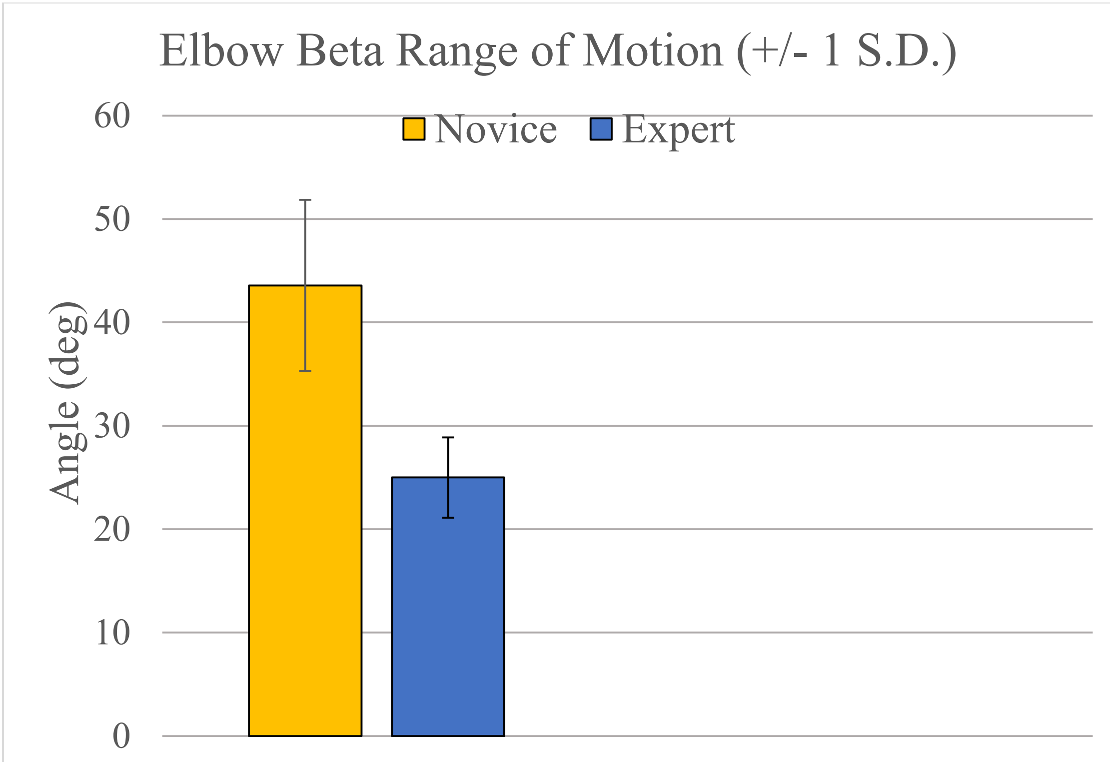

Head Gamma Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
0
10
20
30
40
50
60

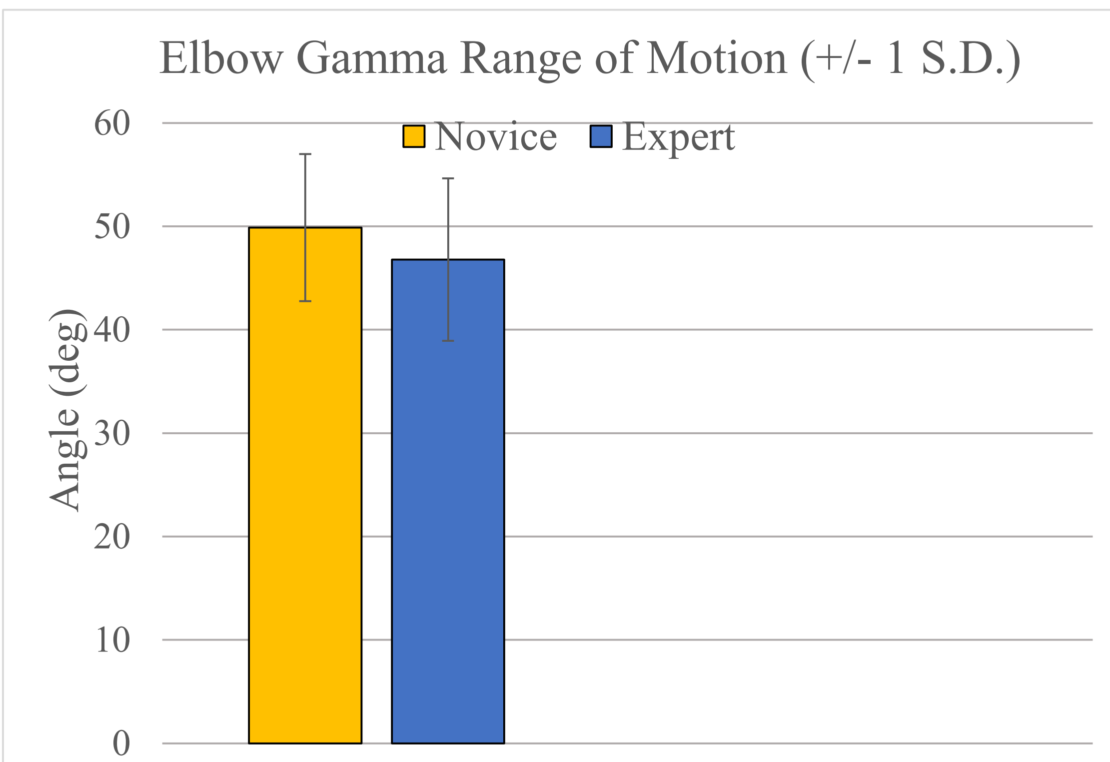

View Alpha Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
70
60
50
40
30
20
10
0

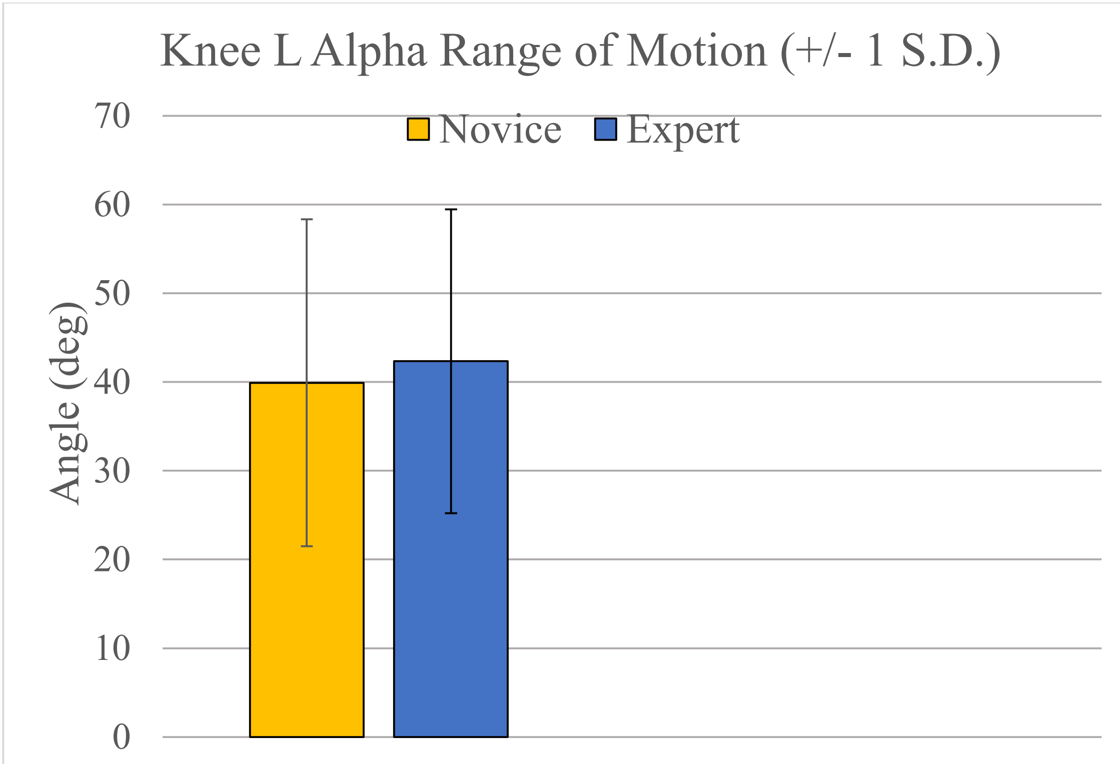

View Beta Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
60
50
40
30
20
10
0

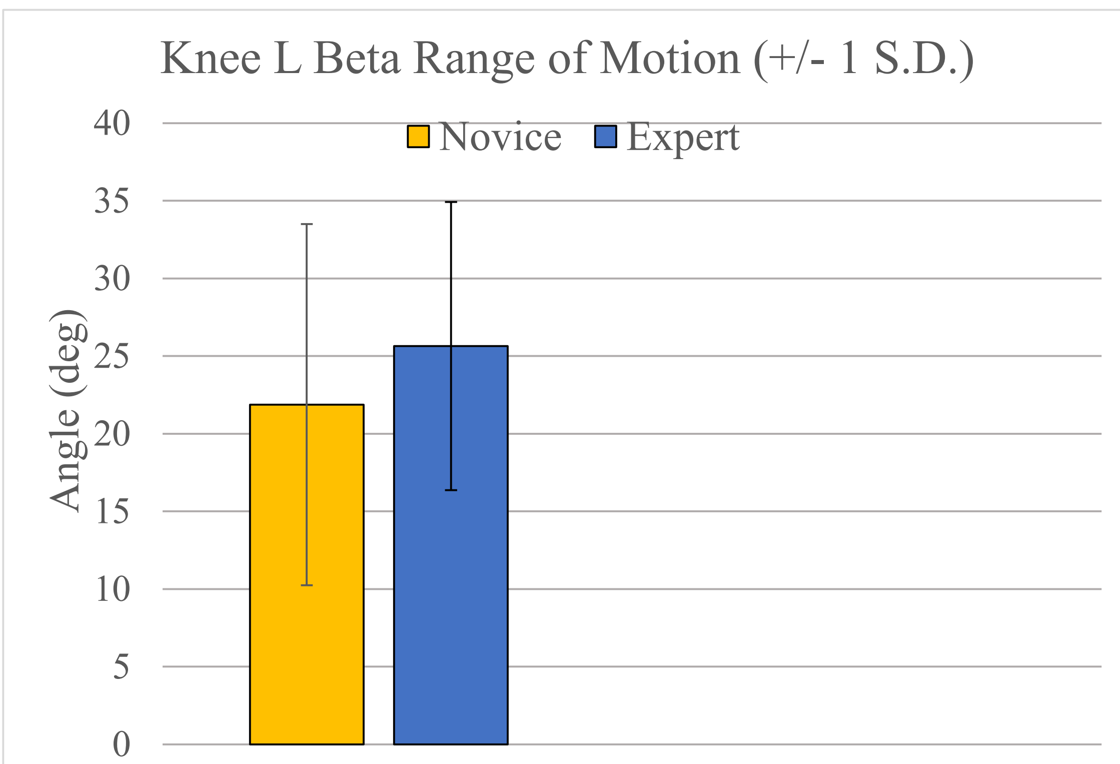

View Gamma Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
60
50
40
30
20
10
0

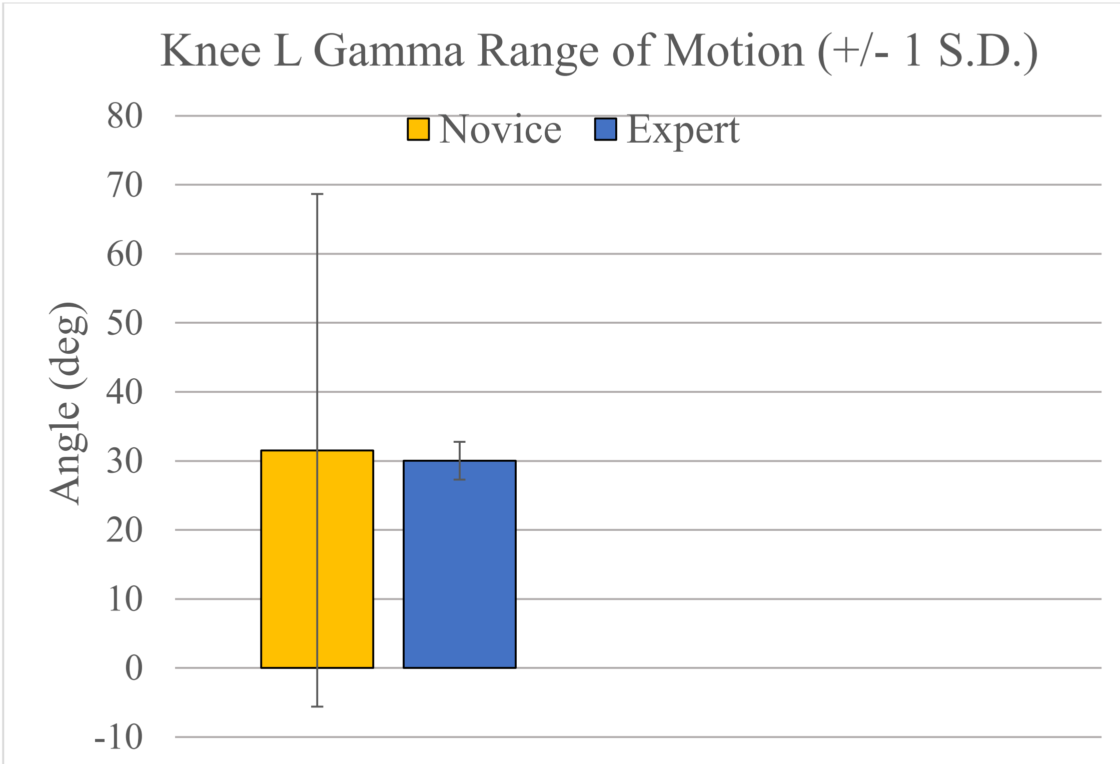

Elbow Alpha Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
60
50
40
30
20
10
0

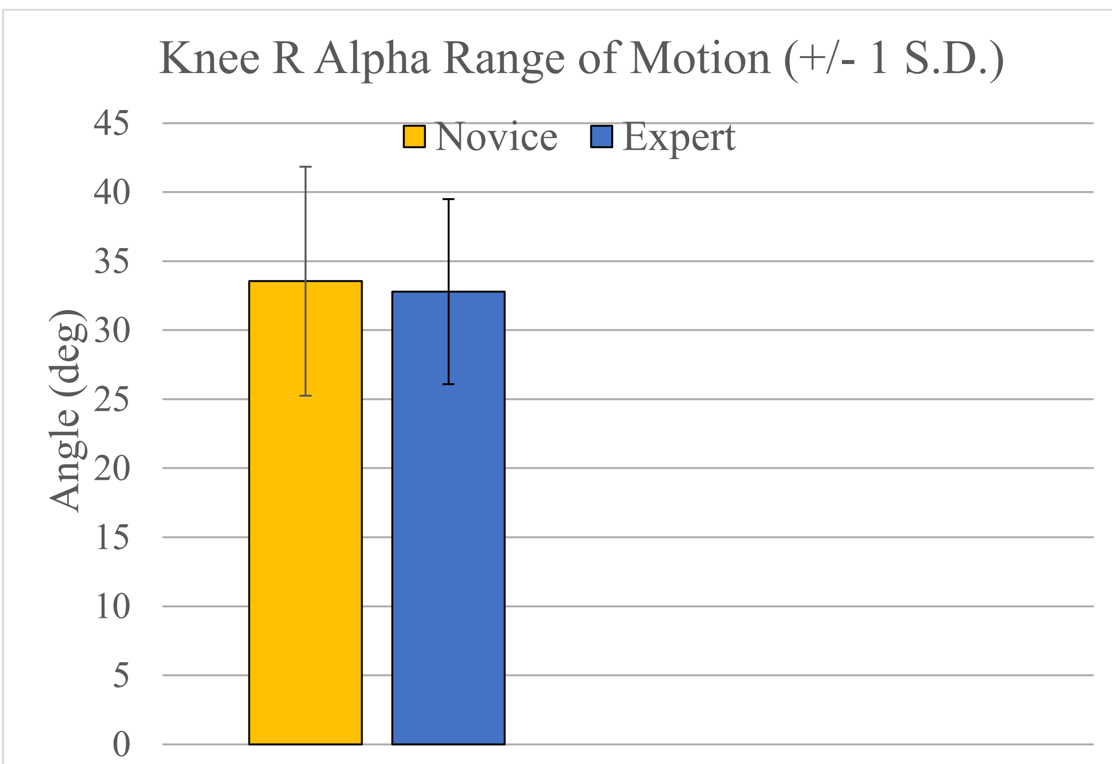

Elbow Beta Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
60
50
40
30
20
10
0

