Surgical Simulation: Markers of Proficiency

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OBJECTIVE: Surgical simulation has become an integral component of surgical training. Simulation proficiency determination has been traditionally based upon time to completion of various simulated tasks. We aimed to determine objective markers of proficiency in surgical simulation by comparing novel assessments with conventional evaluations of technical skill.

DESIGN: Categorical general surgery residents completed 10 laparoscopic cholecystectomy modules using a high-fidelity simulator. We recorded and analyzed simulation task times, as well as number of hand movements, instrument path length, instrument acceleration, and participant affective engagement during each simulation. Comparisons were made to Objective Structured Assessment of Technical Skill (OSATS) and Accreditation Council for Graduate Medical Education Milestones, as well as previous laparoscopic experience, duration of laparoscopic cholecystectomies performed by participants, and postgraduate year. Comparisons were also made to Fundamentals of Laparoscopic Surgery task times. Spearman's rho was utilized for comparisons, significance set at >0.50.

SETTING: University of Missouri, Columbia, Missouri, an academic tertiary care facility.

PARTICIPANTS: Fourteen categorical general surgery residents (postgraduate year 1-5) were prospectively enrolled.

RESULTS: One hundred forty simulations were included. The number of hand movements and instrument path lengths strongly correlated with simulation task times (ρ 0.62-0.87, $p < 0.0001$), FLS task completion times (ρ 0.50-0.53, $p < 0.0001$), and prior real-world laparoscopic cholecystectomy experience (ρ -0.51 to -0.53, $p < 0.0001$). No significant correlations were identified between any of the studied markers with Accreditation Council for Graduate Medical Education Milestones, Objective Structured Assessment of Technical Skill evaluations, total previous laparoscopic experience, or postgraduate year level. Neither instrument acceleration nor participant engagement showed significant correlation with any of the conventional markers of real-world or simulation skill proficiency.

CONCLUSIONS: Simulation proficiency, measured by instrument and hand motion, is more representative of simulation skill than simulation task time, instrument acceleration, or participant engagement. (J Surg Ed 76:234−241. © 2018 Association of Program Directors in Surgery. Published by Elsevier Inc. All rights reserved.)

KEY WORDS: Simulation, Efficiency, Proficiency, Technical skill, Surgical education

COMPETENCIES: Practice-Based Learning and Improvement, Patient Care

INTRODUCTION

Surgical simulation has become an essential part of surgical training programs. The use of modern simulation technology in clinical education began in the 1980s and has become progressively more integrated with resident training.[1] While traditional surgical training may have rested on the "see one, do one, teach one," concept, contemporary educational constructs demand more robust training methodologies.[2,3] Changes in technology, clinical practice, training environments, and patient expectations have enabled and encouraged a shift toward increased utilization of simulation in surgical

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The authors have no competing interests to declare.

Funding: This work was supported by the Association for Surgical Education and the Association of Program Directors in Surgery. The sponsors had no role in study design, collection, analysis, or interpretation of data, or the writing of the report or decision to submit the article for publication.

Meeting Presentation: American College of Surgeons Clinical Congress, San Diego, CA, October 2017.

  1931-7204/$30.00
https://doi.org/10.1016/j.jsurg.2018.05.018

education.[4,5] Further, simulation provides a relatively consequence-free environment to hone both technical and nontechnical skills, while supporting active learner participation.[6,7] As a result, training programs have capitalized on the increased attention and availability of surgical simulation, integrating it into current curricula.

