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Toward effective pediatric minimally invasive surgical simulation

Joshua M. Hamilton [a], **Kanav Kahol** [b,c], **Mithra Vankipuram** [c], **Aaron Ashby** [c], **David M. Notrica** [d,e,*], **John J. Ferrara** [c]

[a] *Phoenix Integrated Surgical Residency, Banner Good Samaritan Hospital, Phoenix, AZ 85006, USA*
[b] *Simulation Education and Training Center, Banner Good Samaritan Hospital, Phoenix, AZ 85006, USA*
[c] *School of Biological and Health Systems Engineering, Arizona State University, Tempe, AZ 85004, USA*
[d] *Department of Surgery, Phoenix Children's Hospital, Phoenix, AZ 85006, USA*
[e] *University of Arizona College of Medicine, Phoenix, AZ 85004, USA*

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Abstract

Background/Purpose: Simulation is increasingly being recognized as an important tool in the training and evaluation of surgeons. Currently, there is no simulator that is specific to pediatric minimally invasive surgery (MIS). A fundamental technical difference between adult and pediatric MIS is the degree of motion scaling. Smaller instruments and areas of dissection under greater optical magnification require finer, more precise hand movements. We hypothesized that this can be used to detect differences in skills proficiency between pediatric and general surgeons.

Methods: We programmed a virtual reality simulation of intracorporeal suturing with modes that used motion scaling to mimic conditions of either adult or pediatric MIS. The participants consisted of pediatric and general surgeons who wore motion-sensing gloves. Metrics included time elapsed, penetration errors, tool movement smoothness, hand movement smoothness, and gesture level proficiency.

Results: For all measures, pediatric surgeons demonstrated superior proficiency on exercises conducted in pediatric conditions ($P < .05$). Performance in adult conditions was similar between the 2 groups.

Conclusion: Pediatric surgeons possess unique skills compared with general surgeons that relate to the technical challenges they routinely face, reinforcing the need for a surgical simulator specific to pediatric MIS. This validates our simulator and the manipulation of motion scaling as a useful training tool.

Simulation training has become a widely accepted and well-researched method of acclimating surgical residents to perform minimally invasive surgical (MIS) procedures [1-4]. Recognizing the benefits of simulation, the American Board of Surgery has recently made satisfactory completion of the Fundamentals in Laparoscopic Surgery course a required element of certification. Some have similarly proposed simulator use in accrediting practicing surgeons to perform MIS procedures. Besides accreditation, simulation may also assist surgeons in acquiring new skills and maintaining existing ones, or perhaps one day provide a way to rehearse novel or particularly complicated cases in advance. Because the specialty of pediatric surgery requires the surgeon to be skilled and efficient at operations that are either unique or

* Corresponding author. Phoenix Children's Hospital, 1919 E Thomas Road, Phoenix, AZ 85016, USA. Tel.: +1 602 254 5561.
E-mail address: Dnotrica@phoenixchildrens.com (D.M. Notrica).

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done infrequently, simulation offers additional advantages but requires simulators specifically designed to address the exceptional challenges of pediatric MIS. There is currently, however, a deficiency in the scientific literature with regard to the subject of pediatric MIS simulation [5].

The principal technical difference between adult and pediatric MIS is the degree of motion scaling: smaller instruments and areas of dissection under greater optical magnification require finer, more precise hand movements. When this circumstance occurs, the surgeon experiences it as exacerbated visiomotor conflict and so must make appropriate psychomotor adjustments to continue operating with precision. These situations exist in certain aspects of MIS in adult patients, but to a much lesser extent.

We created a simulation of intracorporeal suturing, using a deformable virtual tissue plane manipulated by the surgeon through a force-feedback joystick, in which the motion scaling of the virtual scenario could be adjusted to approximate conditions found in pediatric MIS. Adjusting to visiomotor conflict is a definable and measurable psychomotor skill within the practice of laparoscopic surgery [6]; and because the conditions encountered by variations in patient size require pediatric surgeons to compensate for and work within situations of variable and extreme motion scaling, we hypothesized that their performance on our simulator would differ from that of a general surgeon. Elucidating differences between adult and pediatric surgeons will suggest that performance parameters of pediatric MIS are unique and that there is a need for simulator engineering specific to smaller patients. In a second phase of the experiment, we conducted a study to validate the developed simulator's ability to produce learning by seeing if surgical interns benefitted from practicing under conditions of extreme motion scaling.

