Surgical Education

A framework-based approach to designing simulation-augmented surgical education and training programs

Sayra M. Cristancho, Ph.D., Fuad Moussa, M.D., M.Sc, F.R.C.S.C., F.C.C.P., Adam Dubrowski, Ph.D.*

University of Toronto, The Hospital for Sick Children, Toronto, Ontario, Canada

Abstract. The goal of simulation-based medical education and training is to help trainees acquire and refine the technical and cognitive skills necessary to perform clinical procedures. When designers incorporate simulation into programs, their efforts should be in line with training needs, rather than technology. Designers of simulation-augmented surgical training programs, however, face particular problems related to identifying a framework that guides the curricular design activity to fulfill the particular requirements of such training programs. These problems include the lack of (1) an objective identification of training needs, (2) a systematic design methodology to match training objectives with simulation resources, (3) structured assessments of performance, and (4) a research-centered view to evaluate and validate systematically the educational effectiveness of the program. In this report, we present a process called “Aim – FineTune – FollowThrough” to enable the connection of the identified problems to solutions, using frameworks from psychology, motor learning, education and experimental design. © 2011 Elsevier Inc. All rights reserved.

KEYWORDS: Simulation-augmented education and training; Surgical training; Curriculum design

During the past 2 decades, the field of surgical education and training has experienced changes in paradigm, moving from the original apprenticeship model proposed by William Halsted in 1904 to the notion that basic clinical skills should be learned and practiced on simulators before, or concurrently with, performing them in the clinical setting.1–3 This simulation-augmented education and training has been proposed as a safe and potentially effective modality for training new generations of clinicians managing the changing scope of practice and for retraining internationally trained health professionals.1,3 The goal of simulation-augmented education and training is to help trainees acquire and refine the technical and cognitive skills that are necessary for them to function effectively in the clinical setting.4

The recent burgeoning of simulation technology has provided an abundance of simulators, models, virtual learning, and collaborative learning environments.5 However, the growth of evidence-based processes to integrate the most effective simulation into specific programs and curricula has not been as rapid. This discrepancy between simulation technology and integration processes has resulted in some programs and curricula being developed by intuition, availability of funding, and personal biases. A good simulation design should start with the educational issue and then determine the most appropriate technology. This approach requires that the development of simulation-augmented education and training programs be grounded in learning theory to (1) identify and validate the types of tasks to be simulated, (2) design the corresponding simulations, (3) select the appropriate conditions of practice,6,7 and (4) define the corresponding assessment criteria with the appropriate mechanisms for feedback and debriefing.8 To date,
The application of such a systematic process to the development of educationally sound and cost-effective simulation-augmented education and training programs has not been extensively explored.

The standard curriculum and program design activity is a cycling process composed of 6 steps, including conducting a general needs assessment, developing a rationale to target needs, designing goals and objectives, selecting the educational and evaluation strategies, implementing those strategies, and finally performing program evaluation and feedback.

It is not our intention in this report to argue the already well-defined curricular design process. Instead, we aim to complement it with a systematic and research-based approach. In the realm of surgical education, when developing simulation-augmented training programs, designers have usually followed a technology-driven approach, thus facing several specific issues related to the implementation of the curriculum design process:

- **The lack of an objective identification of training needs (ie, needs assessment):** At present, the methodology used to design and implement simulation-augmented education and training programs has often followed the designer’s clinical experience, which may implicate the risk for either decontextualizing or overcontextualizing the skills to be taught.\(^\text{10,11}\)

- **The lack of a systematic design methodology:** A systematic design methodology needs to make use of the needs assessment to define appropriate training objectives and simulation resources and technologies.

- **The lack of structured assessments of performance:** Such assessments should allow for making comparisons between the performance of various cohorts of trainees to revise and optimize the program.

- **The lack of a research-centered evaluation:** Research-centered mechanisms need to be built into training programs a priori to provide systematic evaluation and validation of the effectiveness of such programs, and their modification when necessary, in terms of their educational value and relevance.

In this report, we propose the “Aim – FineTune – FollowThrough” process to enable the connection of the identified issues to solutions, using theoretical frameworks and models rooted in the fields of engineering, psychology, motor learning, education, and experimental design.

