Title
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Publication Date
2018
Modernizing Surgical Education: Motion Tracking of Hand Movements During Surgical Knot Tying

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**Background:**

Surgical training has traditionally been based on an apprenticeship model whereby a resident trainee will acquire surgical competencies through accumulated experience and long hours spent observing a more experienced supervising surgeon in the operating room. However, this method has been criticized for being too subjective, too costly in human resources, time-consuming, and not accurately representing technical skill. Of note, a study showed that only 34% of surgical trainees report feeling they have sufficient training in basic surgical skills. As a result, there has been significant interest in developing cost-effective methods of objectively assessing technical skill in surgery, both for the purposes of credentialing and for formative feedback.

The development of an effective means of evaluating surgical skill is an ongoing challenge. Current evaluation methods include human grading systems and outcomes-based metrics. Human grading systems arose as an extension of the traditional apprenticeship model, whereby a senior surgeon will watch a trainee surgeon perform a surgical procedure and then grade them with a global rating checklist. However, this technique has also received criticism for inherent subjectivity with human observers and high costs in human resources. Outcomes-based metrics rely on the assumption that outcomes rely singularly on technical skill. However, outcomes often strongly depend on the difficulty of the procedure, as well as a host of other factors including patient characteristics. The current literature thus raises concerns about the sustainability of current evaluation methods and points toward a need for more objective and automated means of assessing surgical skill.

The need for more efficient assessment and training paradigms has led to great interest in developing methods to quantify surgical dexterity. Human motion analysis has found use in other fields such as gait analysis and sports, and it has shown promise as a tool for objective surgical skill assessment. Methods in motion analysis typically make use of sensors or markers placed on a body articulation to allow for measurement of motion information. Analyzing digital representations of motion data collected from such motion sensor systems may then offer a more objective, quantifiable, and less costly method of assessing surgical skill than structured human grading scales.

A comprehensive literature review by van Hove et al. in 2010 identified 19 studies addressing motion analysis in either laparoscopic or open surgery. Nine of these studies validated the use of the Imperial College Surgical Assessment Device (ICSAD) - an electromagnetic positional tracking system that could provide information on trajectory, total task time, and number of movements to complete a task. Three studies explored the use of the ADEPT system, a specially fitted box trainer that could provide information on instrument error, execution time, and task completion. Five studies investigated validity of the ProMIS, a hybrid simulator, involving a virtual interface placed over a specially fitted box trainer with cameras allowing for motion tracking of laparoscopic instruments. Other devices studied included the Hiroshima University Endoscopic Surgical Assessment Device (HUESAD) and the TrEndo Tracking System.

The devices in these studies have not found widespread use due to involving high-cost electromagnetic tracking systems or specially fitted box trainers that would be difficult to implement in a real operating room setting. In addition, they measured simple economy of motion metrics such as total path length, total task time, mean values of acceleration and velocity, and number of movements made. While such metrics are...
objective indicators that can be used to evaluate surgical dexterity, they do not provide direct feedback on the quality of a surgeon’s hand movement and are not sufficient in and of themselves to fully assess technical skills.\textsuperscript{22,23}

On a parallel front, the advances in Microelectromechanical Sensors (MEMS) have spurred the production of reliable and affordable gyroscopes and accelerometers in commercial applications from smart phones to car navigation systems. Human motion analysis using this technology has also been used in fields such as gait analysis and sports. More recently, multiple studies have begun to investigate the use of this MEMS-based technology in surgical skill evaluation.\textsuperscript{22-25} We set out to expand on this growing body of work by developing an innovative, MEMS-based motion-sensing device that can capture an individual’s surgical motion data. The use of MEMS technology allows us to use low-cost, unobtrusive, commercially available components to build a device that can be broadly applied to both open and minimally invasive surgical paradigms. In addition, we will use our own proprietary Matlab software, which will analyze various metrics beyond economy of motion, to better characterize an individual’s surgical motion profile.