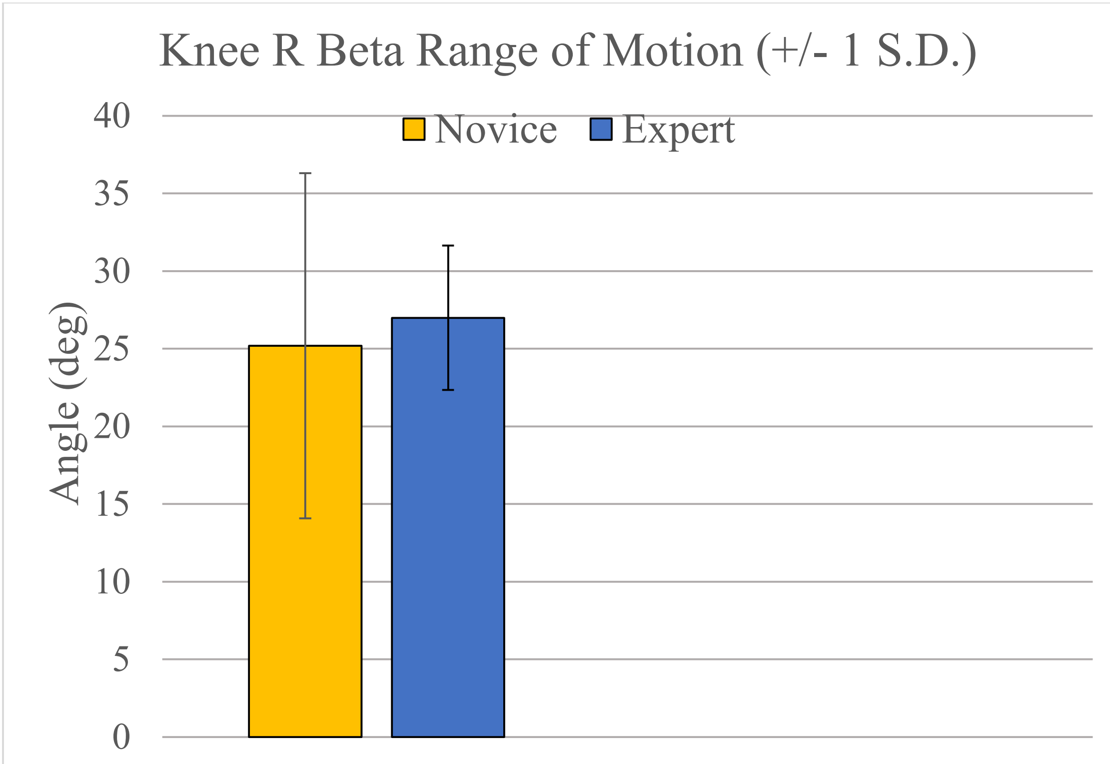

Elbow Gamma Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
60
50
40
30
20
10
0


Knee L Alpha Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
70
60
50
40
30
20
10
0


Knee L Beta Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
40
35
30
25
20
15
10
5
0


Knee L Gamma Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
80
70
60
50
40
30
20
10
0
-10


Knee R Alpha Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
45
40
35
30
25
20
15
10
5
0


Knee R Beta Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
40
35
30
25
20
15
10
5
0

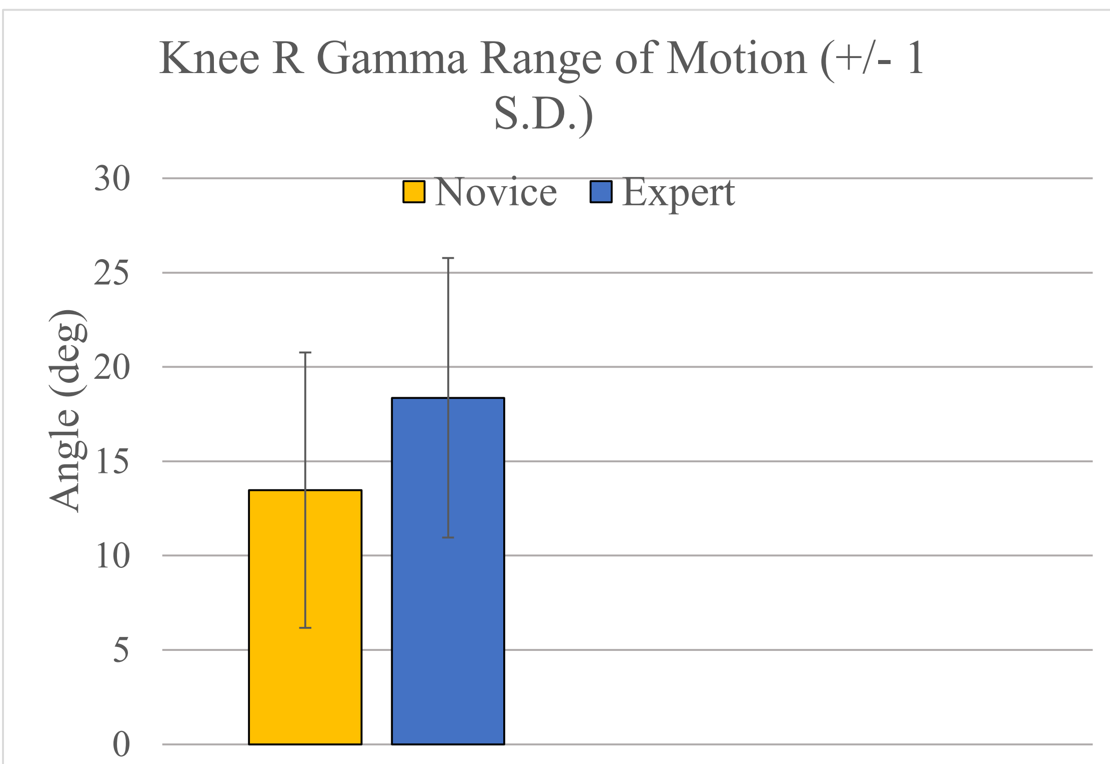

Knee R Gamma Range of Motion (+/- 1 S.D.)
Novice
Expert
Angle (deg)
30
25
20
15
10
5
0

Figure A.13. Statistical Analysis Output from MINITAB

Inverse Cumulative Distribution Function

```
F distribution with 1 DF in numerator and 10 DF in denominator

P( X <= x )        x
       0.95  4.96460


F distribution with 1 DF in numerator and 9 DF in denominator (For Wrist angles)

P( X <= x )        x
       0.95  5.11736
```

One way ANOVA for multiple variables

ANOVA: Multiple variables, versus Group

```
Factor  Type   Levels  Values
Group   fixed       2  1, 2


Analysis of Variance for PL

Source  DF      SS     MS     F      P
Group    1   6.407  6.407  0.98  0.349
Error    9  59.079  6.564
Total   10  65.486


S = 2.56209   R-Sq = 9.78%   R-Sq(adj) = 0.00%


Analysis of Variance for PV

Source  DF       SS       MS     F      P
Group    1  0.00029  0.00029  0.02  0.892
Error    9  0.13527  0.01503
Total   10  0.13556


S = 0.122598   R-Sq = 0.21%   R-Sq(adj) = 0.00%


Analysis of Variance for Laryngoscope Use time

Source  DF      SS      MS     F      P
Group    1  215.91  215.91  2.65  0.138
Error    9  732.82   81.42
Total   10  948.72


S = 9.02353   R-Sq = 22.76%   R-Sq(adj) = 14.18%


Analysis of Variance for Intubation Time
```

Source	DF	SS	MS	F	P
Group	1	367.8	367.8	2.33	0.161
Error	9	1420.9	157.9		
Total	10	1788.7			

S = 12.5650   R-Sq = 20.56%   R-Sq(adj) = 11.74%

Analysis of Variance for Wrist A ROM

Source	DF	SS	MS	F	P
Group	1	121.7	121.7	0.67	0.435
Error	9	1641.0	182.3		
Total	10	1762.7			

S = 13.5031   R-Sq = 6.91%   R-Sq(adj) = 0.00%

Analysis of Variance for Wrist B ROM

Source	DF	SS	MS	F	P
Group	1	1157.1	1157.1	10.84	0.009
Error	9	960.9	106.8		
Total	10	2118.0			

S = 10.3327   R-Sq = 54.63%   R-Sq(adj) = 49.59%

Analysis of Variance for Wrist G ROM

Source	DF	SS	MS	F	P
Group	1	0.7	0.7	0.00	0.975
Error	9	5929.4	658.8		
Total	10	5930.1			

S = 25.6676   R-Sq = 0.01%   R-Sq(adj) = 0.00%

Analysis of Variance for Head A ROM

Source	DF	SS	MS	F	P
Group	1	178.1	178.1	1.63	0.234
Error	9	985.5	109.5		
Total	10	1163.6			

S = 10.4641   R-Sq = 15.31%   R-Sq(adj) = 5.90%

Analysis of Variance for Head B ROM

Source	DF	SS	MS	F	P
Group	1	100.46	100.46	1.70	0.224
Error	9	530.80	58.98		
Total	10	631.26			

S = 7.67973   R-Sq = 15.91%   R-Sq(adj) = 6.57%

Analysis of Variance for Head G ROM

Source	DF	SS	MS	F	P
Group	1	449.10	449.10	4.59	0.061
Error	9	880.93	97.88		
Total	10	1330.04			

S = 9.89350   R-Sq = 33.77%   R-Sq(adj) = 26.41%

Analysis of Variance for View A ROM

Source	DF	SS	MS	F	P
Group	1	840.1	840.1	3.78	0.081
Error	10	2223.6	222.4		
Total	11	3063.7			

S = 14.9119   R-Sq = 27.42%   R-Sq(adj) = 20.16%

Analysis of Variance for View B ROM

Source	DF	SS	MS	F	P
Group	1	249.3	249.3	1.66	0.227
Error	10	1505.4	150.5		
Total	11	1754.7			

S = 12.2694   R-Sq = 14.21%   R-Sq(adj) = 5.63%

Analysis of Variance for View G ROM

Source	DF	SS	MS	F	P
Group	1	146.4	146.4	0.95	0.353
Error	10	1540.5	154.0		
Total	11	1686.8			

S = 12.4116   R-Sq = 8.68%   R-Sq(adj) = 0.00%

Analysis of Variance for Elbow A ROM

Source	DF	SS	MS	F	P
Group	1	139.36	139.36	2.65	0.135
Error	10	525.71	52.57		
Total	11	665.07			

S = 7.25058   R-Sq = 20.95%   R-Sq(adj) = 13.05%

Analysis of Variance for Elbow B ROM

Source	DF	SS	MS	F	P
Group	1	919.66	919.66	17.01	0.002
Error	10	540.54	54.05		
Total	11	1460.20			

```
S = 7.35213   R-Sq = 62.98%   R-Sq(adj) = 59.28%


Analysis of Variance for Elbow G ROM

Source  DF      SS     MS     F      P
Group    1    25.4   25.4  0.12  0.733
Error   10  2065.6  206.6
Total   11  2090.9


S = 14.3721   R-Sq = 1.21%   R-Sq(adj) = 0.00%


Analysis of Variance for KneeL A ROM

Source  DF      SS     MS     F      P
Group    1    15.9   15.9  0.05  0.830
Error   10  3253.2  325.3
Total   11  3269.0


S = 18.0365   R-Sq = 0.49%   R-Sq(adj) = 0.00%


Analysis of Variance for KneeL B ROM

Source  DF      SS     MS     F      P
Group    1    38.0   38.0  0.32  0.587
Error   10  1204.0  120.4
Total   11  1242.0


S = 10.9727   R-Sq = 3.06%   R-Sq(adj) = 0.00%


Analysis of Variance for KneeL G ROM

Source  DF      SS     MS     F      P
Group    1     6.0    6.0  0.01  0.939
Error   10  9674.6  967.5
Total   11  9680.7


S = 31.1041   R-Sq = 0.06%   R-Sq(adj) = 0.00%

Analysis of Variance for KneeR A ROM

Source  DF      SS     MS     F      P
Group    1     1.5    1.5  0.01  0.932
Error   10  2039.3  203.9
Total   11  2040.9


S = 14.2805   R-Sq = 0.08%   R-Sq(adj) = 0.00%


Analysis of Variance for KneeR B ROM

Source  DF      SS     MS     F      P
Group    1    8.58   8.58  0.09  0.768
```

Error	10	929.41	92.94		
Total	11	937.99			

S = 9.64058   R-Sq = 0.91%   R-Sq(adj) = 0.00%

Analysis of Variance for KneeR G ROM

Source	DF	SS	MS	F	P
Group	1	63.83	63.83	1.19	0.301
Error	10	537.01	53.70		
Total	11	600.84			

S = 7.32810   R-Sq = 10.62%   R-Sq(adj) = 1.69%

Two sample t-tests for variables with significant P-values from One way ANOVA

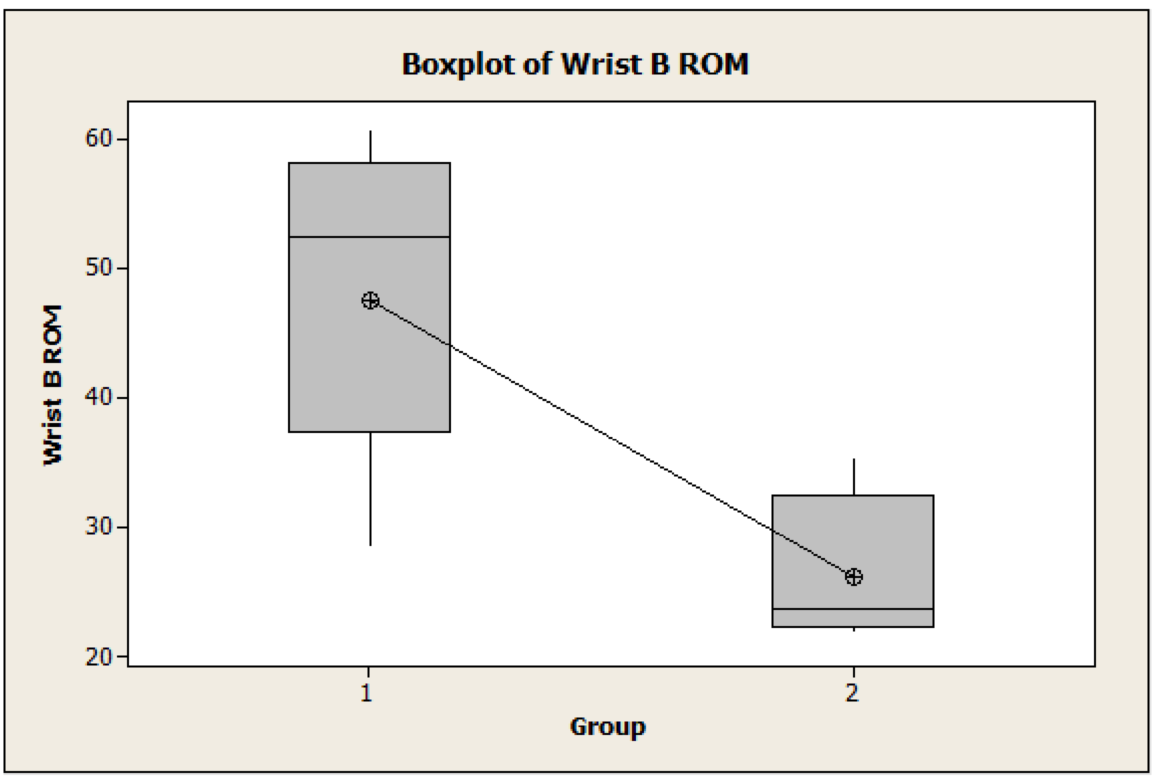
Two-Sample T-Test and CI: Wrist B ROM, Group

