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Working volume: Validity evidence for a motion based metric of surgical efficiency

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Abstract

Background—The study aim was to evaluate working volume as a potential assessment metric for open surgical tasks.

Methods—Surgical attendings (N=6), residents (N=4) and medical students (N=5) performed a suturing task on simulated connective tissue (foam), artery (rubber balloon), and friable tissue (tissue paper). Using a motion tracking system, effective working volume was calculated for each hand. Repeated measures analysis of variance assessed differences in working volume by experience level, dominant/non-dominant hand and tissue type.

Results—Analysis revealed a linear relationship between experience and working volume. Attendings had the smallest working volume and students had the largest ($p=0.01$).

The three-way interaction of experience level, hand and material type showed attendings and residents maintained a similar working volume for dominant and non-dominant hands for all tasks. In contrast, medical students' non-dominant hand covered larger working volumes for the balloon and tissue paper materials ($p<0.05$).

Conclusions—This study provides validity evidence for the use of working volume as a metric for open surgical skills. Working volume may provide a means for assessing surgical efficiency and the operative learning curve.

Keywords

Working volume; Motion tracking; Surgery; Education; Skills assessment; Technical skills

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Introduction

Duty hour restrictions combined with increasing complexity of surgical cases requires that surgical residents develop more specialized skills in a shorter amount of time.¹ To improve training of surgical residents, principles of deliberate practice must be integrated into the curricula.²⁻⁴ Deliberate practice requires immediate and reliable feedback and an environment for exploration and error management.² Motion-based feedback measures have been incorporated into the training of athletes⁵⁻⁷ and improving motor recovery from stroke.^{5,8} The integration of motion-based performance measures into the surgical simulation environment may allow for improved performance evaluation and skills development through feedback. However, prior to integrating motion-based measures into feedback systems, we must first understand how these measures relate to performance in surgery.

Prior work using motion-based measures of performance in open surgical skills have found differentiation of performance based on procedure time⁹⁻¹¹, path length (distance traveled by surgeon's hands)¹²⁻¹⁴, idle time (amount of time surgeon's hands were not moving)¹³ and number of hand movements.^{9-11,15} These measures help describe efficiency of performance during a surgical task.¹⁶⁻¹⁸ Efficiency in this situation relates to the conservation of time and motion when operating. However, the previously mentioned measures of efficiency (procedure time, path length, idle time, and number of hand movements) may not fully capture the complexity of movement displayed in the operating room.

Working volume is a measure of efficiency that has been preliminarily evaluated in laparoscopic skills performance¹⁹⁻²⁰, but has been relatively unexplored in open surgical skills. This metric describes the area of space occupied by the surgeon's hands while completing a task. In laparoscopy, measures of working volume have demonstrated evidence of construct validity to differentiate performance by experience level.¹⁹ Additionally, working volume has been used in composite measures of surgical efficiency comprised of multiple motion metrics including procedure time²¹⁻², path length²¹⁻²², control effort²¹, motion smoothness²², and depth perception²². These composite measures have differentiated performance according to experience.²¹⁻²² Based on these findings from motion studies in laparoscopy, we were interested in evaluating this metric in an open surgical skills task. The study aim was to evaluate working volume as a potential assessment metric for open surgical tasks. Our hypothesis was that more experienced surgeons would have smaller working volumes than less experienced surgeons.

Materials and methods

Setting and participants

Third and fourth year medical students, residents, and attending surgeons at an academic hospital were recruited through email list-serve to participate in the study. Participation was voluntary and based on availability. This study was granted Institutional Review Board (IRB) approval by University of Wisconsin Health Sciences IRB.

Research protocol

Participants performed a suturing task on the variable tissue simulator. See D'Angelo et al., 2015 for a detailed description and images of the simulator. Participants were instructed to place three interrupted sutures on three different simulated materials: foam (dense connective tissue), balloon (artery), and tissue paper (friable tissue). Participants were told to use the instrument tie technique while tying sutures. Needle driver, forceps, suture scissors and 3-0 Prolene suture were provided to complete the suturing task. Prolene suture was selected to increase task complexity given the suture's memory property. The tissue paper task is considered to be a more difficult task than the foam or balloon task.¹³⁻¹⁴

While participants performed the suturing task, data were collected with video recordings and optical motion tracking technology (Visualeyez 3000; Phoenix Technologies, Inc, Burnaby, BC). Prior to starting the suturing task, each of the participant's hands were instrumented with four light emitting diodes (LEDs) affixed to surgical gloves with tape.¹³ While participants sutured, 3-dimensional position data were recorded at 180 Hz by the optical tracking capture sensor and stored for future analysis.