As stated before, there is a strong need for developing a more objective, cost-effective, standardized method of surgical skill assessment. As one might expect, there is evidence that technical skill can have an impact on clinical outcomes for patients. Thus, more effective means of surgical education and evaluation can have a large impact on patient care. The primary goal of this current project will be the development of a low-cost system that can objectively and reliably distinguish hand motion data between individuals of varying levels of surgical expertise. To validate the device, we designed an experiment to test if the device can distinguish what is the level of expertise of a subject performing open surgical knot tying.

Methods:

Equipment

We recorded hand motion data using an inexpensive custom-built tracking device worn on a surgeon’s forearm. We built the device using inexpensive, commercially available electronic components. The primary electronic components of the device included a sensor and a microcontroller board. The sensor was composed of a 9 degree-of-freedom (DOF) inertial measuring unit (IMU) that adhered to the dorsal surface of the surgeon’s hand along the 3rd metacarpal bone and measured movement using a combination of triaxial accelerometers and gyroscopes.

Using our own circuit design, the IMU sensor was connected to and controlled by a programmable circuit board (Arduino Uno – R3), which sat on the dorsal side of a surgeon’s forearm. This microcontroller board was contained in a rigid box that was attached to thin Velcro straps that allowed it to be worn like a wristwatch (Figure 1). The microcontroller board had 128kB of memory for storing software to convert input measurements from the IMU into output data to the computer. The sensitivity of the capturing system was 131 Least Significant Bit (LSB) per unit. This translated to a capture range of up to ±2000 degrees per second on the gyroscope and up to ±16g of acceleration on the accelerometer (InvenSense Document#PS-MPU-6000A-00). The entire device weighed approximately 50 grams. Then, using a USB connection from the Arduino circuit board to a nearby laptop, we ran our proprietary Matlab software and recorded hand motion data from the sensor while the study participant performed a preset task of tying a certain number of open surgical knots.

The entire cost of the individual device itself was less than $40, making it both cheap and accessible.
In order to capture surgical hand motion, we built our own device using off-the-shelf components. Our device was composed of a triple axis accelerometer and gyroscope (MPU-6050) controlled by a commercial programmable circuit board (Arduino Uno – R3). The sensitivity of the capturing system was 131 Least Significant Bits (LSB) per unit. This translated to a capture range of up to ±2000 degrees per second on the gyroscope and up to ±16g of acceleration on the accelerometer (InvenSense Document#PS-MPU-6000A-00). The device was enclosed in a rigid box and could be attached to a subject’s arm and hand through the use of a thin Velcro strap (figure 1). The entire device weighed approximately 50 grams. An USB cable connected the device to a computer where an originally developed Matlab™ code was used to perform data capture and analysis.

**Study participants and design**

This was a prospective study of volunteers performing surgical knot tying at an academic institution. Subjects included third year medical students on their general surgical rotation, general surgery interns, general surgery residents, and general surgery board-certified attending surgeons.

Each subject was asked to perform the task of single handed square knots. Specifically, they were asked to tie 10 square knots in a row without stopping on a silicone suture block using 2-0 silk sutures. They were asked to have their non-dominant hand hold one of the sutures on tension while tying the knot with their dominant hand. If the subject felt his or her standard knot tying technique was different from this method, they were excluded from the study.

The steps followed by each participant are described as follows:

1. The motion-sensing device was attached to the patient’s dominant hand and forearm.
2. The suture block with suture in place was placed in front of the subject.
3. The subject was allowed to adjust for height of suture block, position of their body, or suture length until they felt they could comfortably perform knot tying.
4. The subject rested both hands on the table.
5. The Matlab motion-capturing program was started by the research personnel on the laptop connected to the Arduino microcontroller board.
6. Subjects begins to tie 10 knots uninterrupted.
7. Subjects were instructed to voice out when a knot set was completed or if they made an error on a knot they are working on. This was recorded by the research personnel.
8. After 10 knots total (regardless of error or not), the program was ended by the research personnel.
9. The device was removed from the subject and testing was deemed complete.