While most agree simulation is beneficial to education, assessment of simulation proficiency, and transference of simulation performance to real-world tasks have proven difficult to define.[7] The traditional apprenticeship model of evaluation is pervasive in the simulation realm, and remains largely subjective, creating the opportunity for bias to adversely affect evaluation. Operative case logs, the most basic of historically-measured objective parameters to assess surgical skill, have long been utilized to assess readiness for graduation from resident training.[8] As easily attainable, objective data, they provide useful information regarding operative experience and exposure, but they fall short when characterizing resident surgeon skill.[9] The Accreditation Council for Graduate Medical Education (ACGME) Milestones project is a recent and widely publicized method of assessment, but lacks specific evaluation of surgical skill, as it is not considered a core competency.[10] A number of systems have been created to address the lack of objective performance data, including the Objective Structured Assessment of Technical Skills (OSATS). It is comprised of a skills specific checklist and a set of global rating scales.[11] While the task specific checklist has been validated to objectively measure performance, the global assessment remains entirely subjective and subsequently is subject to interobserver bias.[12] Over the years, modifications of the OSATS model have been created, but still utilize a combination of objective and subjective assessment.[13] Time-to-completion of various simulated tasks with programs such as the Fundamentals of Laparoscopic Surgery (FLS), have historically been the objective benchmark for assessing basic laparoscopic skills, however they lack purely objective means to measure efficiency and proficiency in the surgical simulation learning environment. For instance, completing a task quickly with multiple errors does not convey competence, only speed. Current simulation assessment paradigms therefore often include error penalties when calculating time-to-task completion. While this method is more helpful in elucidating competency, rather than just speed, it lacks the ability to measure surgical operative proficiency.[14]

While operative time and time-to-completion of simulated tasks are important to the trainee as he or she gains competence, other factors must be analyzed to adequately determine task proficiency. We aimed to determine objective markers of proficiency in surgical simulation by comparing novel assessments with conventional evaluations of technical skill.

MATERIALS AND METHODS

Following Institutional Review Board approval, we prospectively enrolled 14 categorical general surgery residents (postgraduate year [PGY] 1-5). Voluntary informed consent was competed for all participants. Results from the study were blinded to the training program and utilized for research purposes only.

Each participant completed 10 identical simulated cholecystectomy procedures using a high-fidelity simulator (Lap Mentor™, 3D Systems, Littleton, Colorado). Participants were oriented to the simulator by completing 3 different practice simulation exercises prior to the start of the study. The simulator employs haptic feedback mechanisms using standard laparoscopic instruments in fixed port positions to provide a realistic simulated environment. Each participant completed the same, medium difficulty, simulated laparoscopic cholecystectomy module. The number or type of errors, if committed, were not recorded, as the errors themselves created increased difficulty to allow completion, much as in the real environment. We recorded total operative times, from the time that the first instrument touched the digital gallbladder, until the gallbladder was removed from the liver bed (Start-End). Additionally, we recorded the time from start to division of the cystic structures (Start-Division). Times were recorded as minutes and seconds. The number of instrument movements was calculated electronically via the simulator software, as was the instrument path length for each hand (right and left). The number of instrument movements were totaled and the mean number of movements occurring during the 10 simulations were determined for each participant. The mean instrument path length was computed in a similar manner. Instrument acceleration was determined as the mean acceleration of each hand's instrument for the 10 simulated procedures.

We aimed to compare markers of simulation performance to both current real-world and simulation measures of competency. To provide comparison to real-world performance, several traditional methods of operative assessment were identified, and data was collected. Operative ACGME case logs for laparoscopic cholecystectomy (codes 47480, 47562, 47563, 47564, 47600, 47605, and 47610), and ACGME defined categories of Laparoscopic Basic and Laparoscopic Complex were compiled for each participating resident. ACGME Milestones evaluations were collected. Operative Objective Structured Assessment of Technical Skill (OSATS) evaluations from actual laparoscopic cholecystectomies were compiled. We also included operative time for real-world laparoscopic cholecystectomies performed over the last six months. In order to evaluate markers of simulation performance, and transferability to other

TABLE 1. Comparison Categories

Simulation Markers Studied	Real-World Performance Measures	Conventional Simulation Assessment
Simulation operative times	Postgraduate year	FLS task performance
Number of hand movements	ACGME milestones	
Instrument path length	Case Logs:	
Instrument acceleration	Laparoscopic cholecystectomy	
Engagement (EDA)	All laparoscopic cases	
	Laparoscopic cholecystectomy operative time	
	OSATS evaluations	

simulated activities, we compiled task times from FLS training exercises (Table 1).