Video recording and analysis

Participants' hand movements were video recorded using two video cameras (Q3HD, Zoom Corporation, ToKoy, Japan) with a resolution of 1920×1080 pixels and frame rate of 30 Hz. These cameras were positioned on the left and right side of the participant at a 45 degree angle from their working location. Videos were stored and further analyzed using Adobe Premiere Pro video editing software (Adobe Systems Inc., San Jose, CA) to select specific time points of the start and end of the procedure. The start of the procedure was defined as the hand leaving the starting position and the end of the procedure was defined as cutting the final suture tails.

Working volume

After data collection, the position data were analyzed and the effective working volume measure was calculated. For each hand, the 3-dimensional center point of the four LED trajectories was calculated. Effective working volume was defined as a sphere with the average distance of all the LED paths from each hand's center point serving as the radius of the sphere.

Path length and procedure time

Path length is the 3-dimensional distance the hands traveled from the starting position until the completion of the suturing task. Procedure time is the total time from when the participant's hands left the starting position until the completion of the suturing task. Analysis of path length and procedure time for this data set has been previously published.¹³⁻¹⁴ This analysis demonstrated that attending surgeons had significantly shorter path lengths and procedure times than residents and medical students during the suturing task.¹³

Data analysis

Repeated measures analysis of variance was used to assess differences in working volume by experience level, dominant/non-dominant hand and tissue type. Pearson's correlation coefficients were calculated to evaluate correlations among working volume and path length. All analyses were performed using IBM SPSS Statistics Version 21.0 (IBM Corp, Armonk, NY) and $p < .05$ was considered significant. Given a sample size of 15 a correlation coefficient greater than 0.514 is needed for a $p < 0.05$ level of significance.

Results

All participants (medical students (third and fourth year students, $n=5$), residents (post-graduate year 1-3, $n=4$), attending surgeons ($n=6$)) completed the suturing task. Analysis revealed a main effect of experience on working volume ($F(2,12) = 4.41$, $p < 0.05$). Attending surgeons had the smallest working volume ($M=954.42\text{cm}^3$, $SD=382.84$) and students had the largest ($M=1728.37\text{cm}^3$, $SD=428.03$, $t(1) = -3.13$, $p=0.01$) (Figure 1 and 2). Residents had a mean working volume of 1151.81cm^3 ($SD = 256.90$). Video 1 shows a snapshot of a participant (attending surgeon) with a small working volume and a participant (medical student) with a large working volume at the same point in the suturing task. The three-way interaction of experience, material type, and hand shows that the attending surgeons and surgical residents maintained a similar working volume between both of their hands with all three material types (Figure 3). In contrast, medical students' non-dominant hand covered significantly larger working volumes than their dominant hand for the balloon and tissue paper materials ($F(2,11)=9.71$, $p=0.004$; $p<0.05$ for pairwise comparisons).

Table 1 reports the correlations between the participants' working volume and path length for each suturing task. There was a significant positive correlation between working volume and path length for the foam task, but not for the more difficult tissue paper task. There were no significant correlations between working volume and procedure time.

Discussion

This study evaluated the effective working volume of participants (medical students, surgical residents and attending surgeons) during a suturing task using motion-tracking. Participants performed the suturing task on three simulated materials: foam (dense connective tissue), balloon (artery), and tissue paper (friable tissue). Attending surgeons had smaller working volumes than medical students across all tasks for both dominant and non-dominant hands. These findings provide validity evidence for the use of working volume as a potential performance metric during an open surgical task.