1. Methods

All experiments were conducted with the approval of the Banner Good Samaritan Medical Center Institutional Review Board.

1.1. Simulator design

A computer simulation was designed to emulate intracorporeal suturing (Fig. 1A). Subjects were charged with penetrating a deformable tissue plane with a virtual needle at a precise indicated point and then bringing this needle back up through an adjacent indicated point. The simulation was implemented using the Sensable haptic joystick (Sensable Technologies, Cambridge, MA), which allows for generation of 3 degrees of force feedback in response to events in the virtual environment. Programming haptic feedback meant that the virtual tissue be both observed and realistically felt to deform to applied pressure, with a certain targeted pressure eventually allowing passage of the virtual needle. While performing the simulated tasks, subjects wore the Cyberglove (Cyberglove Systems, San Jose, CA) and Polhemus Liberty Tracker (Polhemus, Burlington, VT) devices that made possible the recording of hand movements throughout the exercises. This system has been described, validated, and used in previous published works [7-9].

Two modes were created that differed principally in the degree of motion scaling programmed. In the "Adult" (ie, general surgery) mode, actual movements of the subject's instrument corresponded to movements of identical scale by the virtual needle displayed on the screen. In the "Pediatric" (ie, pediatric surgery) mode, movements of the virtual needle were multiplied by a scaling factor (in this study, we used 200%), whereas scaling of the visual field was increased by 150%, so that small movements of the actual instrument generated more exaggerated movements of the virtual needle (Fig. 1B, C). We believe this to be an accurate means by which a virtual reality simulator can be adapted to emulate the conditions of visiomotor conflict created by exaggerated motion scaling such that occurs when a laparoscope magnifies the diminutive size of pediatric anatomy and pediatric laparoscopic instruments.

1.2. Study metrics

Within the simulation, we measured time to completion and penetration errors. The time elapsed was then normalized to a range of 0 through 1, with 0 representing 0 second to complete a task and 1 representing 600 seconds to complete a task (time beyond 600 seconds resulted in abandoning the session). Our simulator was designed to measure errors surgeons may make in placement of a needle as well as errors of penetration depth. For an example of the latter, if a jerky motion is executed upon penetration, then penetration depth may be higher, as the surgeon may have limited control over the motion. Conversely, a smooth controlled motion will result in a more limited penetration depth. Both of these measures of error were combined and treated equally to yield the total number of errors in a given trial, which was likewise normalized to a range of 0 through 1, where 0 represents 0 error and 1 represents 100 errors (the maximum number of errors allowed).

Minimally invasive surgical proficiency was also measured using several forms of motion analysis, all of which have been previously researched and validated [10-13]. Tool movement and hand movement metrics were extrapolated from the simulator program and the motion-tracking gloves, respectively. Both measures are scaled between 0 and 1, with 1 representing the greatest fluidity of movement and 0 representing the absence of movement fluidity. These parameters of tool smoothness and hand smoothness describe economy of motion and overall smoothness of execution and are scaled based on modeling of an "expert" group performance.