Once data capture was complete, it was organized using the logs written down during the experiment. This was done in 3 steps. First, the raw signals were divided into individual knots. Then, the first knot was discarded because it included motions from the setup of the knot. Finally, every knot that the subject admitted to making an error on was
Data analysis was done using Matlab™ running our own originally developed code. Discrete mathematical calculations were applied using existing Matlab™ library functions to calculate motion variables including linear acceleration, linear jerk (derivative of acceleration), angular acceleration, angular velocity, and total angular displacement traveled. The values from the three orthogonal axes (either linear acceleration or angular velocity) were combined through vector addition to reconstruct the original motion vector. The magnitude of this original motion vector was then measured.

A representative image of the raw data captured during knot tying can be seen in Figure 2. From this plot, discrete numerical integration and differentiation was performed to the data. Then the true vectors of motion were constructed from their orthogonal components. The magnitude of this was measured as the motion variables discussed prior. The calculated variables for subjects of the same mastery level (either medical student, intern, resident, or attending) were averaged and any distinguishing features were identified. Statistical testing using two-tailed T-test was applied.

Results:

Nineteen subjects were recruited for this study. This included 6 general surgery attending surgeons, 4 general surgery residents (PGY 2-5), 5 surgery interns (PGY 1), and 4 third year medical students on the surgical rotation. A total of 133 knots were evaluated in this study. A total of 7 variables were identified to distinguish levels of mastery in knot tying (Table 1).

The first variable identified to distinguish level of training was the total time to complete a square knot. (Figure 3) Medical students and interns took a significantly longer time completing the knot compared to the attending surgeons (16.87±9.22 vs 7.17±1.98 seconds vs 4.65±1.25 respectively, p<0.01). Similarly, the medical students and interns also required more total turns of the hand to complete the knot compared to the attending surgeons (1772 ±899 degrees and 1107 ±311 degrees vs 972 ±262 degrees, p<0.01, p<0.042 respectively). (Figure 4)

Although there were no significant differences between the average linear jerk and angular acceleration among skill levels, the attending surgeons had a greater standard deviation in the range of linear jerk. (Figure 5) This value is obtained by taking the average of the standard deviation of either linear acceleration or of angular velocity for each subject. The medical students and interns once again demonstrated significantly narrower range of linear jerk compared to attending surgeons (7749 ±3207 and 8299 ±2604 mm/s^3 vs 12180 ±2686 mm/s, P<0.01 respectively). The same trend is seen in average angular acceleration standard deviation as well (1873 ±491 and 2432 ±527 degree/s^2 vs 3356 ±550 degree/s^2, P<0.01 respectively). (Figure 6)

Next, we looked at the ratio of time each subject spent in high rotational speed (>200 degrees/sec) or low rotational speed (<50 degrees/sec). The ratio of time in high rotational speed was calculated as the fraction of time spent in high speed versus not. The ratio of time in low rotational was calculated as the fraction of time spent in low speed state versus not. Attendings on averaged demonstrated less ratio of time spent
low rotational speed than medical students, interns, and residents (0.136 ± 0.075 vs 0.443 ± 0.222, 0.367 ± 0.187, 0.200 ± 0.114, all p<0.01). Similarly, attendings on average demonstrated more time spent in high rotation speed compared to medical students and interns (0.76±0.22 vs 0.18±0.08 and 0.33±0.18, both p<0.01). Figure 7 demonstrates the trend of these two ratios among training levels.

Finally, we examined angular acceleration. We used angular acceleration greater than 400 deg/sec^2 as a cutoff for highly active hand motion. A decreasing trend in angular acceleration can be seen with more novice subjects (Figure 7). This ratio significantly differentiated attendings from residents, interns, and medical students (5.50 ±2.26 deg/s^2 vs 4.12 ±1.13, 2.95 ±1.28, and 2.63 ±1.19, all p<0.01).