We measured resident engagement throughout the procedure to determine its role in the affective domain of learning, utilizing methods we have published previously regarding electrodermal activity.[13,15,16] Electrodermal activity (EDA) is a measure of the galvanic skin response to stress, and thus effectively measures engagement during task completion. As stress increases, so does the conductivity of the skin. EDA was measured using sensors placed on both wrists of the participants. Each sensor has two 12 mm electrodes spaced 4 mm apart and was positioned to allow unobstructed motion of the participants' hands. Sampling rate was set at 32 Hz. Raw EDA time series were analyzed to determine each participant's tonic and peak phasic measures of arousal and stress. Tonic and peak phasic responses (TPRs) are taken to represent the average and maximal EDA recorded over each simulation exercise. Following application of a moving window average to eliminate high-frequency noise, tonic, and peak phasic EDA were computed as the mean and maximum EDA values of the entire time series, respectively. A 10% trimmed mean of the baseline time series was conducted to eliminate outliers and was used to compute the fractional change in EDA response from baseline. For each of the TPRs, the fractional change (FC_{EDA}) measure was defined as $FC_{EDA} = (TPR - B)/B$, where B is the average baseline EDA.[13,15,16] Use of FC_{EDA}, as opposed to an unadjusted measure, was meant to mitigate the influence of potential confounding variables affecting each individual's level of stress and to isolate the effect of each simulation exercise.

All data was analyzed utilizing standard statistical tests. Correlations were determined by Spearman's coefficients and linear regression. Correlations were tested for both statistical significance (alpha < 0.05) and clinical significance ($\rho > 0.5$). Spearman's rho (ρ) was utilized to test the significance of correlations utilizing rank-ordered data. Rho values <0.5 were considered nonsignificant, as they represent, at best, only weak correlations between examined categories, and are thus inconclusive. Matlab (Mathworks, Natick, Massachusetts) was employed to aid in analysis of the raw EDA data.

RESULTS

Fourteen, of the available 15 total, categorical surgery residents ranging from PGY1-PGY5 participated. Mean age of resident surgeons was 29.9 years and 57% (n = 8) were male. Mean number of human laparoscopic cholecystectomies performed per resident, prior to the study was 43 (range 0-161). Total laparoscopic experience included a mean of 151 (range 18-350) laparoscopic operations prior to the study. A total of 140 simulated laparoscopic cholecystectomy procedures were performed during the study (Table 2).

Simulation Task Times

A conventional method of simulation assessment, task time, correlated well with several of the studied markers of proficiency. Both the Start-Division and Start-End times correlated well with each other (ρ 0.86, $p < 0.0001$). Both time series correlated well with the number of right and left hand movements (ρ 0.74-0.87, $p < 0.0001$), as well as both right and left instrument path length (ρ 0.62-0.85, $p < 0.0001$). No clinically significant correlation was seen with any of the real-world performance measures, including PGY level, ACGME case logs, ACGME Milestones evaluations, mean real-life laparoscopic cholecystectomy completion times, or OSATS evaluations. No correlation was identified between prior

TABLE 2. Participant Demographics

Resident participants (n)	14
Mean age of participants	29.9 years
% Participants Male	57%
Mean pre-study ACGME case log	
Laparoscopic cholecystectomy	43 (range 0-161)
All laparoscopic cases	151 (range 18-350)
Simulation cases analyzed per participant (n)	10