### The Aim – FineTune – FollowThrough process

Given the technological focus in the field of medical simulation, we made use of an analogy between the curriculum design and the engineering product design. Rather than seeking differences between the 2 approaches, we make parallels to point out that there are commonalities across disciplines in terms of design processes to facilitate moving from the conception of an idea to its practical implementation and validation.\(^\text{12}\) In this section, we describe the engineering design process, its adaptation to derive the proposed Aim – FineTune – FollowThrough process, and its application to simulation-augmented education and training. The Aim – FineTune – FollowThrough framework comprises 5 specific stages that seek to adapt the standard curriculum design process to be applied within the simulation context and to highlight the specific points in the process where education and validation research can take place.

### The engineering design

In general, the engineering design process for a technical product may be described in terms of its 3 main phases: conceptualization, concept refinement, and implementation.\(^\text{12}\) It is usually depicted as a well-defined algorithm of activities. At the conceptualization stage, design requirements are established in terms of the expected functionality of the product. This information constitutes the product specifications and is displayed in tables or diagrams. The main activities that move the process from the conceptualization stage to the concept refinement stage are formalization of the specifications, determination of solution strategies, and partitioning of the overall task into independent subtasks. These tasks are subsequently forwarded to specific design teams that focus on issues such as user needs, context exploration, and modeling of the target system to move the process into the implementation stage. Modeling plays a central role in this design phase, because it allows for the creation of the necessary templates for the cyclic testing of the product.

For example, this approach has been adapted to the circuit design process in electrical engineering, using a well-established 5-stage methodology. Initially, the electrical functionality of the system is defined materials and methods definition and requirements, and this is followed by a synthesis of the selected application, using a schematic circuit diagram (mapping). Using computer simulation software, the designer calculates the component values to meet the operating specifications and to test the performance of the circuit under ideal conditions (verification). Later, a prototype is assembled and tested against the specifications (implementation). Finally, the actual system is built, and its performance is measured to test whether compliance has been achieved (validation).

### Application to simulation-augmented education and training

A similar process for designing simulation-augmented programs in surgical education has not yet been well defined; however, by drawing on the concepts of electrical
Aim. This design definition and design mapping stages. First, the procedure, task, or skill to be taught should be selected. In the context, a procedure is understood as a complex clinical activity that can be decomposed into simpler building blocks such as tasks, subtasks, and individual skills. Next, during the design mapping stage, generic task analysis methods may be used to model the components of the procedure into workflow representations. This will enable the identification of specific skills to be simulated individually or concurrently as simulation scenarios. At this stage, we decided to use a new modeling tool (the motor and cognitive modeling diagram [MCMD]) to observe and map the performance of a group of experts, which will serve as templates for the simulation design. This step will also help determine the levels of detail of the training and the necessary fidelity of the simulation resources.

The MCMD is a general task-modeling tool that can be adapted for mapping the steps within any clinical procedure, including laparoscopic and open surgery. The MCMD has been derived from a combination of hierarchical task analysis (mainly to represent motor tasks) and information-processing task analysis (mainly to represent cognitive tasks). This new graphical representation of surgical procedures, which includes conventional symbols from flowchart diagrams and Boolean logic diagrams, together with new symbols needed to describe surgical events, enables us to model both motor and cognitive aspects of surgery in a unified diagram. Therefore, the MCMD is intended to add key features such as the ability to represent various levels of detail, sequencing and flow (including loops and branching or options, as well as order-independent tasks, ie, those that can be done in any order but that all must be done before proceeding), decision points, and interruptions (suspend and resume). Using the MCMD, it is possible record and analyze idiosyncratic sequences selected by surgeons during different procedures.

FineTune. This verification stage should involve developing additional mappings of more experts to validate the workflow diagrams. The Delphi technique, using panels of experts, may be useful at this stage. This set of diagrams will also be useful in the validation stage of the program as a tool to help experts in providing better feedback, especially for those tasks in which the automaticity may prevent them from detailing the constituent steps. In addition to identifying the training goals, the Delphi technique should also be used to reach consensus among experts that allows identifying the best simulation technology and teaching methodologies (eg, self-learning for practicing basic skills, peer learning or problem-based learning for practicing intermediate skills, and expert-guided learning for practicing complex skills) for each level of the diagram.