Two-sample T for Wrist B ROM

Group	N	Mean	StDev	SE Mean
1	7	47.4	11.9	4.5
2	4	26.13	6.11	3.1

Difference = mu (1) - mu (2)
Estimate for difference: 21.32
95% CI for difference: (6.67, 35.97)
T-Test of difference = 0 (vs not =): T-Value = 3.29 P-Value = 0.009 DF = 9
Both use Pooled StDev = 10.3327

Boxplot of Wrist B ROM



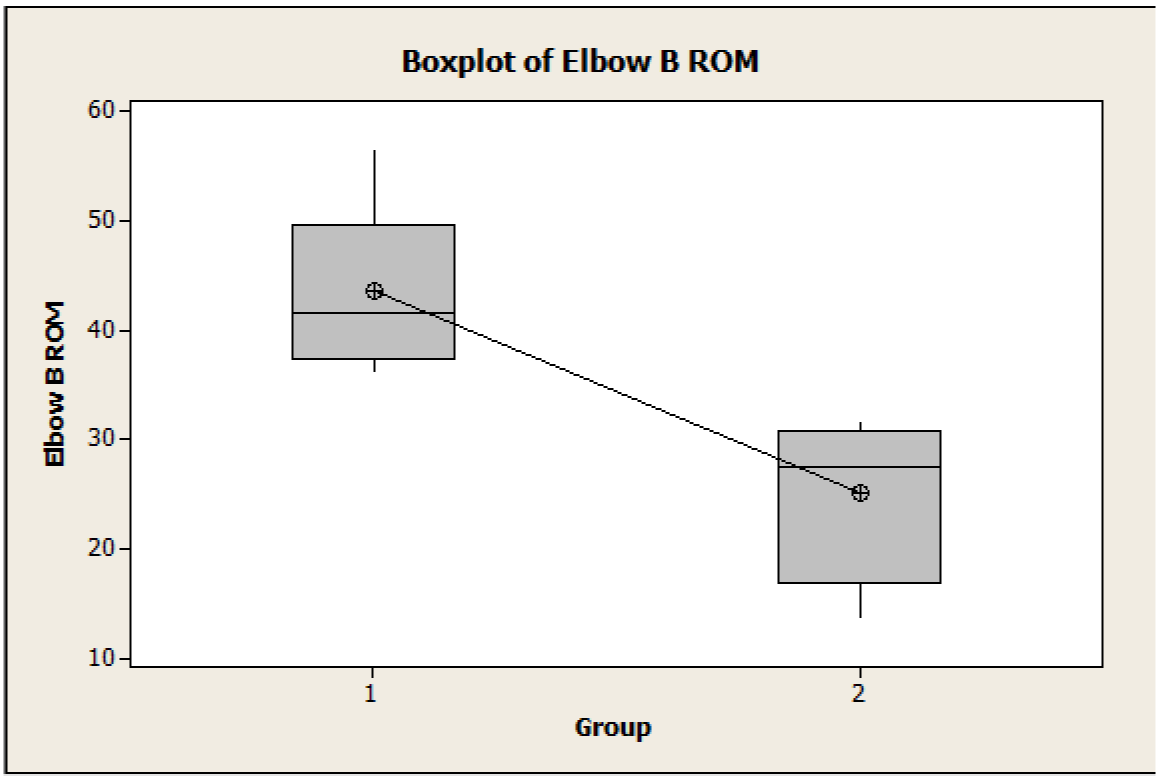
Two-Sample T-Test and CI: Elbow B ROM, Group

```
Two-sample T for Elbow B ROM

Group  N   Mean  StDev  SE Mean
1      8  43.58   7.12      2.5
2      4  25.01   7.87      3.9


Difference = mu (1) - mu (2)
Estimate for difference:  18.57
95% CI for difference:  (8.54, 28.60)
T-Test of difference = 0 (vs not =): T-Value = 4.12  P-Value = 0.002  DF = 10
Both use Pooled StDev = 7.3521
```

Boxplot of Elbow B ROM



APPENDIX B

Tables

Table B.1. De-identified subject biometric data and study bed height

Subject ID	Bed Height (m)	Subject Height (in)	Bed Height/Subject Height	Handedness	Age	Gender	No. of times ETI performed (Self-Reported)	Years of experience	Status
279	0.878495	69	0.5012524	R	24	F	5	2	Med Student - Year 6
620	0.787913	59	0.525766	R	44	F	50	1	EMS Student
972	0.672263	73	0.3625623	L	36	M	50	12	Physician - Surgeon
54	0.878264	73	0.473662	R	47	M	100	20	Physician - Pediatric and Transplant Surgeon
739	0.880674	68	0.5098854	R	37	M	100	12	Pediatric Surgery
411	0.80982	69	0.4620678	R	44	M	150	0.2	M.S. Anesthesiology student
514	0.784257	70	0.4410894	R	25	M	150	0.2	M.S. Anesthesiology student
747	0.887203	70	0.4989893	R	28	M	200	4	Medical Resident - 3rd Year - Anesthesiology
999	0.89483	69	0.5105729	R	46	F	300	22	Paramedic
755	0.794903	70	0.4470771	R	45	M	1000	20	Physician - Emergency Medicine
518	0.849907	75	0.4461454	R	31	M	2000	4	Medical Resident - 3rd Year - Anesthesiology
786	0.862406	68	0.4993087	R	42	F	5000	20	Anesthesiologist Assistant

Table B.2. Path Length, Average path speed, Laryngoscope Use Time and Intubation Time

Subject ID	Path Length	Average path speed	Laryngoscope Use time	Intubation Time
279	3.687695	0.082746	44.56666667	71.36666667
620	12.1	0.525896	23.00833333	54.78333333
972	5.178924	0.206675	25.05833333	39.50833333
54	4.04799	0.103331	39.175	57.23333333
739	3.703126	0.173111	21.39166667	38.78333333
411	3.541674	0.167257	21.175	37.51666667
514	4.533315	0.244493	18.54166667	43.31666667
747	4.555463	0.17674	25.775	41.90833333
999	3.327465	0.214906	15.48333333	33.89166667
755	2.547985	0.201157	12.66666667	24.40833333
518	4.389501	0.159473	27.525	55.19166667
786	4.056957	0.223729	18.13333333	35.51666667

Table B.3. Wrist and Elbow rotation angle ranges of motion

Subject ID	Wrist A ROM	Wrist B ROM	Wrist G ROM	Elbow A ROM	Elbow B ROM	Elbow G ROM
279	53.52785071	54.15475789	87.62269042	39.45740239	39.01140059	39.12128411
620	78.6950177	60.54035866	100.1481551	44.76432836	43.0169814	42.43263988
972	X	X	X	39.89071577	46.09987977	59.04895987
54	44.73192038	52.36070062	44.41845618	34.61184012	36.30274253	39.36786401
739	54.52521363	41.05245363	98.19296729	44.92725311	36.90561539	42.20632594
411	25.77570203	37.38908086	35.97837651	29.79395242	40.0689408	34.46229044
514	39.51050857	58.02104857	84.03943452	50.80804815	56.4372653	77.41123932
747	56.56317836	28.61618445	50.8165084	55.17867558	50.80467527	64.91940653
999	43.09311188	24.16489623	98.81535338	40.73902534	28.44264929	54.87354432
755	42.71604437	22.00189078	82.43564516	34.06947185	31.53514791	58.79942816
518	47.11383074	35.18930595	58.70690904	31.66344426	26.42415153	34.82018344
786	41.31936903	23.15210118	48.51658225	34.328148	13.63895883	38.65393281

Table B.4. Subject Neck Angle and Angle of View between Subject and mannequin ranges of motion

Subject ID	Head A ROM	Head B ROM	Head G ROM	View A ROM	View B ROM	View G ROM
279	51.31335663	41.17417993	57.34352098	67.43255522	55.91136215	58.45726794
620	32.51859437	34.38906021	39.6925923	21.84575494	21.79246104	34.81886133
972	43.74872238	42.80938053	40.18989486	20.46974462	44.04313589	22.28849851
54	49.42913734	20.58817588	39.57421264	42.86936486	24.10272941	49.77404921
739	42.72730035	34.75856315	46.26311831	55.95726963	26.18949757	33.89276762
411	30.42114259	22.48796551	26.68302512	33.11886601	26.30444695	15.58796624
514	39.38741544	35.26789319	43.21563085	24.02761901	42.85945497	23.55445356
747	44.41613526	25.28722942	40.89896179	37.57300155	52.34734571	29.35043586
999	52.77757378	20.97777652	28.78539127	52.9809168	18.69125298	20.90248672
755	34.30511571	19.32885521	13.26776741	46.47499753	25.43353673	32.58314919
518	44.27671742	21.27953576	39.83119263	56.03573058	38.26889935	28.38156871
786	67.93739455	35.5437169	32.79634677	67.15230714	25.70666323	22.3616888

Table B.5. Left and Right Knee angle ranges of motion

Subject ID	KneeL A ROM	KneeL B ROM	KneeL G ROM	KneeR A ROM	KneeR B ROM	KneeR G ROM
279	50.84685922	42.162946	23.64563569	38.30324548	29.7876911	20.23964946
620	63.75884881	28.31419265	25.20115609	40.67097506	32.97448526	20.57014073
972	26.47633207	24.62468046	29.65984848	34.07984235	36.71717956	12.82831963
54	27.17162635	12.15409072	16.42304499	35.30008248	20.73805385	6.37011048
739	21.25531128	8.011894064	14.6030703	22.28288139	16.20137469	7.406917757
411	18.15058486	11.55455305	6.773543146	13.62563952	9.870850248	4.206132805
514	58.64681078	30.48898789	121.6490868	17.98846382	15.3257293	12.57528176
747	52.95732263	17.64795966	14.29312286	66.13151129	39.93465627	23.56159349
999	27.2692913	39.28088247	33.59942795	25.43815435	23.25579258	27.73520907
755	47.3714879	19.26327283	26.96347099	39.77002112	30.66120349	15.08462516
518	30.40442687	20.41653173	30.25066246	28.95848001	22.69325536	10.43818542
786	64.34863299	23.61568515	29.28875368	36.98301495	31.3386599	20.19056808

APPENDIX C

MATLAB Codes

Laryngoscope Virtual Point Calculation: Calibration

```
function [p] = lscope_calibrate(data)
%lscope_calibrate Laryngoscope tip position from calibration data.
%   [P] = LSCOPE_CALIBRATE(DATA) returns a (1x3) vector P containing the
%   laryngoscope tip position in the local coordinate system defined on
the
%   handle of the laryngoscope. DATA is an (Nx15) matrix containing global
%   coordinates of rigid body markers 1-4 (columns 1-12), and global
%   coordinates of the tip marker (column 13-15).
%
%   This function is intended to be used in conjunction with lscope_tip.
%   Once calibration is complete for a particular rigid body
configuration,
%   matrix P may be input to lscope_tip along with rigid body trial data
%   (markers 1-4) to estimate the tip's position without a dedicated
%   marker.
%
%   Developed by Gregory W. King
%   VERSION HISTORY:
%   1. Version 1.0: Original code developed by GWK on 3/6/15

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%

%Define markers from data matrix

m1 = data(:,1:3);    %Local CS origin
m2 = data(:,4:6);
m3 = data(:,7:9);
m4 = data(:,10:12);
mtip = data(:,13:15);

%Create unit vectors (x, y, z) defining scope's local coordinate system

x = [m2(:,1)-m1(:,1) m2(:,2)-m1(:,2) m2(:,3)-m1(:,3)];
xmag = sqrt(sum(x.^2,2));
x = [x(:,1)./xmag x(:,2)./xmag x(:,3)./xmag];

ztemp = [m4(:,1)-m1(:,1) m4(:,2)-m1(:,2) m4(:,3)-m1(:,3)];
ztempmag = sqrt(sum(ztemp.^2,2));
ztemp = [ztemp(:,1)./ztempmag ztemp(:,2)./ztempmag ztemp(:,3)./ztempmag];

y = cross(ztemp,x);
ymag = sqrt(sum(y.^2,2));
y = [y(:,1)./ymag y(:,2)./ymag y(:,3)./ymag];

z = cross(x,y);
zmag = sqrt(sum(z.^2,2));
```

```
z = [z(:,1)./zmag z(:,2)./zmag z(:,3)./zmag];

%Define Global-to-Local transformation matrix; convert tip coordinates
from
%global to local

for i = 1:length(m1)
    T_LtoG = [x(i,:)' y(i,:)' z(i,:)'];
    T_GtoL = T_LtoG';
    mtipL(i,:) = T_GtoL*[mtip(i,:)-m1(i,:)]';
end

p = mean(mtipL);
```

Laryngoscope Virtual Point Calculation: Calculating Tip Coordinates

```
function [mtip] = lscope_tip(sub,base,vec1,vec2)
%lscope_tip Estimate laryngoscope tip position from rigid body data.
%   [MTIP] = LSCOPE_TIP(DATA,P) returns an (Nx3) matrix MTIP containing
%   estimated global coordinates of the laryngoscope tip. DATA is an
(Nx12)
%   matrix containing global coordinates of rigid body markers on the
%   laryngoscope handle. P is a (1x3) vector containing laryngoscope tip
%   position in the local coordinate system defined by the rigid body
%   markers.
%
%   This function is intended to be used in conjunction with
%   lscope_calibrate. Once calibration is complete, using
lscope_calibrate,
%   for a particular rigid body configuration, lscope_tip may be used as
%   described above to estimate the tip's position without a dedicated
%   marker.
%
%   Developed by Gregory W. King
%   VERSION HISTORY
%   1. Version 1.0: Original code developed by GWK on 3/6/15
%   2. Version 1.1: Code modified to be customizable by Safeer F. Siddicky
%   on 04/01/2015

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
load p
%Identify subject

loader = [num2str(sub) '.mat'];

load(loader);

%Define markers from data matrix

m1 = data2(:,1:3);
m2 = data2(:,4:6);
m3 = data2(:,7:9);
m4 = data2(:,10:12);

% conditional to find out which markers

if base == 1
    base = m1;
elseif base == 2
    base = m2;
elseif base == 3
    base = m3;
elseif base == 4
    base = m4;
else
    disp('Error, enter integer between 1 to 4')
```

```
end

if vec1 == 1
    vec1 = m1;
elseif vec1 == 2
    vec1 = m2;
elseif vec1 == 3
    vec1 = m3;
elseif vec1 == 4
    base = m4;
else
    disp('Error, enter integer between 1 to 4')
end

if vec2 == 1
    vec2 = m1;
elseif vec2 == 2
    vec2 = m2;
elseif vec2 == 3
    vec2 = m3;
elseif vec2 == 4
    vec2 = m4;
else
    disp('Error, enter integer between 1 to 4')
end


%Create unit vectors (x, y, z) defining scope's local coordinate system
% 2 to 1
x = [vec1(:,1)-base(:,1) vec1(:,2)-base(:,2) vec1(:,3)-base(:,3)];
xmag = sqrt(sum(x.^2,2));
x = [x(:,1)./xmag x(:,2)./xmag x(:,3)./xmag];
% 4 to 1
ztemp = [vec2(:,1)-base(:,1) vec2(:,2)-base(:,2) vec2(:,3)-base(:,3)];
ztempmag = sqrt(sum(ztemp.^2,2));
ztemp = [ztemp(:,1)./ztempmag ztemp(:,2)./ztempmag ztemp(:,3)./ztempmag];

y = cross(ztemp,x);
ymag = sqrt(sum(y.^2,2));
y = [y(:,1)./ymag y(:,2)./ymag y(:,3)./ymag];

z = cross(x,y)
zmag = sqrt(sum(z.^2,2));
z = [z(:,1)./zmag z(:,2)./zmag z(:,3)./zmag];

%Define Local-to-Global transformation matrix; convert tip coordinates
from
%local to global

for i = 1:length(m1)
    T_LtoG = [x(i,:)' y(i,:)' z(i,:)'];
    mtip(i,:) = [T_LtoG*p'+m1(i,:)']';
end
```