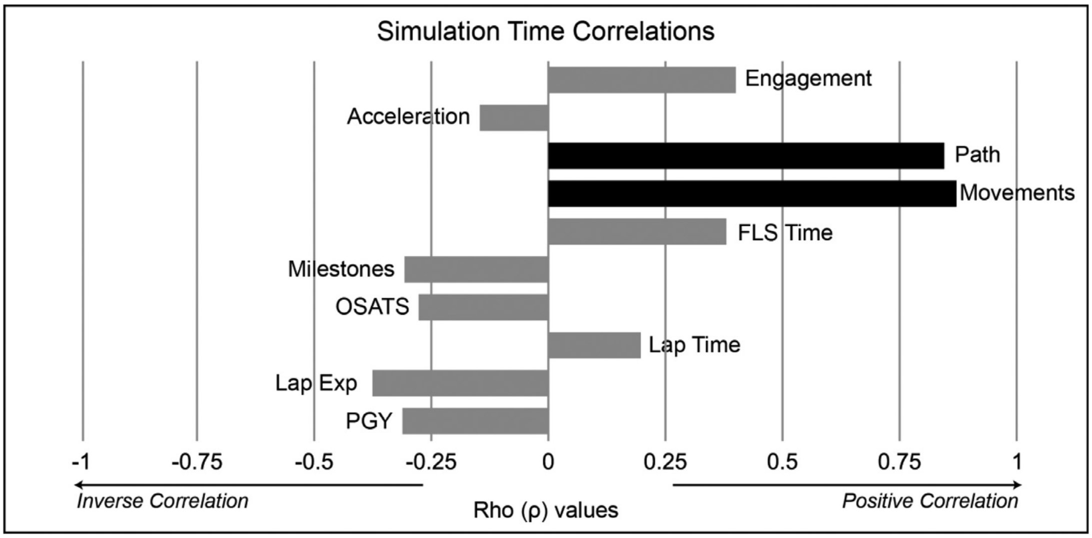

FIGURE 1. Simulation time correlations. Simulation time did not correlate with real-world performance measures. Black bars represent clinical and statistically significant correlations. Engagement: Phasic electrodermal activity; Acceleration: Right hand instrument acceleration (cm/s); Path: Right hand instrument path length (cm); Movements: Number of right hand movements; FLS Time: Mean time for Fundamentals of Laparoscopic Surgery task completion; Milestones: ACGME Milestones mean evaluation score; OSATS: Objective Structured Assessment of Technical Skill mean scores during real-life cholecystectomy procedures; Lap Time: Six-month mean time to complete real-life cholecystectomy procedures; Lap Exp: Number of laparoscopic cholecystectomy cases for each participant prior to the study; PGY: Postgraduate year of training.

laparoscopic experience, or the number of real-world laparoscopic cholecystectomies performed prior to the study. Simulation times did not correlate with FLS task completion times, or simulator instrument acceleration (ρ 0.10-0.41; Fig. 1).

Number of Hand Movements

In addition to the correlates above with task time, clinically significant correlations were identified between the number of hand movements and FLS task completion times (ρ 0.50-0.53, $p < 0.0001$), as well as with instrument path length (ρ 0.82-0.96, $p < 0.0001$). Inverse correlates were seen with the number of pre-study real-life laparoscopic cholecystectomy (ρ −0.51 to −0.53, $p < 0.0001$), signifying fewer hand movements in those participants who had completed more real-life cholecystectomies. No clinically significant correlations were seen between the number of hand movements with total laparoscopic experience, mean real-life laparoscopic cholecystectomy operative times, OSATS or ACGME Milestones evaluations, or PGY level (ρ 0.03-0.44; Fig. 2).

Instrument Path Length

Both the right and left instrument path lengths correlated well the simulation task time and hand movements. Additionally, we identified correlations between the right-hand instrument path length with FLS task completion times (ρ 0.56, $p < 0.0001$) and an inverse correlation with the number of real-life laparoscopic cholecystectomies completed (ρ −0.53, $p < 0.0001$). No significant correlations were seen with PGY level, ACGME Milestones, and OSATS evaluations, prior laparoscopic experience, nor mean real-life operative times (ρ 0.05-0.47; Fig. 3).