FollowThrough. This final implementation and validation stages, in which the simulation scenarios are designed and developed. The notion of learner motivation and progression should be taken into account. Therefore, the task difficulty of the simulations should be adjusted for each training level (ie, novice, intermediate, and advanced). Consequently, the set of training sessions should be designed separately for each training level and for each simulation scenario, because different types of practice and feedback and debriefing techniques might be needed. These strategies should be formulated as hypotheses, and validation studies should be embedded into the design.

Theoretical underpinnings

On the basis of this structure, we provide a connection between the 4 problems that we have initially described with the Aim – FineTune – FollowThrough process stages (Table 1). In addition, we provide a theoretical “umbrella” for each stage to shift this process toward an evidence-based

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Relationship between the identified issues, conceptual framework, AFT stages, and research tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Issues</td>
<td>Conceptual Framework</td>
</tr>
<tr>
<td>Lack of needs assessment</td>
<td>● Challenge point framework ● Zone of proximal development ● Situation awareness ● Practice conditions</td>
</tr>
<tr>
<td>Lack of a systematic design methodology</td>
<td>● Kirkpatrick program evaluation framework</td>
</tr>
<tr>
<td>Lack of structured assessments</td>
<td>● Hierarchy of research</td>
</tr>
</tbody>
</table>

AFT = Aim – FineTune – FollowThrough; MCMD = motor and cognitive modeling diagram.

*Stage 1: design definition; stage 2: design mapping; stage 3: verification; stage 4: implementation; stage 5: validation.
practice. The guiding conceptual frameworks and the development and research tools for our methodology are presented in the following paragraphs.

**Adjusting the level of difficulty to match the learner’s needs.** One of the prevailing arguments for using simulation in the learning process is that it engages the trainee in the active accumulation of knowledge by doing, while maintaining patient safety. This is in line with constructivism theory, which argues that humans generate knowledge and meaning from their experiences. Monitoring these experiences constitutes the best means to conduct a needs assessment within an educational or training process.

Two important frameworks from psychology and kinesiology are used in this stage to show that the learning process is a consequence of a sensitive interaction between the current level of the learner, the difficulty of the task to be learned and the characteristics of the environment in which the task is performed. From the cognitive perspective, the zone of proximal development from Vygotsky assists us in identifying and separating, in a procedure, those tasks for which a learner requires assistance from those tasks the learner is able to carry out by himself or herself. The difference between other-regulated and self-regulated tasks imposes different requirements in the learning process. In addition, the challenge point framework of Guadagnoli and Lee proposes that there are optimal points for learning motor skills that are dynamic, because as a learner’s skill level improves, performance expectations will increase and new challenges will be presented to the learner throughout the training spectrum. These 2 frameworks provide the theoretical arguments to support the belief that the needs assessment process should focus on identifying both the cognitive and technical demands of potential training activities by making explicit the type and amount of assistance required and the way in which those activities could be designed to progressively challenge the trainees.

**Verifying the training objectives.** To perform the aforementioned identification of the learning needs methodically, we follow the ideas from situation awareness, formally defined by Endsley as “the perception of the elements (level 1) in the environment within a volume of time and space, the comprehension of their meaning (level 2) and the projection of their status in the near future (level 3).” Endsley proposed the situation awareness global assessment technique as a method of directly measuring situation awareness. In this method, a simulation is frozen at various points, and learners are asked questions designed to assess their level 1, level 2, and level 3. The answers are then compared with the real situation according to experts’ interpretations, and an objective measure of situation awareness is provided. This process matches well the mapping and verification stages of the Aim – FineTune – Follow-Through process.