Attending surgeons and residents had similar working volumes for both their dominant and non-dominant hands across all tasks. Interestingly, medical students' non-dominant hand covered larger working volumes than their dominant hand for the balloon and tissue paper materials. This result is consistent with prior work demonstrating more consistent motor behavior between more experienced surgeons' dominant and non-dominant hands.²³ This difference in dominant and non-dominant hand working volume may result from medical students making extraneous movements with their non-dominant hand related to suture

management or instrument knot tying. While suturing with the instrument tie technique, the dominant hand is primarily positioned on the needle driver for moving the needle through the tissue and tying the knot. In contrast the non-dominant hand is responsible for handling forceps, pulling the suture through the material and creating the loop during knot tying. The use of Prolene suture with its memory property may have created increased complexity and contributed to difficulty in suture management. Additionally, there may be a tendency for instruction to focus on the dominant hand manipulating the needle and needle driver as this is what is contacting the tissue. Lastly, motor learning adaptations to novel tasks occur more effectively with the dominant arm than the non-dominant.²² The dominant arm benefits from increased usage of feedforward motor control strategies that promote movement efficiency and decrease errors.²³ The training effect along with the control differences between arms may create more proficient movement with one hand but not the other. Medical students may actually have difficulty coordinating the functions of the non-dominant hand during the suture task, which may serve as a focus for more targeted training.²⁴

Our prior work using motion metrics to evaluate surgical performance on the variable tissue simulator have demonstrated differences based on experience level and material type for path length.¹³⁻¹⁴ We calculated the correlation between path length and working volume to evaluate if working volume represented motor behavior beyond that explained by path length. Path length and working volume were significantly positively correlated for both the dominant and non-dominant hand during the foam task and the dominant hand during the balloon task. This demonstrates a moderate to strong correlation amongst these measures of efficiency with between 30 – 50% of the variance in working volume explained by the variance in path length. This indicates that working volume is representing motor behavior that is not characterized by path length alone. There was not a significant correlation between working volume and path length for the non-dominant hand during the balloon task or either dominant or non-dominant hands during the tissue paper task. The tissue paper task has been previously demonstrated to be the more difficult task.¹¹ As task complexity increases there may be a change in the patterns of motor behavior such that increasing path length does not directly correspond to increasing working volume.

As with all research, our study has limitations. The small sample size limits our statistical power to find significant differences. Additionally, the sample size limits the generalizability of our results beyond our study sample. This study serves as preliminary research aimed at exploring evidence of validity for working volume as a performance metric. Further research investigating working volume as a performance metric in open surgery is needed. Another limitation is the simple nature of the task. A well-defined suturing task was specifically selected for this study as it provided a controlled environment in which to evaluate working volume. However, if working volume is to be developed as a performance measure it needs to be investigated in more complex and unconstrained tasks with multiple operative motor behavior components.

The implications of this research relate to the further development of technology-based objective measures of performance. Working volume may represent another measure of surgical efficiency that captures behavior not explained by path length. This measure may

provide insight into the extraneous and uncoordinated movements of novices or the ability to work within a confined anatomical space. The overarching goal of this research is to identify and evaluate objective measures of surgical skill that can be applied to skills training for both formative and summative assessment. Consistent, objective feedback is critical for deliberate practice and development of expertise². We theorize that motion metrics can be used to enhance feedback during surgical skill acquisition. First, we must define metrics that quantify motor behavior that is qualitatively identified to differentiate performance. Our current findings demonstrate construct validity evidence for use of working volume as a performance measure of surgical efficiency. The results of this study warrant the consideration of integrating working volume into the arsenal of motion performance metrics for open surgery.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. Mean working volume for dominant and non-dominant hands of attending surgeons (n = 6), residents (n = 4) and medical students (n = 5).

Figure 2.
Representative working volume for a medical student and an attending during the suturing task.

Table 1

Pearson's coefficients for correlations (r) and coefficient of determination (r^2) between working volume and path length for dominant and non-dominant hands for each material type.

	Dominant hand		Non-dominant hand	
	r	r^2	r	r^2
Foam	0.618 *	0.382 *	0.702 **	0.493 **
Balloon	0.574 *	0.329 *	0.322	0.103
Tissue paper	0.409	0.167	0.442	0.195

*
p < 0.05

**
p < 0.01