Instrument Acceleration

No significant correlations were identified between both right and left instrument acceleration and any of the examined markers of proficiency in either the simulation realm or real-life (ρ 0.0-0.18). All other parameters showed significant internal correlation between right and left, however acceleration did not (ρ 0.48; Fig. 4).

Participant Affective Engagement

Phasic and tonic electrodermal activity levels correlated with one another (ρ 0.98, $p < 0.0001$). However, there were no identifiable significant correlations with either tonic or phasic EDA with any of the examined markers of proficiency, suggesting no link between affective engagement and simulation proficiency (Fig. 5).

DISCUSSION

Overall, we saw few correlations between markers of simulation proficiency and conventional real-world skill assessments. Instrument path length and the number of hand movements were the strongest correlated markers to real-

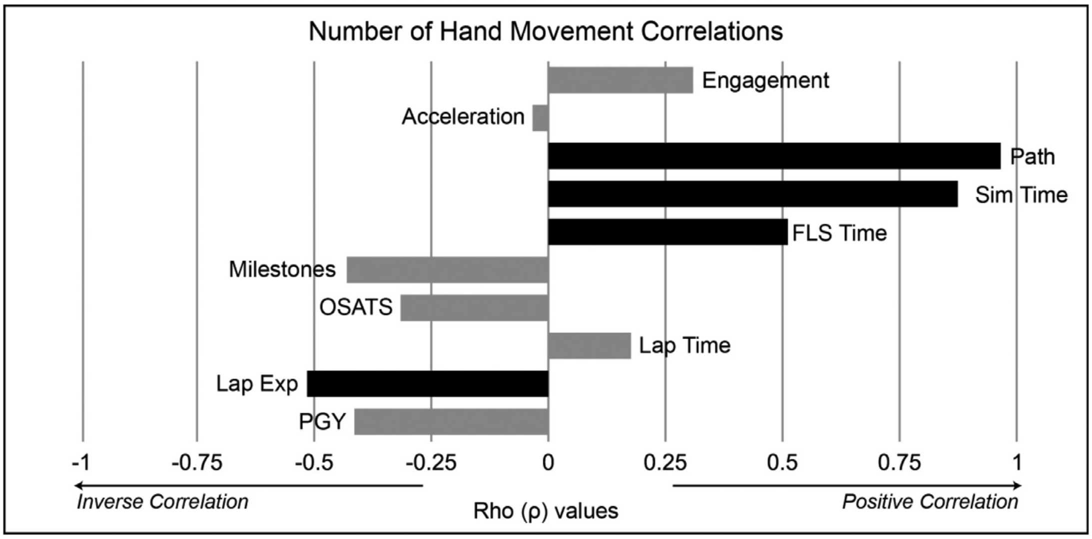

FIGURE 2. Hand movement correlations in simulation. The number of hand movements during simulation correlated with other markers of simulation performance and the number of total laparoscopic cases and FLS task completion times. Black bars represent clinical and statistically significant correlations. Movements: Number of right hand movements; Engagement: Phasic electrodermal activity; Acceleration: Right hand instrument acceleration (cm/s); Path: Right hand instrument path length (cm); Sim Time: Start-end simulation task time; FLS Time: Mean time for Fundamentals of Laparoscopic Surgery task completion; Milestones: ACGME Milestones mean evaluation score; OSATS: Objective Structured Assessment of Technical Skill mean scores during real-life cholecystectomy procedures; Lap Time: Six-month mean time to complete real-life cholecystectomy procedures; Lap Exp: Number of laparoscopic cholecystectomy cases for each participant prior to the study; PGY: Postgraduate year of training.

world measures. Shorter simulation task times corresponded to fewer hand movements and instrument path lengths, but failed to show associations with common performance markers such as ACGME Milestones, prior laparoscopic experience and OSATS evaluations.