**Optimizing the simulations.** Once the content of the training activities is designed and verified by experts, it is necessary to devise the way in which the training will be delivered. This includes the “when,” “how,” and “what” aspects of the training strategy. Gradually, surgical educators are acquiring an understanding of the practice factors that may influence this learning, termed “conditions of practice.” One such principle that may govern surgical skill acquisition is the schedule of practice, also known as “practice distribution,” which refers to the temporal pattern of practice during skill acquisition. Questions such as “What is the optimal time spent in practice versus the optimal time spent resting?” and “Is it better to practice a skill intensely or have rest periods interspersed with practice sessions?” are of major importance. In the field of surgical training, Moulton et al and Mackay et al have explored this issue, finding that technical skills are retained better when trainees follow a distributed schedule. In addition, the way in which elements of skills are arranged, ranging from individual skills to whole tasks and procedures, has also been explored by Brydges et al and Dubrowski et al, who concluded that whole-task practice is more beneficial for learning. Moreover, how the current level of knowledge or skills of the learners influence these findings has not been explored. Other conditions of practice are summarized in Table 2.

**Evaluating the effectiveness.** After the practice conditions are defined to optimize the learning process, subsequent stages include implementing and validating the program. In these stages, surgical educators should also look at program evaluation models to guide the different assessment levels involved in a curriculum. The Kirkpatrick model, which has been developed for assessing training effectiveness, is one of the most extensively used in the education literature. To provide scientific support, studies in the medical education domain should follow the principles of the evidence-based practice, from defining the research question to identifying appropriate designs and methods to selecting corresponding outcomes.

**Research questions.** Defining a research question requires attention to conceptual frameworks and literature reviews. These elements together help situate the question within the appropriate theoretical context, guiding the selection of the study variables and the interpretation of the study results by answering why-type questions.

**Experimental design.** When designing clinical research, researchers first need to decide whether the events under study will be altered. If alterations are expected, the design is experimental, whereas if they are not expected, the design is observational. At the top of the evidence pyramid are randomized controlled trials; these are followed by cohort studies, case-control studies, case series, and expert opinion, at the bottom of the pyramid.

**Outcomes.** Finally, in terms of outcomes, Beckman and Cook proposed a set of steps when selecting outcomes in
educational studies: “First, choose the desired outcome, balancing feasibility with meaningfulness. Second, choose a method for measuring the outcome. Third, choose an instrument appropriate for the chosen method. Also consider whether the instrument has prior evidence of score reliability and validity. If not, then consider conducting a validity study prior to your initially planned study. Last, for every test or assessment, remember to sample the content domain adequately, since score reliability is proportional to the number of observations and instrument items.”

Summary

Using the design process in electrical engineering as a model, we have framed these problems within the 5 stages of the Aim – FineTune – FollowThrough process by providing for each conceptual framework umbrella derived from psychology, motor learning, education and experimental design theories, and the potential development and research tools.

Given this research-centered view, the 3 stages of the framework constitute the needs assessment of the program, in which the core activities are (1) identifying training requirements, (2) mapping of actual practice in the clinical setting, (3) selecting the set of skills to be taught, using simulation, and (4) defining the progression of training. The last 2 stages are the hands-on components, constituting the implementation and validation steps, in which various questions need to be addressed to fine-tune and validate the various components of the program.

The off-pump coronary artery bypass simulation program: a working example

Using the proposed framework, we have developed, at the University of Toronto, a simulation-based program for the off-pump coronary artery bypass surgical procedure. Currently, off-pump coronary artery bypass is performed by 16% of cardiac surgeons in Canada and 30% of cardiac surgeons worldwide.39 The procedure is complex, technically challenging, and difficult to teach using the apprenticeship model, all of which make it suitable for demonstrating the use of simulation as an alternative teaching mechanism.

The Aim stage

Established task analysis and situation awareness techniques20,40 were implemented to identify the training needs by observing and video-recording the performance of 1 expert cardiac surgeon.

The FineTune stage

Using the diagrammatic language of the MCMD modeling tool,13 the expert performance baseline was mapped into a task flow diagram and subsequently refined using additional observations and interview sessions with a panel of experts. The experts indicated the features of the required simulation technology, and it was decided that all the 6 progressive levels will use the same teaching methodology (ie, expert-guided and progressive training program).

The FollowThrough stage

Following the principles of the challenge point framework,11 a set of tasks classified as progressive in difficulty according to the MCMD levels were selected, and the corresponding simulation scenarios, objectives, and assessments were developed for each 1 (Table 3).