Discussion:

This was a prospective study to collect hand motion data during single-handed surgical knot tying using an originally developed motion sensing device at an academic institution. Volunteers of varying levels of mastery were evaluated. Dominant hand motion during single-handed knot tying was analyzed.

The hand motion analysis demonstrated several parameters that could distinguish levels of skill. Time of completion for a surgical task and economy has been shown in the past to be related to level of skill.¹ Our study population demonstrated similar trends with attendings completing each knot significantly faster than novice trainees as well as requiring fewer turns of the hand. Although these parameters could identify a true novice such as a medical student from an attending, they were unable to separate the attendings from the trained residents. Mastery of skill is more complex than just economy of motion and speed alone. More trained subjects also demonstrated a broader range of linear and rotational speeds compared to the novice participants. This shows that the hand motion of the attending was not only faster, but had a larger repertoire of movement speeds.

In-depth analysis of hand motion demonstrated that attendings had a greater proportion of time spent in higher rotational speed and a lesser proportion of time spent in lower rotational speeds. The ratio of low rotational speed was able to separate out the more skilled residents and the attendings. We believe that low rotational speed is a reflection of how much a subject spends in hesitation or non-motion. The less the hesitation, the more likely a subject has developed muscle memory from practice.

Finally, the rotational acceleration describes how actively a subject changes his or her hand rotational speed. A cutoff point of 400 degrees/sec^2 was identified above which the attending’s measurements tended to reside. The ratio of time spent above this threshold compared to below this threshold significantly differed between attendings and all other levels of training. We believe this measurement is a representation of how much time a subject spends actively making changes to his or her hand even if it is already in motion. This may demonstrate foresight and anticipation of future hand motion and is a trait exhibited in the mastery of a skill.

There were several limitations to this study. The most important was the physical specification of the device. Because the device could not directly measure position, it was susceptible to data aliasing given the limited sampling frequency of our equipment. This was why we were unable to accurately measure distance traveled and linear hand
velocities as parameters of hand motion. The next limitation was the theoretical interference in hand motion when a sensor was attached. Although light weight, the device could have affected the performance of the subjects simply by being attached. Additionally, since blinding was not possible in this prospective study, it was difficult to account for the bias that comes with wearing the device or being observed. Finally, this was an initial study looking at the simple task of knot tying. Surgery offers a wide range of complex hand motions beyond this basic task. As a result, the parameters identified here may not be generalizable to other sophisticated tasks.

Despite these shortcomings, this study was a success in creating an affordable and reliable motion-capturing device for surgical hand motion analysis. The entire device was made from standard stock items available through commercially accessible online vendors. The device used a standard USB port for data transmission and existing developer software for analysis.

This device offered several advantages over previously existing technologies. The most obvious benefit was the fact that it can be used in both open and laparoscopic training. This relatively small device could be attached to the back of the hand and forearm of subjects during most surgical training simulations. Secondly, the device offered an economic advantage. Our device was most similar to the ICSAD based off of the Isotrak II system (Polhemus Inc.) but with the added benefit of open source software as well as being much more affordable.

There were several useful outlets for technology in our study. The first of which was objective feedback and quality control. A subject could be tested to see how he or she stacked up to other trainees and attending surgeons. This could be useful for trainees to identify the surgical skills that they are most skillful in or could use the most improvement. The affordability and mobility of this device could also make it much easier for a trainee to be tested frequently to see if any improvement has been made. Trainees could identify if any positive changes were made after they made a change to their technique.

Conclusion:

In conclusion, thanks to advancements in MEMS technology, affordable and reliable motion sensing technology for surgery tasks could be developed. We have identified several motion parameters to identify skill level in single-handed open knot tying. The identification of more parameters in other tasks would increase the applicability of this device for a broader range of surgical tasks. In addition, future work may include the identification of objective surgical task outcomes (e.g., aesthetic outcome of a standardized surgical suturing task, tension measured in a surgical knot, etc...) to correlate with our motion analysis system. This may then allow us to identify specific hand motion patterns during surgical tasks that are associated with better clinical outcomes. Though still early in development, this technology has the possibility of offering trainees a rapid and objective way to evaluate and keep progress on their surgical skill training.