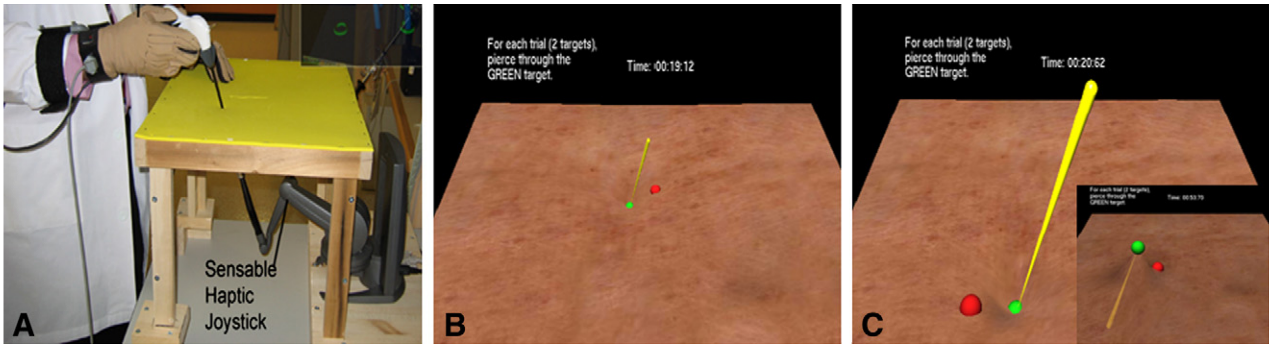

Fig. 1 A, The user interface, consisting of a laparoscopic instrument connected to a sensible haptic joystick; the user is seen wearing the motion-sensing glove. B, The suturing task in Adult mode, demonstrating the indicated point for needle penetration. C, The suturing task in Pediatric mode. The inset demonstrates bringing the needle back up from the underside of the deformable virtual tissue plane.

In addition to these measures, data was calculated to determine the *gesture level proficiency* measure. Task decomposition has previously been validated as a means of studying surgical proficiency, and the algorithm used to derive this measure has been previously shown to correlate closely with subjective skill proficiency ratings obtained by attending surgeons [14-18]. Gesture level proficiency conceptualizes hand or tool movement as being composed of 9 basic gestures: *in, out*, *left*, *right*, *up*, *down*, *rotation clockwise*, *rotation anticlockwise*, and *grasping*. Each individual gesture is analyzed by its similarity to an optimal occurrence of the same gesture, as determined by modeling an expert group performance of that gesture, which then generates a proficiency rating. The measure is estimated through a combination of the kinematic analysis of hand motion and time to completion and is conceptually representative of the ability of surgeons to execute each individual gesture accurately and further combine them in a relevant sequence to accomplish a task. The algorithm generates an overall score scaled to between 0 and 10 for a given exercise; 0 implies least proficiency in accomplishing the task, whereas 10 implies highest proficiency. These 5 measures of proficiency—gesture level proficiency, hand movement smoothness, tool movement smoothness, time elapsed, and penetration errors—provide a broad construct for the study and evaluation of global MIS skills proficiency in an entirely objective manner.

1.3. Study participants and design

One timed trial consisted of 10 pairs of targets provided for the subject to pierce with the virtual needle and then bring

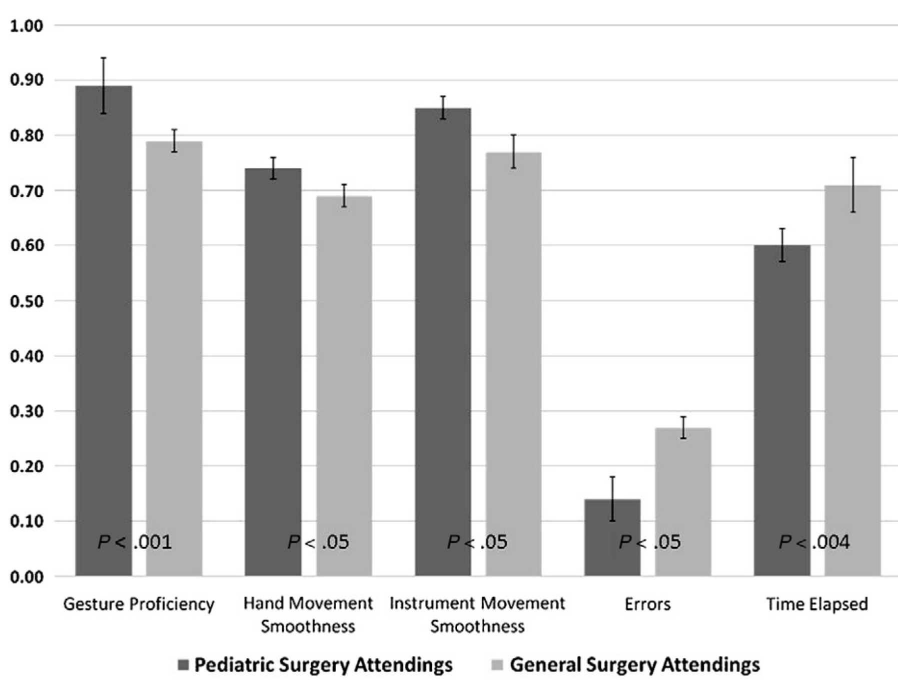

Fig. 2 A comparison of normalized measures of performance from the pediatric surgeon and general surgeon groups on the simulator's Pediatric mode.

back up again. Subjects were aware that they were being timed but were not instructed as to other metrics being recorded. Nine pediatric surgeons and 7 general surgeons each completed 10 trials that were randomly and evenly alternated between the Adult and Pediatric modes. Baseline demographic data were obtained by survey from all participants. Analysis of variance was then used to study the difference between the 5 proficiency measures of surgical skills between the groups. A P value < .05 was accepted as a statistically significant difference.