For the assessment component of the program, we designed a set of 6 checklists, consisting of 12 to 36 assessment items.

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Principles of conditions of practice including feedback with brief descriptions9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principle</td>
<td>Implication for Teaching</td>
</tr>
<tr>
<td>Amount of practice</td>
<td>More is better</td>
</tr>
<tr>
<td>Variability of practice</td>
<td>Go from all angles</td>
</tr>
<tr>
<td>Random vs block practice</td>
<td>Mix it up</td>
</tr>
<tr>
<td>Part vs whole practice</td>
<td>Do it all</td>
</tr>
<tr>
<td>Practice specificity</td>
<td>Do it like it is</td>
</tr>
<tr>
<td>Frequency of feedback</td>
<td>Less is better</td>
</tr>
<tr>
<td>Timing of feedback</td>
<td>Just wait</td>
</tr>
<tr>
<td>Bandwidth feedback</td>
<td>Just give me the extremes</td>
</tr>
<tr>
<td>Observational learning</td>
<td>Learn from others</td>
</tr>
<tr>
<td>Mental practice</td>
<td>Imagine it</td>
</tr>
</tbody>
</table>
validate the proposed assessment checklists for each training level, a Delphi technique was used with a panel of 11 experts (cardiac surgeons from various hospitals in Toronto). We asked the panel of experts to rate each item of each checklist using a scale ranging from 1 (not applicable) to 5 (extremely applicable) and to provide comments on the rating choice. We performed 3 Delphi rounds and analyzed the results in terms of consistency and variability of the ratings. Consistency, also interpreted as consensus, was achieved, similarly to Green, when 70% of experts rated 3.5 on our 5-point, Likert-type scale. The standard deviation was used to measure variability of subjects’ responses in successive iterations.

### Future directions

In the previous sections, we have demonstrated the feasibility of designing a simulation-augmented training program for off-pump coronary artery bypass surgery. In this example, the MCMD technique was used to perform an objective needs assessment and to guide the design of the individual training activities, which trainees are introduced to higher levels of task difficulty as they move from station to station. From our perspective, the training objectives determine both the complexity of the activity and the use of the simulation by changing the context in which the simulator is placed, without necessarily changing the simulator

<table>
<thead>
<tr>
<th>Training Level*</th>
<th>Training Station</th>
<th>Objectives</th>
<th>Simulator</th>
<th>Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skill level</td>
<td>1. Knot tying</td>
<td>● Complete a single 2-handed square knot</td>
<td>Knot tying SmartSIM prototype</td>
<td>● Appropriate tension&lt;br&gt;● Knot security&lt;br&gt;● Efficiency of motion&lt;br&gt;● Watertight anastomosis&lt;br&gt;● Symmetry&lt;br&gt;● Efficiency of motion</td>
</tr>
<tr>
<td></td>
<td>2. Suture of anastomosis</td>
<td>● Perform the suturing step for a standard vascular anastomosis</td>
<td>Penrose drains (5-mm plastic tube model using prosthetic graft and either 6-0 or 7-0 polypropylene suture)</td>
<td></td>
</tr>
<tr>
<td>Subtask level</td>
<td>3. Proximal anastomosis on ascending aorta</td>
<td>● Perform the complete anastomosis on the static heart between the ascending aorta and the SVG to the RCA</td>
<td>Plastic model of a heart, plastic tube model for vascular anastomosis (5 mm), 6-0 polypropylene suture</td>
<td>● Application of clamp&lt;br&gt;● Arteriotomy: round and full thickness&lt;br&gt;● Lie of anastomosis: parallel to aorta&lt;br&gt;● Suturing&lt;br&gt;● Exposure&lt;br&gt;● Application of Octopus stabilizer&lt;br&gt;● Application of Silastic&lt;br&gt;● Arteriotomy and proper shunt</td>
</tr>
<tr>
<td>Task level</td>
<td>4. Distal anastomosis on beating heart</td>
<td>● Perform a complete anastomosis on the beating heart between the LIMA and the LAD</td>
<td>Mechanical model for beating heart surgery, plastic tube model for vascular anastomosis (5 mm)</td>
<td></td>
</tr>
<tr>
<td>Procedure level</td>
<td>5. Distal anastomosis on beating and enucleated heart</td>
<td>● Perform enucleation&lt;br&gt;● Perform complete anastomosis on the enucleated beating heart between the SVG and the OM artery</td>
<td>Mechanical model for beating heart surgery, plastic tube model for vascular anastomosis (5 mm)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6. Distal anastomosis on beating and enucleated heart including crisis management</td>
<td>● Perform enucleation&lt;br&gt;● Prepare for anastomosis on the enucleated beating heart between the SVG and the OM artery&lt;br&gt;● Demonstrate appropriate interaction with the anesthesia team</td>
<td>In-situ simulation: the same equipment for station 5 will be transferred to the operating room and a crisis scenario will be implemented&lt;br&gt;● Suturing&lt;br&gt;● Enucleation of heart&lt;br&gt;● Application of Octopus stabilizer&lt;br&gt;● Application of Silastic&lt;br&gt;● Arteriotomy and proper shunt&lt;br&gt;● Teamwork and communication</td>
<td></td>
</tr>
</tbody>
</table>