Code for Finding the Tip for the Laryngoscope Movement of Each Subject

```
clear all
clc
close all

%% Script file to bring in all Tip trajectories

[Tip_279] = lscope_tip(279,1,2,4);

[Tip_411] = lscope_tip(411,1,2,3);

[Tip_514] = lscope_tip(514,2,3,4);

[Tip_786] = lscope_tip(786,1,2,4);

[Tip_972] = lscope_tip(972,1,2,4);

[Tip_620] = lscope_tip(620,1,2,4);

% neededdata
load Tip_279
load Tip_411
load Tip_514
load Tip_786
load Tip_972
load Tip_620

[PL279, PV279, ET279] = tipPLPV(Tip_279);

[PL411, PV411, ET411] = tipPLPV(Tip_411);

[PL514, PV514, ET514] = tipPLPV(Tip_514);

[PL786, PV786, ET786] = tipPLPV(Tip_786);

[PL972, PV972, ET972] = tipPLPV(Tip_972);

[PL620, PV620, ET620] = tipPLPV(Tip_620);

function [PLB1, PVB1, ETI_time] = tipPLPV(data)
close all

% Code for Laryngoscope tip Movement
% 01/12/2015

%% Sub 1 ETI Sub 2 Assist

fs = 120;       % Sampling frequency
data = lowbutter(data,2,6,fs); %Low pass butterworth

%Blade Data
```

```
B1x = data(:,1); %xyz-coords of blade tip
B1y = data(:,2);
B1z = data(:,3);

t1 = 1:1:length(B1x);   % Extract time from data
% t1 = t1-t1(1);     % Normalize time to start from 0
t1 = t1/fs;
ETI_time = length(t1)/fs;

% Path Length, Average path speed
   B1 = [B1x,B1y,B1z];  % x y z position matrix for Blade Tip
   PLB1 = 0;            % Initialize Path Length for Blade Tip variable
    for i = 1:length(B1)-1

        P11 = B1(i+1,:);
        P21 = B1(i,:);
        dL1 = sqrt((P21(1)-P11(1))^2 + ((P21(2)-P11(2))^2));
        PLB1 = PLB1 + dL1;
    end

    T1 =(1/fs)*length(B1);
    PVB1 = PLB1/T1;

figure(1)
subplot(2,1,1)
plot(t1,B1x,t1,B1y,t1,B1z)
xlabel('Time (s)')
ylabel('Position of xyz trajectories (mm)')
legend('x traj1','y traj1', 'z traj1')
title('x y z trajectories of Blade Tip of Subject XX')

subplot(2,1,2)
plot3(B1x,B1y,B1z)
title('Overall 3D trajectory of Blade Tip of Subject XX')
```