In the second experiment, we enrolled 10 PGY-1 general surgery residents (7 men and 3 women) who performed 10 similar trials of the suturing exercise in both modes. The 5 measures of proficiency were recorded. We plotted learning curves of the group and compared their learning to baseline performances of the general surgery and pediatric surgery attending groups.

2. Results

Fig. 2 shows the comparison of the performance of general surgeons and pediatric surgeons on the simulator's Pediatric mode. For all measures of MIS proficiency, the pediatric surgeons outperformed the general surgeons in a statistically significant manner. In the Adult mode, there was no significant difference between the 2 groups. Fig. 3 demonstrates the results of the experiment on learning curves, showing PGY-1 performance in each mode plotted against baseline performances of the pediatric surgery attending and general surgery attending groups. The residents demonstrated learning across trials in both modes. Errors reduced by 63% in pediatric surgery exercises and by 68% in general surgery exercises, whereas gesture proficiency improved by 86% in pediatric surgery exercises and 76% in general surgery exercises. In

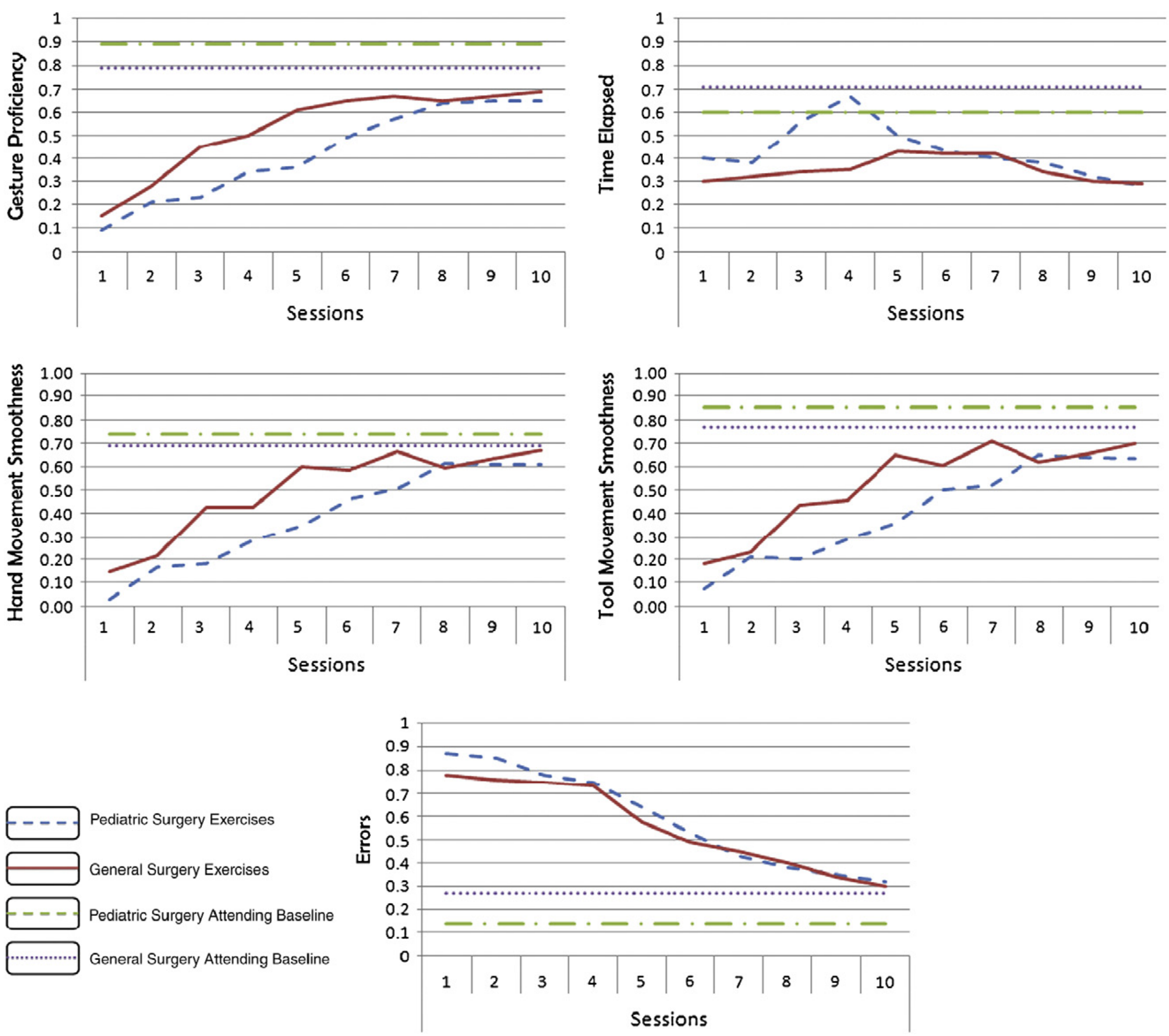

Fig. 3 The performance of PGY-1 surgery trainees on both exercises over 10 trials compared with baseline performances of the pediatric surgeon and general surgeon groups.

general, learning was slightly more pronounced in the Adult mode; but this difference did not achieve significance. It is important to note that, by the end of the 10th trial, PGY-1 residents were approaching the scores of the general surgical attending group.

3. Discussion

Simulation continues to receive a large amount of attention in surgical literature and within surgical training programs. In the wake of the 2000 publication of *To err is human* [19], there has been a broad effort to make all aspects of health care safer for patients; and simulation has been heralded by the surgical community as a valuable tool in this endeavor. In addition, there is increasing pressure to maximize the efficiency of surgical training, both because of increasing time constraints imposed by the Accreditation Council for Graduate Medical Education