The interaction between less hand movements and shorter instrument path lengths to quicker simulation task times is obvious, and our results support strong correlations between these parameters. We expected to see associations between simulation times and real-life

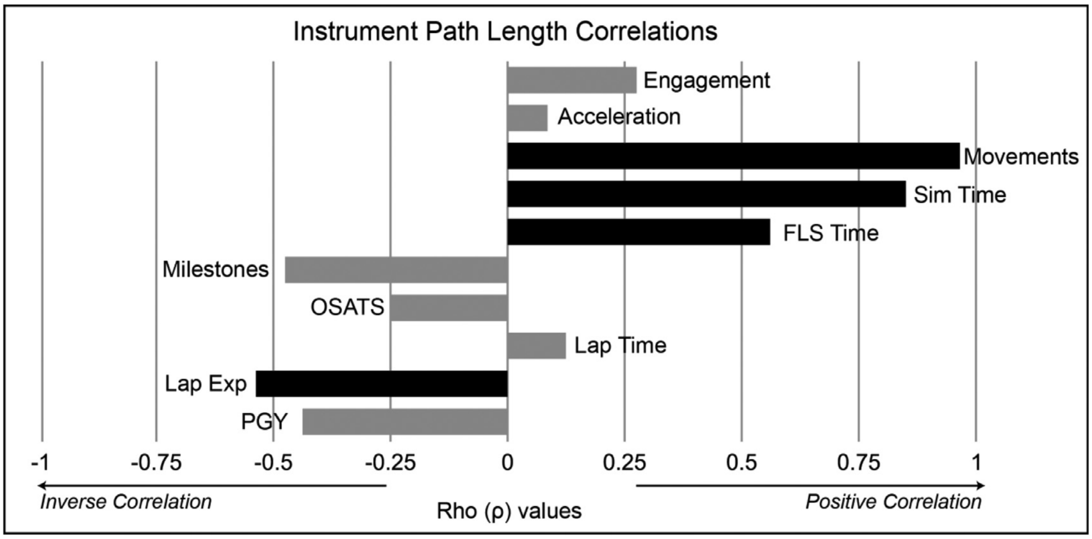

FIGURE 3. Instrument path length correlations in simulation. Instrument path length during simulation exercises correlated with other markers of simulation performance and the number of total laparoscopic cases and FLS task completion times. Black bars represent clinical and statistically significant correlations. Path: Right hand instrument path length (cm); Engagement: Phasic electrodermal activity; Acceleration: Right hand instrument acceleration (cm/s); Movements: Number of right hand movements; Sim Time: Start-end simulation task time; FLS Time: Mean time for Fundamentals of Laparoscopic Surgery task completion; Milestones: ACGME Milestones mean evaluation score; OSATS: Objective Structured Assessment of Technical Skill mean scores during real-life cholecystectomy procedures; Lap Time: Six-month mean time to complete real-life cholecystectomy procedures; Lap Exp: Number of laparoscopic cholecystectomy cases for each participant prior to the study; PGY: Postgraduate year of training.