Function to obtain outcome variables, and all written functions (nested)

```
function [ETIData, NoviceVar, ExpertVar] = GetVariables()

clc
close all

% Loop to get all variables tabulated inside ETIData (13 rows for 13
subjects)

for i = 1:13
ETIData(i,:) = processETI(i);
disp(['Processing iteration' num2str(i) ''])
end

% i = 1 excluded from study
% i = 2:9   NOVICE
% i = 10:13 EXPERT

NoviceInd = 2:9; ExpertInd = 10:13; %Row Indices for which rows are
novices and which are experts

NoviceMat = ETIData(NoviceInd,:); %Separate the ETIData matrix into Novice
and Expert Data matrices
ExpertMat = ETIData(ExpertInd,:);

NoviceVar=[mean(NoviceMat);std(NoviceMat)]; NoviceVar =
(NoviceVar(:,3:end))'; %Mean and std for all
ExpertVar=[mean(ExpertMat);std(ExpertMat)]; ExpertVar =
(ExpertVar(:,3:end))';
end

%% Beginning of nested functions

function ETIData = processETI(i)
%Function processETI will process the data from Intubation trials
%   Identify subject by Subject ID no. It is usually a 3 digit number.
Please
%   enter only the number in the sublist on Line 13
%   Example usage ===> ETIData = processETI(123)
%   Developed by Safeer F. Siddicky
%   VERSION HISTORY
%   1. Version 1.0: Original code developed by SFS on 4/5/15

clc
close all

sublist = [775,279,620,972,54,739,411,514,747,999,755,518,786];     %
Subject ID list
numlist = [0,5,50,50,100,100,150,150,200,300,1000,2000,5000];       % No.
of times ETI performed

sub = sublist(i);
```

```
%% Load Data
eval(['load ' num2str(sub) 'Data'])

    if sub == 54 || sub == 739 % Conditional to switch Chest 1 and Chest 2
markers
        Chest1temp = Chest2;
        Chest2 = Chest1;
        Chest1 = Chest1temp;
    end
%% Bed Height (Mean of Stomach Y)

BedHeight = mean(Stomach(100,2));

%% Laryngoscope analysis
data2=[m1 m2 m3 m4]; % Concatenate all 4 marker data streams to form a
(NX12) matrix

% Generate Lscope marker data via active frames (frames where Lscope
moving)
[Frame0,FrameEnd] = findLscopeframe(sub); % Active frames output by
function

data2 = data2(Frame0:FrameEnd,:); % Lscope data limited by frames

mAv = (m1+m2+m3+m4)/4; %Average of 4 marker data
mAv = mAv(Frame0:FrameEnd,:); %Restricted by lscope use time

% % Lscopesaver = [num2str(sub) '_LscopeData.mat' ]; % String for filename
for Tip data
% % save(Lscopesaver) % Save Lscope raw data for each subject

%% Generate Blade Tip data
    % File allCalib prepares the 1X3 calibration coordinates using
function
    % lscopeCalibrate
    % The output from allCalib is saved as SUB_Calib
    % Function lscope_tip loads SUB_Calib and SUB_LscopeData (saved above)
    % It generates the Tip data in global coordinates
    % File alltip calls lscope_tip for each subject and saves Tip data in
    % the format SUB_Tip.mat. This is loaded below

TipLoader = [num2str(sub) '_Tip.mat']; % Generate filename string
load(TipLoader); % Outputs as Tip_Data - used later in function tipPLPV()
Tip_Data= meanremove(Tip_Data,100); % Remove mean of first 100 frames
% Calculate Path Length, Path Velocity, ETI Time

[ETI_PathLength, ETI_PathVelocity, ETI_Lscope_Time] =
tipPLPV(sub,Tip_Data);

% Find overall intubation time - will use Frame0 as beginning (start of
% Lscope pickup) and first peak of LungL(Y traj) as end of intubation. To
% make peak finding easier, will separate out the lung data from FrameEnd
% (i.e end of use of Lscope) to the end of the data stream. That way peaks
```

```
% will be significantly visualized. A peakfinder function will be easily
% able to find the first peak. Then the index location of the first peak
% will be added to FrameEnd to give us total frames of intubation. Divide
% that by Sampling frequency and we have reliable total intubation time.

LungPk_frames = LungL(FrameEnd:end,2); %just Y traj, y is superior
inferior axis

[Pk_Ind] = peakfinder(LungPk_frames); %function peakfinder gives
significant peaks of Lung Y
% Function peakfinder.m was not written by author.
% License agreement enclosed within function.
% Function in this link -
http://www.mathworks.com/matlabcentral/fileexchange/25500-peakfinder

Pkframe = Pk_Ind(1); % Extract index of first frame
ETI_Time = (FrameEnd + Pkframe)/fs; % (Lscope put down + first lung
peak)/fs = total ETI time

%% Absolute Joint angle calculations (Absolute angles: Not used in thesis)

% Skeleton Plane normals
    % Point#3 is base
% Head Plane Normal
Head_planeNormal = makePlaneNormal(Head1,Head2,Head3);
% Right Hand Normals
RHand_planeNormal = makePlaneNormal(RHand1,RHand2,RHand3);
RFArm_planeNormal = makePlaneNormal(RFArm1,RFArm2,RUArm1);
RUArm_planeNormal = makePlaneNormal(RUArm1,RUArm2,RShldr1);

% Right Hand Angles (Absolute angles: Not used in thesis)
RWrist_Angle = Twovecangle(RHand_planeNormal,RFArm_planeNormal);
RElbow_Angle = Twovecangle(RFArm_planeNormal,RUArm_planeNormal);

%Left Hand Normals
LHand_planeNormal = makePlaneNormal(LHand1,LHand2,LHand3);
LFArm_planeNormal = makePlaneNormal(LFArm1,LFArm2,LUArm1);
LUArm_planeNormal = makePlaneNormal(LUArm1,LUArm2,LShldr1);

%Left Hand Angles (Absolute angles: Not used in thesis)
LWrist_Angle = Twovecangle(LHand_planeNormal,LFArm_planeNormal);
LElbow_Angle = Twovecangle(LFArm_planeNormal,LUArm_planeNormal);

% Mannequin Plane normals
Face_planeNormal = makePlaneNormal(Forehead,EarR,EarL);
Chest_planeNormal = makePlaneNormal(ShldrR,ShldrL,Sternum);

% Mannequin and subject neck angles (Absolute angles: Not used in thesis)
Mannequin_neckAngle = Twovecangle(Face_planeNormal,Chest_planeNormal);
AngleOfView = (180/pi)*Twovecangle(Head_planeNormal,Face_planeNormal);
ViewAngle_ROM = rom(AngleOfView);

%AP Neck Angle during intubation (Absolute angles: Not used in thesis)
HeadVec1 = Head2(Frame0:FrameEnd,:) - Head1(Frame0:FrameEnd,:);
```

```
HeadVec2 = ((RShldr1(Frame0:FrameEnd,:)+LShldr1(Frame0:FrameEnd,:)))/2 -
Head1(Frame0:FrameEnd,:);
NeckAngle_AP = (180/pi)*(Twovecangle(HeadVec1,HeadVec2));

Neck_ROM = rom(NeckAngle_AP);

%% Rotational Joint Angle calculations
%% Alpha Beta Gamma rotation angle calculations
RWrist_abg =  wristangle(RHand1,RHand2,RHand3,RFArm1,RFArm2,RUArm1);
RWrist_abg = meanremove(RWrist_abg,100);
RElbow_abg = elbowangle(RFArm1,RFArm2,RUArm1,RUArm2,RShldr1);
RElbow_abg = meanremove(RElbow_abg,100);

LWrist_abg =  wristangle(LHand1,LHand2,LHand3,LFArm1,LFArm2,LUArm1);
LWrist_abg = meanremove(LWrist_abg,100);
LElbow_abg = elbowangle(LFArm1,LFArm2,LUArm1,LUArm2,LShldr1);
LElbow_abg = meanremove(LElbow_abg,100);

DHand = SubHand(sub); % Outputs a logical to find out which hand the
subject intubated with;
                      % All subjects intubated with left, except 279 who
switched

if DHand            % If true, it is Right Hand
    %Active frames, aka frames where Lscope in use = Frame0:FrameEnd
    Wrist_abg = RWrist_abg(Frame0:FrameEnd,:);
    Wrist_ROM = rom(Wrist_abg,3); %Function rom generates range of motion
    WristA_ROM = Wrist_ROM(1); WristB_ROM = Wrist_ROM(2); WristG_ROM =
Wrist_ROM(3);
    Elbow_abg = RElbow_abg(Frame0:FrameEnd,:);
    Elbow_ROM = rom(Elbow_abg,3);
    ElbowA_ROM = Elbow_ROM(1); ElbowB_ROM = Elbow_ROM(2); ElbowG_ROM =
Elbow_ROM(3);
    tper = t(Frame0:FrameEnd)-t(Frame0);
    tper = tper*100/max(tper); % Time expressed as percentage to be able
to compare all streams

elseif DHand == 3   % Used for Subject 279 who switches hands @ Frame 3270

    Wrist_abg = [RWrist_abg(Frame0:3270,:) LWrist_abg(3271:FrameEnd,:)];
    Wrist_ROM = rom(Wrist_abg,3);
    WristA_ROM = Wrist_ROM(1); WristB_ROM = Wrist_ROM(2); WristG_ROM =
Wrist_ROM(3);
    Elbow_abg = [RElbow_abg(Frame0:3270,:) LElbow_abg(3271:FrameEnd,:)];
    Elbow_ROM = rom(Elbow_abg,3);
    ElbowA_ROM = Elbow_ROM(1); ElbowB_ROM = Elbow_ROM(2); ElbowG_ROM =
Elbow_ROM(3);
    tper = t(Frame0:FrameEnd)-t(Frame0);
    tper = tper*100/max(tper);

else                  % If false, it is Left Hand

    Wrist_abg = LWrist_abg(Frame0:FrameEnd,:);
    Wrist_ROM = rom(Wrist_abg,3);
```

```
    WristA_ROM = Wrist_ROM(1); WristB_ROM = Wrist_ROM(2); WristG_ROM =
Wrist_ROM(3);
    Elbow_abg = LElbow_abg(Frame0:FrameEnd,:);
    Elbow_ROM = rom(Elbow_abg,3);
    ElbowA_ROM = Elbow_ROM(1); ElbowB_ROM = Elbow_ROM(2); ElbowG_ROM =
Elbow_ROM(3);
    tper = t(Frame0:FrameEnd)-t(Frame0);
    tper = tper*100/max(tper);

end

%% Exclude Sub 972 from Wrist Data: Did not use rigid body hand definition
if sub == 972
   Wrist_abg = Wrist_abg-Wrist_abg;
   Wrist_ROM = Wrist_ROM-Wrist_ROM;
   WristA_ROM = Wrist_ROM(1); WristB_ROM = Wrist_ROM(2); WristG_ROM =
Wrist_ROM(3);
end

%% Head angles
[Head_abg,View_abg] =
headangle(LShldr1,RShldr1,Head1,Head2,Head3,Chest1,Chest2,Forehead,Sternum
,ShldrL,ShldrR);
Head_abg = meanremove(Head_abg,100); View_abg = meanremove(View_abg,100);
Head_abg = Head_abg(Frame0:FrameEnd,:); View_abg =
View_abg(Frame0:FrameEnd,:);
HeadA = Head_abg(:,1); HeadB = Head_abg(:,2); HeadG = Head_abg(:,3);
Head_ROM = rom(Head_abg,3); % Add +Pkframe for Intubation time profile
HeadA_ROM = Head_ROM(1); HeadB_ROM = Head_ROM(2); HeadG_ROM = Head_ROM(3);
ViewA = View_abg(:,1); ViewB = View_abg(:,2); ViewG = View_abg(:,3);
View_ROM = rom(View_abg,3); % Add +Pkframe for Intubation time profile
ViewA_ROM = View_ROM(1); ViewB_ROM = View_ROM(2); ViewG_ROM = View_ROM(3);

%% Knee angles
[KneeL_abg,KneeR_abg] =
kneeangle(Hip1,Hip2,LThigh1,LThigh2,RThigh1,RThigh2,LShin1,LShin2,RShin1,R
Shin2);
KneeL_abg = KneeL_abg(Frame0:FrameEnd,:);
KneeLA = KneeL_abg(:,1); KneeLB = KneeL_abg(:,2); KneeLG = KneeL_abg(:,3);
KneeL_ROM = rom(KneeL_abg,3); % Add +Pkframe for Intubation time profile
KneeLA_ROM = KneeL_ROM(1); KneeLB_ROM = KneeL_ROM(2); KneeLG_ROM =
KneeL_ROM(3);

KneeR_abg = KneeR_abg(Frame0:FrameEnd,:);
KneeRA = KneeR_abg(:,1); KneeRB = KneeR_abg(:,2); KneeRG = KneeR_abg(:,3);
KneeR_ROM = rom(KneeR_abg,3); % Add +Pkframe for Intubation time profile
KneeRA_ROM = KneeR_ROM(1); KneeRB_ROM = KneeR_ROM(2); KneeRG_ROM =
KneeR_ROM(3);




%% Assign data - Save all subject data as matrix to export to Excel later
```

```
ETIData=[sub numlist(i) ETI_PathLength ETI_PathVelocity...
            ETI_Lscope_Time ETI_Time...
            WristA_ROM WristB_ROM WristG_ROM...
            HeadA_ROM HeadB_ROM HeadG_ROM...
            ViewA_ROM ViewB_ROM ViewG_ROM...
            ElbowA_ROM ElbowB_ROM ElbowG_ROM...
            KneeLA_ROM KneeLB_ROM KneeLG_ROM...
            KneeRA_ROM KneeRB_ROM KneeRG_ROM];

eval(['save ' num2str(sub) '_AllData mAv ETIData Wrist_abg Elbow_abg
Head_abg View_abg KneeL_abg KneeR_abg Tip_Data tper'])

end

function [Frame0,FrameEnd] = findLscopeframe(sub)
% Need to update for new subjects
if sub == 279
    Frame0 = 905; FrameEnd = 6252;
elseif sub == 411
    Frame0 = 700; FrameEnd = 3240;
elseif sub == 514
    Frame0 = 476; FrameEnd = 2700;
elseif sub == 620
    Frame0 = 555; FrameEnd = 3315;
elseif sub == 786
    Frame0 = 290; FrameEnd = 2465;
elseif sub == 972
    Frame0 = 408; FrameEnd = 3414;
elseif sub == 755
    Frame0 = 566; FrameEnd = 2085;
elseif sub == 747
    Frame0 = 487; FrameEnd = 3579;
elseif sub == 518
    Frame0 = 589; FrameEnd = 3891;
elseif sub == 775
    Frame0 = 452; FrameEnd = 3175;
elseif sub == 739
    Frame0 = 382; FrameEnd = 2948;
elseif sub == 999
    Frame0 = 836; FrameEnd = 2693;
elseif sub == 054
    Frame0 = 622; FrameEnd = 5322;

else

error('Please enter correct subject ID');

end


end
```

```
function Mat3N = meanremove(vecORmat,ind)
% Subtract the mean value of the first Ind indices of a vecORmattor or
Matrix
[r,c]=size(vecORmat);

meanvecORmat = mean(vecORmat(1:ind,:));

for i = 1:c
vecORmat(:,i) = vecORmat(:,i)-meanvecORmat(:,i);
end

Mat3N = vecORmat;

end

function [PLB1, PVB1, ETI_time] = tipPLPV(sub,mtip)
close all

% Code for Laryngoscope tip Movement

fs = 120;       % Sampling frequency

filtsub = [279,411,514,620,786];
filtnum = [0.625,1,2,5,1.3];

if sum(sub == filtsub) == 1 % to check if the subject data needs filtering

    if sub == 279   % Filter conditions based on mAv analysis
        filt = filtnum(1);
    elseif sub == 411
        filt = filtnum(2);
    elseif sub == 514
        filt = filtnum(3);
    elseif sub == 620
        filt = filtnum(4);
    elseif sub == 786
        filt = filtnum(5);
    end

    mtip = lowbutter(mtip,2,filt,fs); %Low pass butterworth 4 Hz cutoff
for swapping markers

else
    mtip = mtip;
end
%Blade Data
B1x = mtip(:,1); %xyz-coords of blade tip
B1y = mtip(:,2);
B1z = mtip(:,3);

t1 = 1:1:length(B1x);   % Extract time from data

t1 = t1/fs;
ETI_time = length(t1)/fs;
```

```
% Path Length, Path Velocity
   B1 = [B1x,B1y,B1z];  % x y z position matrix for Blade Tip
   PLB1 = 0;            % Initialize Path Length for Blade Tip variable
    for i = 1:length(B1)-1

        P11 = B1(i+1,:);
        P21 = B1(i,:);
        dL1 = sqrt((P21(1)-P11(1))^2 + ((P21(2)-P11(2))^2) + (P21(3)-
P11(3))^2);
        PLB1 = PLB1 + dL1;
    end

    T1 =(1/fs)*length(B1);
    PVB1 = PLB1/T1;

end

function varargout = peakfinder(x0, sel, thresh, extrema,
include_endpoints)
%PEAKFINDER Noise tolerant fast peak finding algorithm
%   INPUTS:
%       x0 - A real vector from the maxima will be found (required)
%       sel - The amount above surrounding data for a peak to be
%           identified (default = (max(x0)-min(x0))/4). Larger values mean
%           the algorithm is more selective in finding peaks.
%       thresh - A threshold value which peaks must be larger than to be
%           maxima or smaller than to be minima.
%       extrema - 1 if maxima are desired, -1 if minima are desired
%           (default = maxima, 1)
%       include_endpoints - If true the endpoints will be included as
%           possible extrema otherwise they will not be included
%           (default = true)
%   OUTPUTS:
%       peakLoc - The indicies of the identified peaks in x0
%       peakMag - The magnitude of the identified peaks
%
%   [peakLoc] = peakfinder(x0) returns the indicies of local maxima that
%       are at least 1/4 the range of the data above surrounding data.
%
%   [peakLoc] = peakfinder(x0,sel) returns the indicies of local maxima
%       that are at least sel above surrounding data.
%
%   [peakLoc] = peakfinder(x0,sel,thresh) returns the indicies of local
%       maxima that are at least sel above surrounding data and larger
%       (smaller) than thresh if you are finding maxima (minima).
%
%   [peakLoc] = peakfinder(x0,sel,thresh,extrema) returns the maxima ofthe
%       data if extrema > 0 and the minima of the data if extrema < 0
%
%   [peakLoc, peakMag] = peakfinder(x0,...) returns the indicies of the
%       local maxima as well as the magnitudes of those maxima
%
%   If called with no output the identified maxima will be plotted along
%       with the input data.
%
```

```
%   Note: If repeated values are found the first is identified as the peak
%
% Ex:
% t = 0:.0001:10;
% x = 12*sin(10*2*pi*t)-3*sin(.1*2*pi*t)+randn(1,numel(t));
% x(1250:1255) = max(x);
% peakfinder(x)
%
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% Available at -
http://www.mathworks.com/matlabcentral/fileexchange/25500-peakfinder

% Perform error checking and set defaults if not passed in
error(nargchk(1,5,nargin,'struct'));
error(nargoutchk(0,2,nargout,'struct'));

s = size(x0);
flipData =  s(1) < s(2);
len0 = numel(x0);
if len0 ~= s(1) && len0 ~= s(2)