Achievements:
Our preliminary work was presented in an oral presentation at the 37th annual Meeting for the Association for Surgical Education in San Diego, CA. In addition, our work has
provided the groundwork for further studies on innovation in surgical skills education.

References:


Appendix

Table 1. Parameters of motion identified during data analysis

<table>
<thead>
<tr>
<th></th>
<th>Time to Knot Completion</th>
<th>Total Turning Distance</th>
<th>Variability of Hand Jerk</th>
<th>Variability of Rotational Accel</th>
<th>Ratio Spent in Low Rotation</th>
<th>Ratio Spent in High Rotation</th>
<th>Ratio Spent Actively Adjusting Rotation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Attending</strong></td>
<td>4.65 ±1.25 (sec)</td>
<td>972 ±262 (deg)</td>
<td>12180 ±2686 (m/s^3)</td>
<td>3356 ±550 (deg/s^2)</td>
<td>0.136 ±0.075</td>
<td>1.40 ±0.38</td>
<td>5.50 ±2.26</td>
</tr>
<tr>
<td><strong>Resident (R4-5)</strong></td>
<td>4.68 ±0.84 (sec)</td>
<td>946 ±176 (deg)</td>
<td>10988 ±2702 (m/s^3)</td>
<td>3715 ±4332 (deg/s^2)</td>
<td>*0.200 ±0.114</td>
<td>1.88 ±1.20</td>
<td>*4.12 ±1.1</td>
</tr>
<tr>
<td><strong>Intern</strong></td>
<td>*7.17 ±1.98 (sec)</td>
<td>1107 ±311 (deg)</td>
<td>*8299 ±2604 (m/s^3)</td>
<td>*2432 ±527 (deg/s^2)</td>
<td>*0.367 ±0.187</td>
<td>*2.63 ±1.12</td>
<td>*2.95 ±1.2</td>
</tr>
<tr>
<td><strong>Medical Student</strong></td>
<td>*16.87 ±9.22 (sec)</td>
<td>*1772 ±899 (deg)</td>
<td>*7749 ±3207 (m/s^3)</td>
<td>*1873 ±491 (deg/s^2)</td>
<td>*0.443 ±0.222</td>
<td>*6.65 ±3.18</td>
<td>*2.63 ±1.1</td>
</tr>
</tbody>
</table>
Figure 1: Demonstration of how the device is worn during a surgical task

Figure 2: Representative image of raw data captured by the motion sensor
Figure 3: Average time subjects of each training level took to complete one square knot

![Time to Knot Completion](image)

Figure 4: Average degrees of hand turns for subjects of each training level to complete one square knot

![Total Hand Turning](image)

Figure 5: Average standard deviation of linear jerk of each subject during one square knot by training level

![Average Standard Deviation of Linear Jerk](image)
Figure 6: Average standard deviation of angular acceleration of each subject during one square knot by training level

Figure 7: Average ratio of time each subject spent in high and low rotational speeds by training level
Ratio of Time in High and Low Speed

<table>
<thead>
<tr>
<th>Role</th>
<th>Low Rotational Speed</th>
<th>High Rotational Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attending</td>
<td>0.1269</td>
<td>0.7</td>
</tr>
<tr>
<td>Resident</td>
<td>0.0028</td>
<td>0.6</td>
</tr>
<tr>
<td>Intern</td>
<td>*P&lt;0.001</td>
<td>*P&lt;0.001</td>
</tr>
<tr>
<td>Medstud</td>
<td>*P&lt;0.001</td>
<td>*P&lt;0.001</td>
</tr>
</tbody>
</table>

*P<0.001, *P<0.001, *P<0.001, *P<0.001