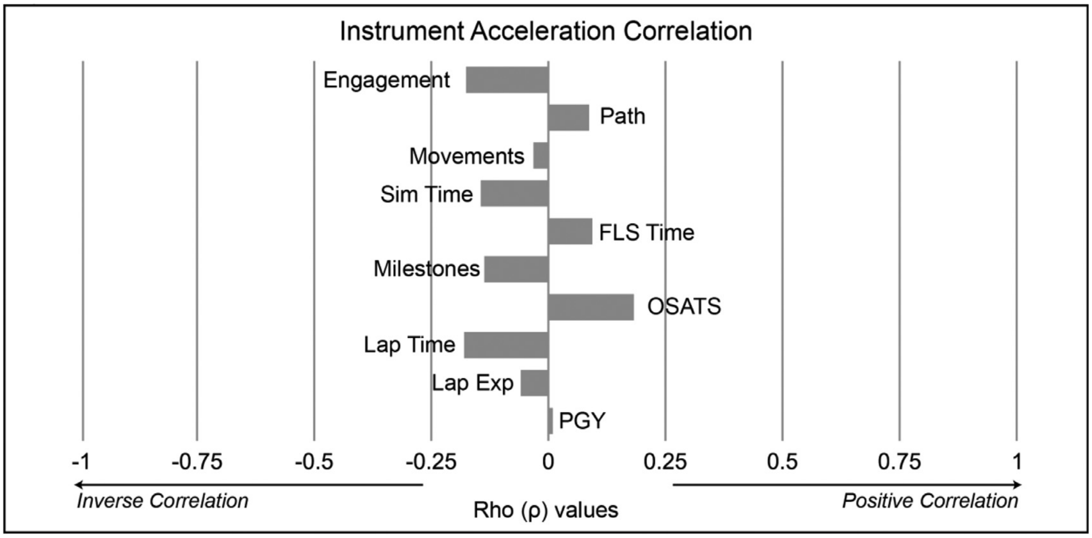

FIGURE 4. Instrument acceleration correlations in simulation. Instrument acceleration did not correlate with any of the examined parameters, suggesting it is a poor marker of simulation performance. Black bars represent clinical and statistically significant correlations. Acceleration: Right hand instrument acceleration (cm/s); Engagement: Phasic electrodermal activity; Path: Right hand instrument path length (cm); Movements: Number of right hand movements; Sim Time: Start-end simulation task time; FLS Time: Mean time for Fundamentals of Laparoscopic Surgery task completion; Milestones: ACGME Milestones mean evaluation score; OSATS: Objective Structured Assessment of Technical Skill mean scores during real-life cholecystectomy procedures; Lap Time: Six-month mean time to complete real-life cholecystectomy procedures; Lap Exp: Number of laparoscopic cholecystectomy cases for each participant prior to the study; PGY: Postgraduate year of training.

operative times, but at best, there was a weak and insignificant correlation. Additionally, one would expect simulation times to be shorter with participants who were at higher PGY levels, had more real-life laparoscopic operative experience and who had higher operative evaluation scores. However, this is not reflected in our study. These findings bring into question the validity of using task times as the mainstay of simulation performance assessment, given the lack of correlation with real-world operative evaluations. Previous