    error('PEAKFINDER:Input','The input data must be a vector')
```

```
elseif isempty(x0)
    varargout = {[],[]};
    return;
end
if ~isreal(x0)
    warning('PEAKFINDER:NotReal','Absolute value of data will be used')
    x0 = abs(x0);
end

if nargin < 2 || isempty(sel)
    sel = (max(x0)-min(x0))/4;
elseif ~isnumeric(sel) || ~isreal(sel)
    sel = (max(x0)-min(x0))/4;
    warning('PEAKFINDER:InvalidSel',...
        'The selectivity must be a real scalar.  A selectivity of %.4g
will be used',sel)
elseif numel(sel) > 1
    warning('PEAKFINDER:InvalidSel',...
        'The selectivity must be a scalar.  The first selectivity value in
the vector will be used.')
    sel = sel(1);
end

if nargin < 3 || isempty(thresh)
    thresh = [];
elseif ~isnumeric(thresh) || ~isreal(thresh)
    thresh = [];
    warning('PEAKFINDER:InvalidThreshold',...
        'The threshold must be a real scalar. No threshold will be used.')
elseif numel(thresh) > 1
    thresh = thresh(1);
    warning('PEAKFINDER:InvalidThreshold',...
        'The threshold must be a scalar.  The first threshold value in the
vector will be used.')
end

if nargin < 4 || isempty(extrema)
    extrema = 1;
else
    extrema = sign(extrema(1)); % Should only be 1 or -1 but make sure
    if extrema == 0
        error('PEAKFINDER:ZeroMaxima','Either 1 (for maxima) or -1 (for
minima) must be input for extrema');
    end
end

if nargin < 5 || isempty(include_endpoints)
    include_endpoints = true;
else
    include_endpoints = boolean(include_endpoints);
end

x0 = extrema*x0(:); % Make it so we are finding maxima regardless
thresh = thresh*extrema; % Adjust threshold according to extrema.
dx0 = diff(x0); % Find derivative
dx0(dx0 == 0) = -eps; % This is so we find the first of repeated values
```

```
ind = find(dx0(1:end-1).*dx0(2:end) < 0)+1; % Find where the derivative
changes sign

% Include endpoints in potential peaks and valleys as desired
if include_endpoints
    x = [x0(1);x0(ind);x0(end)];
    ind = [1;ind;len0];
    minMag = min(x);
    leftMin = minMag;
else
    x = x0(ind);
    minMag = min(x);
    leftMin = x0(1);
end

% x only has the peaks, valleys, and possibly endpoints
len = numel(x);

if len > 2 % Function with peaks and valleys
    % Set initial parameters for loop
    tempMag = minMag;
    foundPeak = false;

    if include_endpoints
        % Deal with first point a little differently since tacked it on
        % Calculate the sign of the derivative since we tacked the first
        %  point on it does not neccessarily alternate like the rest.
        signDx = sign(diff(x(1:3)));
        if signDx(1) <= 0 % The first point is larger or equal to the
second
            if signDx(1) == signDx(2) % Want alternating signs
                x(2) = [];
                ind(2) = [];
                len = len-1;
            end
        else % First point is smaller than the second
            if signDx(1) == signDx(2) % Want alternating signs
                x(1) = [];
                ind(1) = [];
                len = len-1;
            end
        end
    end

    % Skip the first point if it is smaller so we always start on a
    %   maxima
    if x(1) >= x(2)
        ii = 0;
    else
        ii = 1;
    end

    % Preallocate max number of maxima
    maxPeaks = ceil(len/2);
    peakLoc = zeros(maxPeaks,1);
    peakMag = zeros(maxPeaks,1);
```

```
    cInd = 1;
    % Loop through extrema which should be peaks and then valleys
    while ii < len
        ii = ii+1; % This is a peak
        % Reset peak finding if we had a peak and the next peak is bigger
        %   than the last or the left min was small enough to reset.
        if foundPeak
            tempMag = minMag;
            foundPeak = false;
        end

        % Make sure we don't iterate past the length of our vector
        if ii == len
            break; % We assign the last point differently out of the loop
        end

        % Found new peak that was lager than temp mag and selectivity
larger
        %   than the minimum to its left.
        if x(ii) > tempMag && x(ii) > leftMin + sel
            tempLoc = ii;
            tempMag = x(ii);
        end

        ii = ii+1; % Move onto the valley
        % Come down at least sel from peak
        if ~foundPeak && tempMag > sel + x(ii)
            foundPeak = true; % We have found a peak
            leftMin = x(ii);
            peakLoc(cInd) = tempLoc; % Add peak to index
            peakMag(cInd) = tempMag;
            cInd = cInd+1;
        elseif x(ii) < leftMin % New left minima
            leftMin = x(ii);
        end
    end

    % Check end point
    if include_endpoints
    if x(end) > tempMag && x(end) > leftMin + sel
        peakLoc(cInd) = len;
        peakMag(cInd) = x(end);
        cInd = cInd + 1;
    elseif ~foundPeak && tempMag > minMag % Check if we still need to add
the last point
        peakLoc(cInd) = tempLoc;
        peakMag(cInd) = tempMag;
        cInd = cInd + 1;
    end
    elseif ~foundPeak
        if tempMag > x0(end) + sel
            peakLoc(cInd) = tempLoc;
            peakMag(cInd) = tempMag;
            cInd = cInd + 1;
        end
    end
```

```
    % Create output
    peakInds = ind(peakLoc(1:cInd-1));
    peakMags = peakMag(1:cInd-1);
else % This is a monotone function where an endpoint is the only peak
    [peakMags,xInd] = max(x);
    if include_endpoints && peakMags > minMag + sel
        peakInds = ind(xInd);
    else
        peakMags = [];
        peakInds = [];
    end
end

% Apply threshold value.  Since always finding maxima it will always be
%   larger than the thresh.
if ~isempty(thresh)
    m = peakMags>thresh;
    peakInds = peakInds(m);
    peakMags = peakMags(m);
end

% Rotate data if needed
if flipData
    peakMags = peakMags.';
    peakInds = peakInds.';
end

% Change sign of data if was finding minima
if extrema < 0
    peakMags = -peakMags;
    x0 = -x0;
end

% Plot if no output desired
if nargout == 0
    if isempty(peakInds)
        disp('No significant peaks found')
    else
%         figure;
%         plot(1:len0,x0,'.-',peakInds,peakMags,'ro','linewidth',2);
    end
else
    varargout = {peakInds,peakMags};
end
end

function Normal = makePlaneNormal(p1,p2,p3)

for i = 1:length(p1)

% Unit vectors
vec1(i,:) = unitvector(p1(i,:)-p3(i,:));
vec2(i,:) = unitvector(p2(i,:)-p3(i,:));
```

```
Normal(i,:) = cross(vec1(i,:),vec2(i,:));

end
end

function ret = unitvector(vec)

ret = vec/norm(vec);

end

function angle = Twovecangle(a,b)

for i = 1:length(a)

    % %Method One
    % angle(i,:) = atan2(norm(cross(a(i,:),b(i,:))), dot(a(i,:),b(i,:)));

    % Method Two
    CosTheta(i,:) = dot(a(i,:),b(i,:))/(norm(a(i,:))*norm(b(i,:))); %
Cosine = Dot product of vec a and vec b divided by the multiple of their
respective magnitudes
    angle(i,:) = acos(CosTheta(i,:)); % cosine inverse to find the angle

end

end

function ROM = rom(vec,col)
% Range of Motion calculation. Please enter a vector.
% If you have multiple columns, please sepcify no. of columns
% Otherwise 1 column will be specified by default

if nargin < 2
    col = 1;
elseif nargin <1
    error('Please enter a vector of at least 1 column')
end

for i = 1:col

    ROM(i) = max(vec(:,i))-min(vec(:,i));

end

end
```

```
function [angles] = wristangle(Hand1,Hand2,Hand3,FArm1,FArm2,UArm1);

%Establish local coordinate system axes on hand

kHand = Hand1 - Hand2;
iHand_temp = Hand3 - Hand2;
jHand = cross(kHand,iHand_temp);
iHand = cross(jHand,kHand);

iHand = [iHand(:,1)./sqrt(iHand(:,1).^2+iHand(:,2).^2+iHand(:,3).^2),...
         iHand(:,2)./sqrt(iHand(:,1).^2+iHand(:,2).^2+iHand(:,3).^2),...
         iHand(:,3)./sqrt(iHand(:,1).^2+iHand(:,2).^2+iHand(:,3).^2)];
jHand = [jHand(:,1)./sqrt(jHand(:,1).^2+jHand(:,2).^2+jHand(:,3).^2),...
         jHand(:,2)./sqrt(jHand(:,1).^2+jHand(:,2).^2+jHand(:,3).^2),...
         jHand(:,3)./sqrt(jHand(:,1).^2+jHand(:,2).^2+jHand(:,3).^2)];
kHand = [kHand(:,1)./sqrt(kHand(:,1).^2+kHand(:,2).^2+kHand(:,3).^2),...
         kHand(:,2)./sqrt(kHand(:,1).^2+kHand(:,2).^2+kHand(:,3).^2),...
         kHand(:,3)./sqrt(kHand(:,1).^2+kHand(:,2).^2+kHand(:,3).^2)];

%Establish local coordinate system axes on forearm

kArm = FArm1 - UArm1;
iArm_temp = FArm2 - UArm1;
jArm = cross(kArm,iArm_temp);
iArm = cross(jArm,kArm);

iArm = [iArm(:,1)./sqrt(iArm(:,1).^2+iArm(:,2).^2+iArm(:,3).^2),...
         iArm(:,2)./sqrt(iArm(:,1).^2 + iArm(:,2).^2 + iArm(:,3).^2),...
         iArm(:,3)./sqrt(iArm(:,1).^2+iArm(:,2).^2 + iArm(:,3).^2)];
jArm = [jArm(:,1)./sqrt(jArm(:,1).^2+jArm(:,2).^2+jArm(:,3).^2),...
         jArm(:,2)./sqrt(jArm(:,1).^2 + jArm(:,2).^2 + jArm(:,3).^2),...
         jArm(:,3)./sqrt(jArm(:,1).^2+jArm(:,2).^2 + jArm(:,3).^2)];
kArm = [kArm(:,1)./sqrt(kArm(:,1).^2+kArm(:,2).^2+kArm(:,3).^2),...
         kArm(:,2)./sqrt(kArm(:,1).^2 + kArm(:,2).^2 + kArm(:,3).^2),...
         kArm(:,3)./sqrt(kArm(:,1).^2+kArm(:,2).^2 + kArm(:,3).^2)];

for i = 1:length(Hand1)

    %Unit vector matrices for hand and arm segments

    THand = [iHand(i,:);jHand(i,:);kHand(i,:)];
    TArm = [iArm(i,:);jArm(i,:);kArm(i,:)];

    %Construct transformation matrix and extract angles

    R = THand.*TArm';
    beta(i) = asind(R(3,1));     %Abduction/adduction - Radial/Ulnar
Deviation
    gamma(i) = acosd(R(1,1)/cosd(beta(i))); %Axial rotation -
Pronation/Supination
    alpha(i) = acosd(R(3,3)/cosd(beta(i))); %Flextion/extension

end
```

```
angles = [alpha' beta' gamma'];
end

function [angles] = elbowangle(FArm1,FArm2,UArm1,UArm2,Shldr1);

%Establish local coordinate system axes on hand

kArm = FArm1 - UArm1;
iArm_temp = FArm2 - UArm1;
jArm = cross(kArm,iArm_temp);
iArm = cross(jArm,kArm);

iArm = [iArm(:,1)./sqrt(iArm(:,1).^2+iArm(:,2).^2+iArm(:,3).^2),...
        iArm(:,2)./sqrt(iArm(:,1).^2+iArm(:,2).^2+iArm(:,3).^2),...
        iArm(:,3)./sqrt(iArm(:,1).^2+iArm(:,2).^2+iArm(:,3).^2)];
jArm = [jArm(:,1)./sqrt(jArm(:,1).^2+jArm(:,2).^2+jArm(:,3).^2),...
        jArm(:,2)./sqrt(jArm(:,1).^2+jArm(:,2).^2+jArm(:,3).^2),...
        jArm(:,3)./sqrt(jArm(:,1).^2+jArm(:,2).^2+jArm(:,3).^2)];
kArm = [kArm(:,1)./sqrt(kArm(:,1).^2+kArm(:,2).^2+kArm(:,3).^2),...
        kArm(:,2)./sqrt(kArm(:,1).^2+kArm(:,2).^2+kArm(:,3).^2),...
        kArm(:,3)./sqrt(kArm(:,1).^2+kArm(:,2).^2+kArm(:,3).^2)];

%Establish local coordinate system axes on forearm

kUArm = UArm1 - Shldr1;
iUArm_temp = Shldr1 - UArm2;
jUArm = cross(kUArm,iUArm_temp);
iUArm = cross(jUArm,kUArm);

iUArm = [iUArm(:,1)./sqrt(iUArm(:,1).^2+iUArm(:,2).^2+iUArm(:,3).^2),...
        iUArm(:,2)./sqrt(iUArm(:,1).^2 + iUArm(:,2).^2 +
iUArm(:,3).^2),...
        iUArm(:,3)./sqrt(iUArm(:,1).^2+iUArm(:,2).^2 + iUArm(:,3).^2)];
jUArm = [jUArm(:,1)./sqrt(jUArm(:,1).^2+jUArm(:,2).^2+jUArm(:,3).^2),...
        jUArm(:,2)./sqrt(jUArm(:,1).^2 + jUArm(:,2).^2 +
jUArm(:,3).^2),...
        jUArm(:,3)./sqrt(jUArm(:,1).^2+jUArm(:,2).^2 + jUArm(:,3).^2)];
kUArm = [kUArm(:,1)./sqrt(kUArm(:,1).^2+kUArm(:,2).^2+kUArm(:,3).^2),...
        kUArm(:,2)./sqrt(kUArm(:,1).^2 + kUArm(:,2).^2 +
kUArm(:,3).^2),...
        kUArm(:,3)./sqrt(kUArm(:,1).^2+kUArm(:,2).^2 + kUArm(:,3).^2)];

for i = 1:length(FArm1)

    %Unit vector matrices for hand and arm segments

    THand = [iArm(i,:);jArm(i,:);kArm(i,:)];
    TArm = [iUArm(i,:);jUArm(i,:);kUArm(i,:)];

    %Construct transformation matrix and extract angles

    R = THand.*TArm';
    beta(i) = asind(R(3,1));     %Abduction/adduction
```

```
    gamma(i) = acosd(R(1,1)/cosd(beta(i))); %Axial rotation
    alpha(i) = acosd(R(3,3)/cosd(beta(i))); %Flextion/extension

end


angles = [alpha' beta' gamma'];
end

% Subject Hand when doing ETI
function Hand = SubHand(sub)

SubHnd = [279 411 514 620 786 972 755 518 747 999 739 775 54]; % List of
Subjects
R= true;    % Right Hand
L= false;    % Left Hand

SubHnd(2,1) = R; % 279  - Changes hands to L around 3170 or 3270
SubHnd(2,2) = L; % 411
SubHnd(2,3) = L; % 514
SubHnd(2,4) = L; % 620
SubHnd(2,5) = L; % 786
SubHnd(2,6) = L; % 972
SubHnd(2,7) = L; % 755
SubHnd(2,8) = L; % 518
SubHnd(2,9) = L; % 747
SubHnd(2,10) = L; % 54
SubHnd(2,11) = L; % 739
SubHnd(2,12) = L; % 999
SubHnd(2,13) = L; % 775

[Row,C] = find(SubHnd == sub);

if isempty(C)
    error('Please enter correct Subject ID')
end

Hand = logical(SubHnd(Row+1,C));

if C == 1             %Will use this for switching hands
    Hand = 3;
end

end

function [headangles,viewangles] =
headangle(LShldr1,RShldr1,Head1,Head2,Head3,Chest1,Chest2,Forehead,Sternum
,ShldrL,ShldrR)


%STEP 1: Define virtual vector during T-pose representing a line between
the
%shoulder midpoint and the top of the head. This will be defined later as
%the long axis of the head.
```

```
ShldrDist = mean(LShldr1(1:100,:) - RShldr1(1:100,:),1);
ShldrMid = mean(RShldr1(1:100,:),1) + ShldrDist/2;
k = mean(Head1(1:100,:)) - ShldrMid;
k = k./sqrt(k(1)^2+k(2)^2+k(3)^2);

%STEP 2: Define a localizing coordiante system using head markers during
T-pose. This is a
%non-anatomical CS used only for transforming the head axis defined above

ihead_loc_init = mean(Head2(1:100,:)) - mean(Head1(1:100,:));
vtemp = mean(Head3(1:100,:)) - mean(Head1(1:100,:));
khead_loc_init = cross(vtemp,ihead_loc_init);
jhead_loc_init = cross(khead_loc_init,ihead_loc_init);
ihead_loc_init =
ihead_loc_init./sqrt(ihead_loc_init(1)^2+ihead_loc_init(2)^2+ihead_loc_ini
t(3)^2);
jhead_loc_init =
jhead_loc_init./sqrt(jhead_loc_init(1)^2+jhead_loc_init(2)^2+jhead_loc_ini
t(3)^2);
khead_loc_init =
khead_loc_init./sqrt(khead_loc_init(1)^2+khead_loc_init(2)^2+khead_loc_ini
t(3)^2);

%STEP 3: Transform head axis defined in STEP 1 from global coordinates
into
%localizing coordinates as defined in STEP 2

Thead_loc_init = [ihead_loc_init;jhead_loc_init;khead_loc_init];
kheadL = Thead_loc_init*k';

%STEP 4: Define localizing head coordinate system for entire trial (same
%process as in STEP 2, except now for the whole trial duration

ihead_loc = Head2 - Head1;
vtemp = Head3 - Head1;
khead_loc = cross(vtemp,ihead_loc);
jhead_loc = cross(khead_loc,ihead_loc);
ihead_loc =
[ihead_loc(:,1)./sqrt(ihead_loc(:,1).^2+ihead_loc(:,2).^2+ihead_loc(:,3).^
2)
ihead_loc(:,2)./sqrt(ihead_loc(:,1).^2+ihead_loc(:,2).^2+ihead_loc(:,3).^2
)
ihead_loc(:,3)./sqrt(ihead_loc(:,1).^2+ihead_loc(:,2).^2+ihead_loc(:,3).^2
)];
jhead_loc =
[jhead_loc(:,1)./sqrt(jhead_loc(:,1).^2+jhead_loc(:,2).^2+jhead_loc(:,3).^
2)
jhead_loc(:,2)./sqrt(jhead_loc(:,1).^2+jhead_loc(:,2).^2+jhead_loc(:,3).^2
)
jhead_loc(:,3)./sqrt(jhead_loc(:,1).^2+jhead_loc(:,2).^2+jhead_loc(:,3).^2
)];
khead_loc =
[khead_loc(:,1)./sqrt(khead_loc(:,1).^2+khead_loc(:,2).^2+khead_loc(:,3).^
2)
```

```
khead_loc(:,2)./sqrt(khead_loc(:,1).^2+khead_loc(:,2).^2+khead_loc(:,3).^2
)
khead_loc(:,3)./sqrt(khead_loc(:,1).^2+khead_loc(:,2).^2+khead_loc(:,3).^2
)];

%STEP 5: Define local coordinate system for shoulders:
%Origin = Shoulder midpoint
%+i = lateral right
%+j = anterior
%+k = superior


ShldrMid = LShldr1 + (RShldr1 - LShldr1)./2;
jbody = Chest2 - Chest1;
ibody_temp = RShldr1 - LShldr1;
kbody = cross(ibody_temp,jbody);
ibody = cross(jbody,kbody);
ibody = [ibody(:,1)./sqrt(ibody(:,1).^2+ibody(:,2).^2+ibody(:,3).^2)
ibody(:,2)./sqrt(ibody(:,1).^2+ibody(:,2).^2+ibody(:,3).^2)
ibody(:,3)./sqrt(ibody(:,1).^2+ibody(:,2).^2+ibody(:,3).^2)];
jbody = [jbody(:,1)./sqrt(jbody(:,1).^2+jbody(:,2).^2+jbody(:,3).^2)