and because of the financial burden surgical training has on governmental resources, training institutions, and teaching hospitals [20-22]. All of these pressures are applicable to the subspecialty of pediatric surgery, yet the academic literature to date regarding the development and application of pediatric surgical simulation is sparse. A recent survey by Lasko et al [22] revealed that most pediatric surgery fellows and program directors place value in MIS simulation. However, only half of respondents reported regular availability of simulators; and formal simulator training was present or being planned in only 1 in 5 fellowship programs. This deficiency persists despite literature describing significantly steep learning curves associated with performing pediatric MIS [23-25].

There are substantial technical differences between adult and pediatric MIS. Diminutive anatomy, when under the magnification of an endoscope, creates a loss of equivalency between movement of a surgeon's hands and the movement of the instrument as it is displayed on the monitor, which is a defined technical characteristic of a tactile work environment known as *motion scaling*. The sensation of altered motion scaling creates *visiomotor conflict* for the surgeon, who must make various psychomotor adjustments to compensate. For a pediatric surgeon, this means that hand movements must be made finer and more precise. The ability of surgical robots to allow the operator to adjust motion scaling has been found to significantly improve technical proficiency in that domain, suggesting that changes in motion scaling are considered an impediment to MIS that must be overcome [26,27]. There are additional differences in pediatric MIS that were not evaluated in the design of this study. There is an increased overall range of movement in pediatric laparoscopic surgery owing to a decrease in the "keyhole effect" from thinner, more pliable abdominal walls as well as the increased freedom of movement from the occasional use of instruments without trocars. Very young patients

Table 1 Common types of validation that can be used to describe a simulator, listed with how these are addressed by the design of our simulator, our study, or precedence in the literature