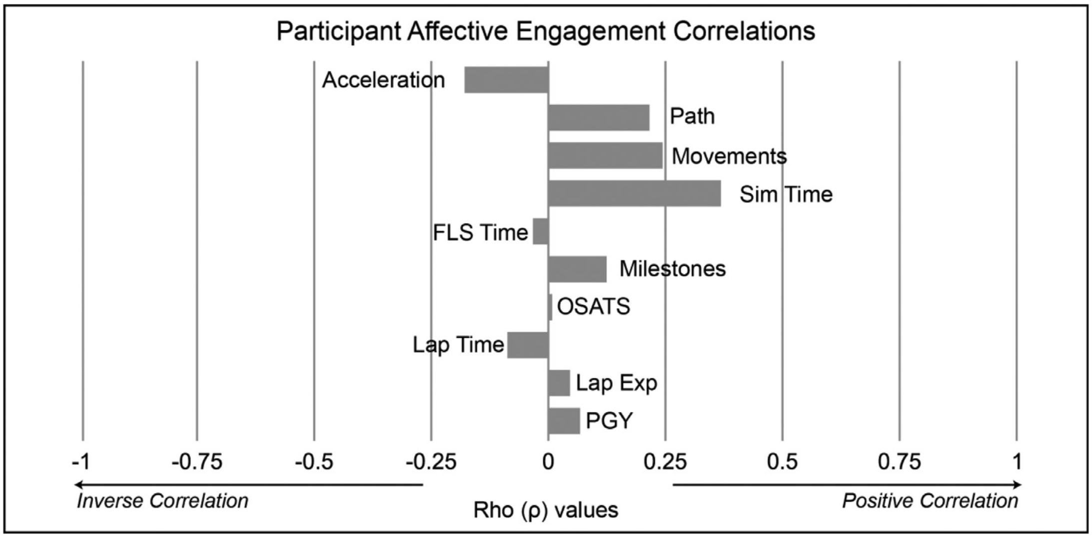

FIGURE 5. Affective engagement correlations in simulation. Affective engagement, as measured by electrodermal activity, did not correlate with any of the examined parameters, signifying limited utility as a marker of simulation performance. Black bars represent clinical and statistically significant correlations. Engagement: Phasic electrodermal activity; Acceleration: Right hand instrument acceleration (cm/s); Path: Right hand instrument path length (cm); Movements: Number of right hand movements; Sim Time: Start-end simulation task time; FLS Time: Mean time for Fundamentals of Laparoscopic Surgery task completion; Milestones: ACGME Milestones mean evaluation score; OSATS: Objective Structured Assessment of Technical Skill mean scores during real-life cholecystectomy procedures; Lap Time: Six-month mean time to complete real-life cholecystectomy procedures; Lap Exp: Number of laparoscopic cholecystectomy cases for each participant prior to the study; PGY: Postgraduate year of training.

studies have also highlighted the shortcomings of traditional means of simulation assessment, such as task completion time.[7,17]

More difficult to quantify outside the realm of virtual reality and high-fidelity simulation, instrument path length and hand motion showed significant correlations to several real-life operative skill evaluations. Overall, these markers of simulation proficiency had stronger correlations than any of the other simulation parameters studied. Both correlated well with laparoscopic operative experience, and had nearly significant, albeit weak, correlations with ACGME Milestones (ρ 0.38-0.47), OSATS evaluations (ρ −0.18 to −0.32), and PGY level (ρ 0.36-0.41). This implies that measuring the number of hand movements and instrument path length during simulation may have both validity and transference to real-world skills. Cost and practical concerns of obtaining these values in day-to-day simulation activities, however, prohibit their widespread use at this time. With additional evidence to support more refined simulation performance measures, the availability of technological methods to obtain motion kinetic data may increase.

Instrument acceleration is often erroneously referred to as "speed," and generally thought of as a desirable quality—as in, "she has quick hands." However, instrument acceleration showed no significant correlations with any of the studied parameters both in simulation and real-world domains. Lack of correlation suggests accelerometry data is of limited utility in the evaluation of simulation task proficiency.

Regarding participant engagement, phasic and tonic electrodermal activity showed no significant correlations with any of the studied parameters. As the range for electrodermally measured engagement can vary widely, we utilized rank correlation statistics to avoid skewing of the results by one or two participants with especially high or low levels of engagement. Surprisingly, learner engagement appeared to have no link to simulation task proficiency. This is contrary to our earlier findings during real-life laparoscopic cholecystectomy, where EDA levels were directly related to performance.[13] Simulation exercises are often designed to be relatively consequence-free. This aspect of the simulation methodology used in this study likely contributed to the lack of significant correlation between engagement and any of the other parameters.

Our study is limited by resident participant sample size, thus results may differ by inclusion of resident surgeons from other programs in a multi-institutional study. ACGME Milestones and OSATS evaluations were completed by faculty at a single institution, which may have skewed the results as well. We did not set a criterion standard of proficiency for the studied methods of assessment, but rather studied the parameters themselves. Using each participant as his/her own control, we delineated the interactions and correlations between conventional evaluation methods and novel means outlined in this study. Future work will move toward expansion of these methods, both in simulation and the real-world, with set proficiency benchmarks outlined by increased sample size and refinement.

CONCLUSIONS

Conventional assessment methods of simulation proficiency, such as time to complete tasks, show poor correlation and transference to real-world operative performance. Markers of efficiency, hand movements and instrument path length, show promise as objective, measurable, and transferable skill assessments.

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SUPPLEMENTARY INFORMATION

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.jsurg.2018.05.018.