jbody(:,2)./sqrt(jbody(:,1).^2+jbody(:,2).^2+jbody(:,3).^2)
jbody(:,3)./sqrt(jbody(:,1).^2+jbody(:,2).^2+jbody(:,3).^2)];
kbody = [kbody(:,1)./sqrt(kbody(:,1).^2+kbody(:,2).^2+kbody(:,3).^2)
kbody(:,2)./sqrt(kbody(:,1).^2+kbody(:,2).^2+kbody(:,3).^2)
kbody(:,3)./sqrt(kbody(:,1).^2+kbody(:,2).^2+kbody(:,3).^2)];


%STEP 6: Define mannequin local coordinate system:
%+i = lateral right (relative to mannequin)
%+j = anterior
%+k = superior

kM = Forehead - Sternum;
iM_temp = ShldrR - ShldrL;
jM = cross(kM,iM_temp);
iM = cross(jM,kM);
iM = [iM(:,1)./sqrt(iM(:,1).^2+iM(:,2).^2+iM(:,3).^2)
iM(:,2)./sqrt(iM(:,1).^2+iM(:,2).^2+iM(:,3).^2)
iM(:,3)./sqrt(iM(:,1).^2+iM(:,2).^2+iM(:,3).^2)];
jM = [jM(:,1)./sqrt(jM(:,1).^2+jM(:,2).^2+jM(:,3).^2)
jM(:,2)./sqrt(jM(:,1).^2+jM(:,2).^2+jM(:,3).^2)
jM(:,3)./sqrt(jM(:,1).^2+jM(:,2).^2+jM(:,3).^2)];
kM = [kM(:,1)./sqrt(kM(:,1).^2+kM(:,2).^2+kM(:,3).^2)
kM(:,2)./sqrt(kM(:,1).^2+kM(:,2).^2+kM(:,3).^2)
kM(:,3)./sqrt(kM(:,1).^2+kM(:,2).^2+kM(:,3).^2)];

%STEP 7: Transform head long axis from localizing coordinate system (from
%STEP 2) back into global coordinates

for i = 1:length(LShldr1)
    Thead_loc = [ihead_loc(i,:);jhead_loc(i,:);khead_loc(i,:)];
    kHead = Thead_loc'*kheadL;
```

```
%STEP 8: Use head global long axis and head markers to define remaining
axes of anatomical head coordinate system


    jHead = Head2(i,:) - Head1(i,:);
    iHead = cross(jHead,kHead);
    jHead = cross(kHead,iHead);
    iHead = iHead./sqrt(iHead(1)^2+iHead(2)^2+iHead(3)^2);
    jHead = jHead./sqrt(jHead(1)^2+jHead(2)^2+jHead(3)^2);

    iHeadOut(i,:) = iHead;
    jHeadOut(i,:) = jHead;
    kHeadOut(i,:) = kHead;


%STEP 9: Define 3x3 coordinate system matrices for shoulders, head, and
%mannequin head; use these to define rotational transformation matrices
%linking subject head and shoulders (RSub); and subject and mannequin
heads
%(RMan)
    Tbody = [ibody(i,:);jbody(i,:);kbody(i,:)];
    TheadSub = [iHead;jHead;kHead'];
    TheadMan = [iM(i,:);jM(i,:);kM(i,:)];
    RSub = TheadSub*Tbody';
    RMan = TheadSub*TheadMan';

%STEP 10:

%STEP 10: Extract head angles from rotation matrices (alpha =
%head flexion/extension; beta = lateral flexion; gamma = rotation)

    betaHead(i) = asind(RSub(3,1));
    gammaHead(i) = -asind(RSub(2,1)/cosd(betaHead(i)));
    alphaHead(i) = asind(RSub(3,2)/-cosd(betaHead(i)));

    betaView(i) = asind(RMan(3,1));
    gammaView(i) = -asind(RMan(2,1)/cosd(betaView(i)));
    alphaView(i) = asind(-RMan(3,2)/cosd(betaView(i)));

end

%STEP 11: Subtract initial mean off of angles so they start at zero;
package into
%'angles' variable for export

headangles = [alphaHead(:) betaHead(:) gammaHead(:)];

viewangles = [alphaView(:) betaView(:) gammaView(:)];

end

function [kneeL,kneeR] =
kneeangle(Hip1,Hip2,LThigh1,LThigh2,RThigh1,RThigh2,LShin1,LShin2,RShin1,R
Shin2)
```

```
%STEP 1: Define medial-lateral axis vectors, for thighs and legs, averaged
during
%T-pose

iLThigh_global_init = mean(Hip1(1:100,:)) - mean(Hip2(1:100,:));
iLThigh_global_init =
iLThigh_global_init/(sqrt(iLThigh_global_init(1)^2+iLThigh_global_init(2)^
2+iLThigh_global_init(3)^2));

iRThigh_global_init = mean(Hip2(1:100,:)) - mean(Hip1(1:100,:));
iRThigh_global_init =
iRThigh_global_init/(sqrt(iRThigh_global_init(1)^2+iRThigh_global_init(2)^
2+iRThigh_global_init(3)^2));

iLLeg_global_init = mean(LThigh2(1:100,:)) - mean(RThigh2(1:100,:));
iLLeg_global_init =
iLLeg_global_init/sqrt(iLLeg_global_init(1)^2+iLLeg_global_init(2)^2+iLLeg
_global_init(3)^2);

iRLeg_global_init = mean(RThigh2(1:100,:)) - mean(LThigh2(1:100,:));
iRLeg_global_init =
iRLeg_global_init/sqrt(iRLeg_global_init(1)^2+iRLeg_global_init(2)^2+iRLeg
_global_init(3)^2);


%STEP 2: Define localizing coordinate systems, for thighs and legs, that
will be
%used to find fixed orientation of ML axis vectors from STEP 1

ktempLThigh_global_init = mean(Hip1(1:100,:)) - mean(LThigh1(1:100,:));
vtemp = mean(LThigh2(1:100,:)) - mean(LThigh1(1:100,:));
itempLThigh_global_init = cross(vtemp,ktempLThigh_global_init);
jtempLThigh_global_init =
cross(ktempLThigh_global_init,itempLThigh_global_init);
itempLThigh_global_init =
itempLThigh_global_init/sqrt(itempLThigh_global_init(1)^2+itempLThigh_glob
al_init(2)^2+itempLThigh_global_init(3)^2);
jtempLThigh_global_init =
jtempLThigh_global_init/sqrt(jtempLThigh_global_init(1)^2+jtempLThigh_glob
al_init(2)^2+jtempLThigh_global_init(3)^2);
ktempLThigh_global_init =
ktempLThigh_global_init/sqrt(ktempLThigh_global_init(1)^2+ktempLThigh_glob
al_init(2)^2+ktempLThigh_global_init(3)^2);

ktempRThigh_global_init = mean(Hip2(1:100,:)) - mean(RThigh1(1:100,:));
vtemp = mean(RThigh2(1:100,:)) - mean(RThigh1(1:100,:));
itempRThigh_global_init = cross(vtemp,ktempRThigh_global_init);
jtempRThigh_global_init =
cross(ktempRThigh_global_init,itempRThigh_global_init);
itempRThigh_global_init =
itempRThigh_global_init/sqrt(itempRThigh_global_init(1)^2+itempRThigh_glob
al_init(2)^2+itempRThigh_global_init(3)^2);
```

```
jtempRThigh_global_init =
jtempRThigh_global_init/sqrt(jtempRThigh_global_init(1)^2+jtempRThigh_glob
al_init(2)^2+jtempRThigh_global_init(3)^2);
ktempRThigh_global_init =
ktempRThigh_global_init/sqrt(ktempRThigh_global_init(1)^2+ktempRThigh_glob
al_init(2)^2+ktempRThigh_global_init(3)^2);

ktempLLeg_global_init = mean(LThigh2(1:100,:)) - mean(LShin2(1:100,:));
vtemp = mean(LShin1(1:100,:)) - mean(LShin2(1:100,:));
itempLLeg_global_init = cross(vtemp,ktempLLeg_global_init);
jtempLLeg_global_init =
cross(ktempLLeg_global_init,itempLLeg_global_init);
itempLLeg_global_init =
itempLLeg_global_init/sqrt(itempLLeg_global_init(1)^2+itempLLeg_global_ini
t(2)^2+itempLLeg_global_init(3)^2);
jtempLLeg_global_init =
jtempLLeg_global_init/sqrt(jtempLLeg_global_init(1)^2+jtempLLeg_global_ini
t(2)^2+jtempLLeg_global_init(3)^2);
ktempLLeg_global_init =
ktempLLeg_global_init/sqrt(ktempLLeg_global_init(1)^2+ktempLLeg_global_ini
t(2)^2+ktempLLeg_global_init(3)^2);

ktempRLeg_global_init = mean(RThigh2(1:100,:)) - mean(RShin2(1:100,:));
vtemp = mean(RShin1(1:100,:)) - mean(RShin2(1:100,:));
itempRLeg_global_init = cross(vtemp,ktempRLeg_global_init);
jtempRLeg_global_init =
cross(ktempRLeg_global_init,itempRLeg_global_init);
itempRLeg_global_init =
itempRLeg_global_init/sqrt(itempRLeg_global_init(1)^2+itempRLeg_global_ini
t(2)^2+itempRLeg_global_init(3)^2);
jtempRLeg_global_init =
jtempRLeg_global_init/sqrt(jtempRLeg_global_init(1)^2+jtempRLeg_global_ini
t(2)^2+jtempRLeg_global_init(3)^2);
ktempRLeg_global_init =
ktempRLeg_global_init/sqrt(ktempRLeg_global_init(1)^2+ktempRLeg_global_ini
t(2)^2+ktempRLeg_global_init(3)^2);

%STEP 3: Convert ML axis vectors from STEP 1 from global to local
%coordinate systems

TtempLThigh_global_init =
[itempLThigh_global_init;jtempLThigh_global_init;ktempLThigh_global_init];
iLThigh_local = TtempLThigh_global_init*iLThigh_global_init';

TtempRThigh_global_init =
[itempRThigh_global_init;jtempRThigh_global_init;ktempRThigh_global_init];
iRThigh_local = TtempRThigh_global_init*iRThigh_global_init';

TtempLLeg_global_init =
[itempLLeg_global_init;jtempLLeg_global_init;ktempLLeg_global_init];
iLLeg_local = TtempLLeg_global_init*iLLeg_global_init';

TtempRLeg_global_init =
[itempRLeg_global_init;jtempRLeg_global_init;ktempRLeg_global_init];
iRLeg_local = TtempRLeg_global_init*iRLeg_global_init';
```

```
%STEP 4: Define localizing coordinate systems, for thighs and legs, for
the
%duration of the trial; to be used to find moving orientation of ML axis
%from STEP 1 throughout the trial

ktempLThigh_global = Hip1 - LThigh1;
vtemp = LThigh2 - LThigh1;
itempLThigh_global = cross(vtemp,ktempLThigh_global);
jtempLThigh_global = cross(ktempLThigh_global,itempLThigh_global);
itempLThigh_global =
[itempLThigh_global(:,1)./sqrt(itempLThigh_global(:,1).^2+itempLThigh_glob
al(:,2).^2+itempLThigh_global(:,3).^2)
itempLThigh_global(:,2)./sqrt(itempLThigh_global(:,1).^2+itempLThigh_globa
l(:,2).^2+itempLThigh_global(:,3).^2)
itempLThigh_global(:,3)./sqrt(itempLThigh_global(:,1).^2+itempLThigh_globa
l(:,2).^2+itempLThigh_global(:,3).^2)];
jtempLThigh_global =
[jtempLThigh_global(:,1)./sqrt(jtempLThigh_global(:,1).^2+jtempLThigh_glob
al(:,2).^2+jtempLThigh_global(:,3).^2)
jtempLThigh_global(:,2)./sqrt(jtempLThigh_global(:,1).^2+jtempLThigh_globa
l(:,2).^2+jtempLThigh_global(:,3).^2)
jtempLThigh_global(:,3)./sqrt(jtempLThigh_global(:,1).^2+jtempLThigh_globa
l(:,2).^2+jtempLThigh_global(:,3).^2)];
ktempLThigh_global =
[ktempLThigh_global(:,1)./sqrt(ktempLThigh_global(:,1).^2+ktempLThigh_glob
al(:,2).^2+ktempLThigh_global(:,3).^2)
ktempLThigh_global(:,2)./sqrt(ktempLThigh_global(:,1).^2+ktempLThigh_globa
l(:,2).^2+ktempLThigh_global(:,3).^2)
ktempLThigh_global(:,3)./sqrt(ktempLThigh_global(:,1).^2+ktempLThigh_globa
l(:,2).^2+ktempLThigh_global(:,3).^2)];

ktempRThigh_global = Hip2 - RThigh1;
vtemp = RThigh2 - RThigh1;
itempRThigh_global = cross(vtemp,ktempRThigh_global);
jtempRThigh_global = cross(ktempRThigh_global,itempRThigh_global);
itempRThigh_global =
[itempRThigh_global(:,1)./sqrt(itempRThigh_global(:,1).^2+itempRThigh_glob
al(:,2).^2+itempRThigh_global(:,3).^2)
itempRThigh_global(:,2)./sqrt(itempRThigh_global(:,1).^2+itempRThigh_globa
l(:,2).^2+itempRThigh_global(:,3).^2)
itempRThigh_global(:,3)./sqrt(itempRThigh_global(:,1).^2+itempRThigh_globa
l(:,2).^2+itempRThigh_global(:,3).^2)];
jtempRThigh_global =
[jtempRThigh_global(:,1)./sqrt(jtempRThigh_global(:,1).^2+jtempRThigh_glob
al(:,2).^2+jtempRThigh_global(:,3).^2)
jtempRThigh_global(:,2)./sqrt(jtempRThigh_global(:,1).^2+jtempRThigh_globa
l(:,2).^2+jtempRThigh_global(:,3).^2)
jtempRThigh_global(:,3)./sqrt(jtempRThigh_global(:,1).^2+jtempRThigh_globa
l(:,2).^2+jtempRThigh_global(:,3).^2)];
ktempRThigh_global =
[ktempRThigh_global(:,1)./sqrt(ktempRThigh_global(:,1).^2+ktempRThigh_glob
al(:,2).^2+ktempRThigh_global(:,3).^2)
ktempRThigh_global(:,2)./sqrt(ktempRThigh_global(:,1).^2+ktempRThigh_globa
l(:,2).^2+ktempRThigh_global(:,3).^2)
```

```
ktempRThigh_global(:,3)./sqrt(ktempRThigh_global(:,1).^2+ktempRThigh_globa
l(:,2).^2+ktempRThigh_global(:,3).^2)];

ktempLLeg_global = LThigh2 - LShin2;
vtemp = LShin1 - LShin2;
itempLLeg_global = cross(vtemp,ktempLLeg_global);
jtempLLeg_global = cross(ktempLLeg_global,itempLLeg_global);
itempLLeg_global =
[itempLLeg_global(:,1)./sqrt(itempLLeg_global(:,1).^2+itempLLeg_global(:,2
).^2+itempLLeg_global(:,3).^2)
itempLLeg_global(:,2)./sqrt(itempLLeg_global(:,1).^2+itempLLeg_global(:,2)
.^2+itempLLeg_global(:,3).^2)
itempLLeg_global(:,3)./sqrt(itempLLeg_global(:,1).^2+itempLLeg_global(:,2)
.^2+itempLLeg_global(:,3).^2)];
jtempLLeg_global =
[jtempLLeg_global(:,1)./sqrt(jtempLLeg_global(:,1).^2+jtempLLeg_global(:,2
).^2+jtempLLeg_global(:,3).^2)
jtempLLeg_global(:,2)./sqrt(jtempLLeg_global(:,1).^2+jtempLLeg_global(:,2)
.^2+jtempLLeg_global(:,3).^2)
jtempLLeg_global(:,3)./sqrt(jtempLLeg_global(:,1).^2+jtempLLeg_global(:,2)
.^2+jtempLLeg_global(:,3).^2)];
ktempLLeg_global =
[ktempLLeg_global(:,1)./sqrt(ktempLLeg_global(:,1).^2+ktempLLeg_global(:,2
).^2+ktempLLeg_global(:,3).^2)
ktempLLeg_global(:,2)./sqrt(ktempLLeg_global(:,1).^2+ktempLLeg_global(:,2)
.^2+ktempLLeg_global(:,3).^2)
ktempLLeg_global(:,3)./sqrt(ktempLLeg_global(:,1).^2+ktempLLeg_global(:,2)
.^2+ktempLLeg_global(:,3).^2)];

ktempRLeg_global = RThigh2 - RShin2;
vtemp = RShin1 - RShin2;
itempRLeg_global = cross(vtemp,ktempRLeg_global);
jtempRLeg_global = cross(ktempRLeg_global,itempRLeg_global);
itempRLeg_global =
[itempRLeg_global(:,1)./sqrt(itempRLeg_global(:,1).^2+itempRLeg_global(:,2
).^2+itempRLeg_global(:,3).^2)
itempRLeg_global(:,2)./sqrt(itempRLeg_global(:,1).^2+itempRLeg_global(:,2)
.^2+itempRLeg_global(:,3).^2)
itempRLeg_global(:,3)./sqrt(itempRLeg_global(:,1).^2+itempRLeg_global(:,2)
.^2+itempRLeg_global(:,3).^2)];
jtempRLeg_global =
[jtempRLeg_global(:,1)./sqrt(jtempRLeg_global(:,1).^2+jtempRLeg_global(:,2
).^2+jtempRLeg_global(:,3).^2)
jtempRLeg_global(:,2)./sqrt(jtempRLeg_global(:,1).^2+jtempRLeg_global(:,2)
.^2+jtempRLeg_global(:,3).^2)
jtempRLeg_global(:,3)./sqrt(jtempRLeg_global(:,1).^2+jtempRLeg_global(:,2)
.^2+jtempRLeg_global(:,3).^2)];
ktempRLeg_global =
[ktempRLeg_global(:,1)./sqrt(ktempRLeg_global(:,1).^2+ktempRLeg_global(:,2
).^2+ktempRLeg_global(:,3).^2)
ktempRLeg_global(:,2)./sqrt(ktempRLeg_global(:,1).^2+ktempRLeg_global(:,2)
.^2+ktempRLeg_global(:,3).^2)
ktempRLeg_global(:,3)./sqrt(ktempRLeg_global(:,1).^2+ktempRLeg_global(:,2)
.^2+ktempRLeg_global(:,3).^2)];
```

```
%STEP 5: For each time step in the trial, convert ML axis (STEP 3) from
%local back to global coordinates; also define AP and axial axes for each
%segment

for i = 1:length(Hip1)
    TLThigh_global =
[itempLThigh_global(i,:);jtempLThigh_global(i,:);ktempLThigh_global(i,:)];
    iLThigh = TLThigh_global'*iLThigh_local;
    kLThigh = Hip1(i,:) - LThigh1(i,:);
    jLThigh = cross(kLThigh,iLThigh);
    iLThigh = cross(jLThigh,kLThigh);
    iLThigh = iLThigh./sqrt(iLThigh(1)^2+iLThigh(2)^2+iLThigh(3)^2);
    jLThigh = jLThigh./sqrt(jLThigh(1)^2+jLThigh(2)^2+jLThigh(3)^2);
    kLThigh = kLThigh./sqrt(kLThigh(1)^2+kLThigh(2)^2+kLThigh(3)^2);

    TRThigh_global =
[itempRThigh_global(i,:);jtempRThigh_global(i,:);ktempRThigh_global(i,:)];
    iRThigh = TRThigh_global'*iRThigh_local;
    kRThigh = Hip2(i,:) - RThigh1(i,:);
    jRThigh = cross(kRThigh,iRThigh);
    iRThigh = cross(jRThigh,kRThigh);
    iRThigh = iRThigh./sqrt(iRThigh(1)^2+iRThigh(2)^2+iRThigh(3)^2);
    jRThigh = jRThigh./sqrt(jRThigh(1)^2+jRThigh(2)^2+jRThigh(3)^2);
    kRThigh = kRThigh./sqrt(kRThigh(1)^2+kRThigh(2)^2+kRThigh(3)^2);

    TLLeg_global =
[itempLLeg_global(i,:);jtempLLeg_global(i,:);ktempLLeg_global(i,:)];
    iLLeg = TLLeg_global'*iLLeg_local;
    kLLeg = LThigh2(i,:) - LShin1(i,:);
    jLLeg = cross(kLLeg,iLLeg);
    iLLeg = cross(jLLeg,kLLeg);
    iLLeg = iLLeg./sqrt(iLLeg(1)^2+iLLeg(2)^2+iLLeg(3)^2);
    jLLeg = jLLeg./sqrt(jLLeg(1)^2+jLLeg(2)^2+jLLeg(3)^2);
    kLLeg = kLLeg./sqrt(kLLeg(1)^2+kLLeg(2)^2+kLLeg(3)^2);

    TRLeg_global =
[itempRLeg_global(i,:);jtempRLeg_global(i,:);ktempRLeg_global(i,:)];
    iRLeg = TRLeg_global'*iRLeg_local;
    kRLeg = RThigh2(i,:) - RShin1(i,:);
    jRLeg = cross(kRLeg,iRLeg);
    iRLeg = cross(jRLeg,kRLeg);
    iRLeg = iRLeg./sqrt(iRLeg(1)^2+iRLeg(2)^2+iRLeg(3)^2);
    jRLeg = jRLeg./sqrt(jRLeg(1)^2+jRLeg(2)^2+jRLeg(3)^2);
    kRLeg = kRLeg./sqrt(kRLeg(1)^2+kRLeg(2)^2+kRLeg(3)^2);

    %STEP 6: Define rotational transformation matrices between thighs and
    %legs

    RL = TLLeg_global*TLThigh_global';
    RR = TRLeg_global*TRThigh_global';

    %STEP 7: extract knee angles from rotational transformation matrices

    betaL(i) = asind(RL(3,1));
    gammaL(i) = asind(-RL(2,1)/cosd(betaL(i)));
```

```
    alphaL(i) = asind(-RL(3,2)/cosd(betaL(i)));

    betaR(i) = asind(RR(3,1));
    gammaR(i) = asind(-RR(2,1)/cosd(betaR(i)));
    alphaR(i) = asind(-RR(3,2)/cosd(betaR(i)));

end

%STEP 8: subtract means and package for export

alphaL = alphaL(:) - mean(alphaL(1:100));
betaL = betaL(:) - mean(betaL(1:100));
gammaL = gammaL(:) - mean(gammaL(1:100));

alphaR = alphaR(:) - mean(alphaR(1:100));
betaR = betaR(:) - mean(betaR(1:100));
gammaR = gammaR(:) - mean(gammaR(1:100));

kneeL = [alphaL betaL gammaL];
kneeR = [alphaR betaR gammaR];

end
```