Type of validity	Definition	Criteria met?	How validity was addressed
Face validity	Does the simulation resemble actual surgical tasks?	Yes	The needle-penetration task resembles situations encountered in actual laparoscopic operations, and this realism is enhanced by the haptic feedback provided to subjects. Motion scaling as it is adjusted in our study accurately evokes the visiomotor conflict found in pediatric MIS.
Content validity	Does performance on the simulator actually test for proficiency in laparoscopic skills?	Yes	Conditions for all participants were identical, and subjects were grouped for study according to their similar experiences with pediatric MIS. The only manipulated variable was the degree of motion scaling the subjects encountered while completing the simulated tasks.
Construct validity	Does performance on the simulator accurately differentiate skill levels?	Yes	Performance on virtual reality simulators has been shown to be equivalent to physical simulators in being able to accurately differentiate between novice and expert skill levels [33-35]. Tool tip, hand movement, and gesture level proficiency measures have all been previously shown to be valid metrics for distinguishing MIS skill level [6-18].
Concurrent validity	Does performance on the simulator correlate with other assessment tools?	Unknown	There is currently no other validated assessment tool for pediatric MIS skill proficiency with which to compare this simulator.
Predictive validity	Does performance on the simulator predict future surgical proficiency?	Yes/unknown	Previous studies have demonstrated similar simulation components to correlate well with subjective measurements of actual intraoperative proficiency [35,36]. However, it is unknown if this simulation correlates well with actual pediatric MIS proficiency.

may also have exaggerated background movement owing to a faster respiratory rate and greater transmission of respiratory movements.

Because pediatric surgeons who use MIS techniques overcome these psychomotor challenges through experience and practice, one might expect pediatric surgeons to demonstrate greater proficiency compared with general surgeons when these factors are manipulated in a controlled study. Retrospective reviews comparing general to pediatric surgeons have mostly described better outcomes when children were treated by specialty-trained surgeons [28-31]. One study, by Kokoska et al [32], found that differences in surgical outcomes following appendectomy statistically disappeared when the patient's age exceeded 12 years, which may be because of, in some measure, the equivocation of patient size and anatomy that follows the onset of puberty.

In studying the benefits of simulator use, metrics traditionally used to assess laparoscopic proficiency included subjective evaluations of performance by panels of expert surgeons, time to completion of a task, or error rate while completing a task. The first measure is limited by its inherent subjectivity and manpower requirement, whereas the latter 2 measure surrogates assumed to represent technical ability and efficiency. Our research has been crafted around the fundamental belief that assessing the benefits of simulators in surgical training is best accomplished by analysis of entirely objective measures of psychomotor proficiency in tasks representative of actual surgical skills.

This study, in which motion scaling has been altered to better emulate conditions present in pediatric MIS, attempts to more closely evoke the skills necessary to achieve real-world proficiency. The results show that extremes of motion scaling do uniquely separate the skill sets of general surgery and pediatric surgery. Whereas pediatric attending surgeons performed well in environments analogous to general surgery in terms of motion scaling, the converse was not true. This suggests that pediatric MIS conditions do require increased psychomotor effort from surgeons to compensate for motion scaling as compared with general adult MIS conditions. To our knowledge, this is the first study that compares psychomotor acuity of pediatric surgeons and general surgeons.

The results of the learning experiment show that it is possible to learn to adapt to visiomotor conflict in a simulated environment. In a related experiment, we have shown that general surgery interns that practice with variations in motion scaling benefit with improved motion control and fluidity [6]. Time elapsed showed that attending surgeons in both groups generally took more time to complete tasks compared with the resident group. This result is because of the fact that, in general, attending surgeons are very careful when exposed to novel environments; and although they take more time to complete the task, they also make fewer errors. On the other hand, residents generally take less time during initial trials but make a greater number of errors. These types of relations between expertise, time to completion, and error rate have been reported in a past work [17].

The results of this study achieve validation for our simulator in a number of commonly described ways (Table 1). It would therefore seem to serve as a good model for pediatric MIS and demonstrates that the alteration of motion scaling should contribute fundamentally to the design of future pediatric surgical simulators. The results also reinforce previous data indicating that pediatric patients are better served by a specialty-trained surgeon because of the possession of a unique skill set. Pediatric simulation should be further developed to include not only other technical considerations that are unique and important to pediatric MIS, but also the kinds of cognitive assessment and decision trees currently embedded in general surgery simulation exercises but that are unique to pediatric surgery [37]. Further validation of our simulator could be achieved by demonstrating transfer of learned skills to actual surgical performance and by testing the robustness of the learning produced by the simulator through the assessment of skill retention over a longer period. One particularly interesting area of future study is using pediatric MIS simulation to describe the pattern of skills acquisition in pediatric surgery training over time, which would help better define the role of surgical simulation in improving the efficiency of pediatric surgical training.

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