APPENDIX D

Study Forms and Documents

Study Recruitment Flyer

Subject Consent Form

UMKC IRB # 14-469

Consent for Participation in a Research Study

Analysis of Human Performance in a Clinical Simulation Setting

Mark A. Hoffman, Ph.D., Gregory W. King, Ph.D.

Request to Participate

You are being asked to take part in a research study. This study is being conducted at the Clinical Training Facility (CTF) within UMKC's School of Medicine.

The primary investigator of this study is Dr. Mark Hoffman, Associate Professor in the UMKC School of Medicine. While he will run the study, other qualified research personnel on the study may act on his behalf. This study is sponsored by a grant from the University of Missouri System IDIC Program.

The study team is asking you to take part in this research study because you routinely perform (or are likely to routinely perform in the future) the clinical procedures simulated in the CTF as part of your regular clinical practice or curriculum. Research studies only include people who choose to take part. This document is called a consent form. Please read this consent form carefully and take your time making your decision. The researcher or study staff will go over this consent form with you. Ask him/her to explain anything that you do not understand. Think about it and talk it over with your family and friends before you decide if you want to take part in this research study. This consent form explains what to expect: the risks, discomforts, and benefits, if any, if you consent to be in the study.

Background

You will be one of about 40 subjects in the study at the CTF. You are being asked to participate because you routinely perform (or are likely to routinely perform in the future) the clinical procedures simulated in the CTF as part of your regular clinical practice or curriculum. The investigators will use the data gathered in this study to better understand the movements used during the procedures and improve the way the clinical procedures are taught and practiced.

Purpose

The purpose of this study is to evaluate performance of simulated clinical procedures among groups with various levels of experience. The tasks used in this study (including endotracheal intubation, central line placement, and laparoscopic training procedures) have significantly high first-attempt failure rates when performed on living patients. Learning these procedures in simulated environments using high-fidelity mannequins has the potential to reduce failure rates in living patients. This study will use sensors to measure performance of subjects conducting these procedures in a simulated setting, which may be used to improve the way students learn.

UMKC IRB
Approved
from: 02/05/2015 to: 02/04/2016
IRB #:14-469 Version: 01/28/2015

Procedures

If you choose to participate, you will complete up to three different simulated clinical procedures in the CTF, performed during a single or multiple visits. Before beginning the simulation session, you will complete a questionnaire related to the procedure(s) for that session. Performing multiple procedures in a single visit will reduce the total time required. Activities occurring during each simulation are described as follows:

Intubation Simulation (approximately 60 minutes)

- Fill out questionnaire including questions about skill level, level of comfort, current program/specialty and basic knowledge about intubation procedure
- Put on a full-body motion capture suit and attach reflective markers with the assistance of the research team
- Perform simulated endotracheal intubation procedure on a medical mannequin: inserting a laryngoscope into the mannequin's mouth to open and secure the airway, and then inserting a flexible tube into the trachea to ventilate the mannequin

Central Line Simulation (approximately 60 minutes)

- Fill out questionnaire including questions about skill level, level of comfort, current program/specialty and basic knowledge about central line placement procedure
- Put on a full-body motion capture suit and attach reflective markers with the assistance of the research team
- Perform simulated central venous catheter procedure on a medical mannequin: identifying and visualizing the mannequin's internal jugular vein and confirming correct placement of the catheter

Laparoscopy simulation (approximately 60 minutes)

- Fill out questionnaire including questions about skill level, level of comfort, current program/specialty and basic knowledge about laparoscopic procedures
- Put on a full-body motion capture suit and attach reflective markers with the assistance of the research team
- Perform a training exercise using a Fundamentals of Laparoscopic Surgery Trainer Box: manipulating two graspers to perform tasks (such as transferring objects, precision cutting, and suturing) inside an enclosed box via video visualization

The experimental portions of this study include the simulated intubation, catheter placement, and laparoscopic training procedures described above. Each of these will be videotaped, which is required in order to provide a qualitative assessment of your performance. Only the investigators authorized to work on this study will view the video. Video will be stored on a computer for no more than five years.

If you agree to take part in this study, you will be involved in this study only for the amount of time needed to complete up to three simulations as described above (a total of up to 3 hours). No follow-up information will be collected. Your participation in this study is voluntary, and you may choose to withdraw from the study at any time, for any reason.

Risks and Inconveniences

There are no known risks associated with the motion capture suit or markers. There is a possibility of a clean needle stick injury during the Simulated Central Line Placement. However, this risk is not expected to be more than what you would experience in your clinical practice or curriculum.

There is a possible loss of privacy or breach of confidentiality. If you perform poorly on any of the study tasks, a breach of confidentiality could be damaging to your reputation among peers, instructors, or supervisors. We will take measures to reduce this risk, such as assigning an anonymous number to your data that is collected for the study.

Benefits

You will receive either a video DVD or an emailed link to download a video file (based on your preference) depicting 3D renderings of your movements for each of the sessions you participate in. Additionally, the data you provide will help the investigators to better understand movement patterns during the procedures studied, which are likely to help improve the way students learn these procedures in the future.

Fees and Expenses

There are no fees or expenses for any of the tests performed during this study.

Compensation

There is no payment for taking part in this study, but you will be provided with the opportunity to receive the video output from you session.

Alternatives to Study Participation

The alternative is not to take part in the study.

Confidentiality

While we will do our best to keep the information you share with us confidential, it cannot be absolutely guaranteed. Individuals from the University of Missouri-Kansas City Institutional Review Board (a committee that reviews and approves research studies), Research Protections Program, and Federal regulatory agencies may look at records related to this study to make sure we are doing proper, safe research and protecting human subjects. The results of this research may be published or presented to others. You will not be named or otherwise identified in any reports of the results.

Identifiable, video, animated (de-identified videos) or still images captured during testing will not be published or shared without your permission. Rendering a motion capture session as an animation can mask many identifiable attributes but does not guarantee de-identification. Please choose whether you approve the use of each category of information resulting from your participation:.

Please select among the following options:

- ☐ I agree that video in which my identity is visible may be utilized in presentations and publications.
- ☐ I agree that video in which my participation has been rendered as an animation may be utilized in presentations and publications.
- ☐ I agree that still images in which my identity is visible may be utilized in presentations and publications.
- ☐ I agree that still images resulting from motion capture animations may be utilized in presentations and publications.

Or choose this option:

- ☐ I do not want any visuals resulting from my participation to be included in presentations or publications.

If you leave the study or are removed from the study, the study data collected before you left may still be used along with other data collected as part of the study. For purposes of follow-up studies and if any unexpected events happen, subject identification will be filed at UMKC's Center for Health Insights under appropriate security and with access limited to research personnel only. Security measures include controlled physical access to the data center used to host the information and data security measures used to protect the system from intrusion or malware.

In Case of Injury

The University of Missouri-Kansas City appreciates people who help it gain knowledge by being in research studies. It is not the University's policy to pay for or provide medical treatment for persons who are in studies. If you think you have been harmed because you were in this study, please seek appropriate medical attention. Then call PI at 816-235-6068.

Contacts for Questions about the Study

You should contact the Office of UMKC's Institutional Review Board at 816-235-5927 if you have any questions, concerns or complaints about your rights as a research subject. You may call the researcher, Dr. Hoffman, at 816-235-6068 if you have any questions about this study. You may also call him if any problems arise.

Voluntary Participation

Taking part in this research study is voluntary. If you choose to be in the study, you are free to stop participating at any time and for any reason. If you choose not to be in the study or decide to stop participating, your decision will not affect any care or benefits you are entitled to (nor will it affect any aspect of your education, if you are a student). The researchers, doctors or sponsors may stop the study or take you out of the study at any time if they decide that it is in your best interest to do so. They may do this for medical or administrative reasons or if you no longer meet the study criteria.

You have read this Consent Form or it has been read to you. You have been told why this research is being done and what will happen if you take part in the study, including the risks and benefits. You have had the chance to ask questions, and you may ask questions at any time in the future by calling Dr. Hoffman at 816-235-6068. By signing this consent form, you volunteer and consent to take part in this research study. Study staff will give you a copy of this consent form.

_________________________________ __________________

Signature (Volunteer Subject) **Date**

____

Printed Name (Volunteer Subject)

_______________________________ __________________

Signature of Person Obtaining Consent **Date**

____

Printed Name of Person Obtaining Consent

Subject Questionnaire

Questionnaire

Please select among the following options:

- ☐ I agree that video in which my identity is visible may be utilized in presentations and publications.
- ☐ I agree that video in which my participation has been rendered as an animation may be utilized in presentations and publications.
- ☐ I agree that still images in which my identity is visible may be utilized in presentations and publications.
- ☐ I agree that still images resulting from motion capture animations may be utilized in presentations and publications.OR, Choose this option:
- ☐ I do not want any visuals resulting from my participation to be included in presentations or publications.

ERROR

You have indicated that you DO consent to visuals resulting from your participation to be included in presentations and publications. However, you also indicated above that you DO NOT agree to the use of such visuals in presentations or publications.

These are conflicting indications. Please correct this before continuing with the questionnaire.

If you have any questions about this agreement or the potential use of visuals in presentations/publications, please speak with the Research Assistant accompanying you today.

Please answer the questions below to the best of your ability, as thoroughly and honestly as possible. Additional questions may appear depending on the responses that you provide to previous questions. Your responses will remain confidential. Refer to your Consent Form for more information on participant confidentiality as it pertains to this study.

Thank you for your participation in this study.

Please type the number that the Research Assistant has given you. If the Research Assistant has not yet assigned you a number, please ask him or her for your randomized number. This is to ensure your confidentiality as a study participant. ____________________

Height (in total inches): Tip: 4 ft = 48 inches 5 ft = 60 inches 6 ft = 72 inches ____________________ (inches)

Handedness:

- ○ Right-handed
- ○ Left-handed

Age: ____________________

Gender:

- ○ Male
- ○ Female
- ○ Other
- ○ Prefer not to respond

Procedure being performed today:	☐ Central line placement ☐ Endotracheal intubation ☐ Laparoscopic procedure (FLS Trainer Box)
Please indicate the approximate number of times you have performed Central Line Placement in the past	__________________
Please indicate the approximate number of times you have performed Endotracheal Intubation in the past	__________________
Please indicate the approximate number of times you have performed Laparoscopic procedures in the past	__________________
Please identify your status:	☐ Medical student ☐ EMS student ☐ Medical resident ☐ Fellow ☐ Physician ☐ Instructor ☐ Nurse ☐ EMT ☐ Paramedic ☐ Physician Assistant program student ☐ Master's in Anesthesiology student ☐ Other
Please specify "Other":	__________________
Are you in the 4-year program or the 6-year program?	◯ 4-year program ◯ 6-year program ◯ Other
Please specify "Other"	__________________
How far are you in the 4-year program?	◯ Year 1 ◯ Year 2 ◯ Year 3 ◯ Year 4
How far are you in the 6-year program?	◯ Year 1 ◯ Year 2 ◯ Year 3 ◯ Year 4 ◯ Year 5 ◯ Year 6
Which year of your medical residency are you in?	◯ 1st year ◯ 2nd year ◯ 3rd year ◯ 4th year ◯ Beyond 4th year
In your medical residency, what is your specialty?	__________________
How many years of experience have you had as a physician?	__________________ (years)
What is your specialty as a physician?	__________________
What field(s) or specialty(ies) do you instruct?	__________________
How many years of experience have you had as a nurse?	__________________ (years)
What is your specialty as a nurse?	__________________
How many years of experience have you had as an EMT?	__________________ (years)

How many years of experience have you had as a paramedic? ______________ (years)

Use the scale provided below to assess your own ability level in INSERTING CENTRAL LINES. Please mark the appropriate rating for each component as well as an overall performance rating.

0: I am completely unfamiliar

1: I perform at the level of a beginner

2: I have some familiarity but lack proper technique

3: I initiate and perform independently, but make some errors

4: I execute independently, smoothly, with total confidence, and without error

	0Completely unfamiliar	1Beginner level	2Some familiarity, lack proper technique	3Initiate & perform independently, some errors	4Execute independently & with confidence, without error
Image (ultrasound)	○	○	○	○	○
Cannulate	○	○	○	○	○
Pass guidewire	○	○	○	○	○
Remove needle	○	○	○	○	○
Insert and dilate catheter	○	○	○	○	○
Remove dilator	○	○	○	○	○
Place central line over guidewire to insert	○	○	○	○	○
Aspirate blood and flush	○	○	○	○	○
OVERALL PERFORMANCE	○	○	○	○	○

Use the scale provided below to assess your own ability level in PERFORMING ENDOTRACHEAL INTUBATION. Please mark the appropriate rating for each component as well as an overall performance rating.

0: I am completely unfamiliar
1: I perform at the level of a beginner
2: I have some familiarity but lack proper technique
3: I initiate and perform independently, but make some errors
4: I execute independently, smoothly, with total confidence, and without error

	0Completely unfamiliar	1Beginner level	2Some familiarity, lack proper technique	3Initiate & perform independently, some errors	4Execute independently & with confidence, without error
Adjust patient position (tilt head slowly)	○	○	○	○	○
Insert laryngoscope blade and displace tongue	○	○	○	○	○
Elevate mandible with laryngoscope	○	○	○	○	○
Visualize vocal cords	○	○	○	○	○
Insert ET tube (and stylet, if applicable) into the oral cavity and ensure insertion to proper depth (1 cm) beyond vocal cords	○	○	○	○	○
Remove stylet slowly (if stylet is being used) while maintaining control of the ET tube	○	○	○	○	○
Inflate cuff to proper pressure and immediately remove syringe	○	○	○	○	○
Ventilate patient and watch for rise and fall of chest	○	○	○	○	○
OVERALL PERFORMANCE	○	○	○	○	○

Use the scale provided below to assess your own ability level in LAPAROSCOPIC TRAINER BOX PROCEDURES using a Fundamentals of Laparoscopic Surgery (FLS) Trainer box. Please mark the appropriate rating for each component as well as an overall performance rating.

0: I am completely unfamiliar
1: I perform at the level of a beginner
2: I have some familiarity but lack proper technique
3: I initiate and perform independently, but make some errors
4: I execute independently, smoothly, with total confidence, and without error

	0Completely unfamiliar	1Beginner level	2Some familiarity, lack proper technique	3Initiate & perform independently, some errors	4Execute independently & with confidence, without error
Handling Maryland Dissectors	○	○	○	○	○
Handling endoscissors	○	○	○	○	○
Handling graspers (locking handle)	○	○	○	○	○
Handling laparoscopic needle drivers	○	○	○	○	○
Handling knot pusher (open & closed)	○	○	○	○	○
Performing transferring tasks	○	○	○	○	○
Performing precision cutting tasks	○	○	○	○	○
Performing placement and securing of litigating loop	○	○	○	○	○
Performing simple suture with intracorporeal knot	○	○	○	○	○
Performing simple suture with extracorporeal knot	○	○	○	○	○
OVERALL PERFORMANCE	○	○	○	○	○

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VITA

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