LAD = left anterior descending coronary artery; LIMA = left internal mammary artery; OM = obtuse marginal; OPCAB = off-pump coronary artery bypass; RCA = right coronary artery; SVG = saphenous vein graft.

*Skill level: 1 technical activity with no cognitive load; subtask level: 1 technical activity with low cognitive load; task level: >2 technical activities with medium cognitive load; procedure level: >2 technical activities with high cognitive load.
itself (from “an isolated bench top” to “a bench top attached to a standardized patient” to “a bench top within a team activity in the operating room”). In addition, assessment tools were provided and validated.

Comments

Since the inception of simulation in surgical education and training in the early 1990s, much effort has been focused on validating the individual simulators, which were promoted initially by the demonstration of engineering principles. In the early 2000s, designers focused on achieving clinical reality for those simulators. However, the time has come to start developing ways of integrating simulators into surgical training. Therefore, efforts should now turn toward education-based designs that require a research-centered view to develop validated simulation-augmented curricula.

In this report, we have provided the Aim – FineTune – FollowThrough process for guiding the design of simulation-augmented surgical education and training programs. We have identified 4 issues within the current design process of simulation-augmented programs: (1) the lack of an objective identification of training needs (ie, needs assessment), (2) the lack of a systematic design methodology, (3) the lack of structured assessments of performance, and (4) the lack of a research-centered evaluation.

We believe that our Aim – FineTune – FollowThrough process is in accordance with existing literature about simulation and its integration into surgical curricula. Specifically, the Aim components allow us to address Kneebone’s criteria for evaluating simulations: “(1) Simulations should allow for sustained, deliberate practice within a safe environment, ensuring that recently acquired skills are consolidated within a defined curriculum which assures regular reinforcement; (2) simulations should provide access to expert tutors when appropriate, ensuring that such support fades when no longer needed; (3) simulations should map onto real-life clinical experience, ensuring that learning supports the experience gained within communities of actual practice; and (4) simulation-based learning environments should provide a supportive, motivational, and learner-centered milieu which is conducive to learning.” Furthermore, our FineTune and FollowThrough components, serve as a guide to address Windsor’s questions for designing evidence-based proficiency curricula: “What should be the difficulty setting for each task?” “Has the validity for each difficulty setting been established?” “Has the learning curve for each setting and task been assessed?” and “Have performance proficiency criteria been established for procedures on the basis of expert assessment?” Additionally, in accordance with Sweet et al., we believe that the Aim – FineTune – FollowThrough process provides a clear structure to perform validity studies running concurrently with the design development. Following Sweet et al’s logic, the learning outcomes are initially defined during the Aim stage, which guide the design of the training exercises (ie, selecting the simulation resources and defining the conditions of the exercise). Content validity of both the training exercises and the assessments can be tested during the FineTune stage. Defining the standards to determine relative competence and mastery of skills will take place during the initial phase of the FollowThrough stage; substantive, structural, generalizability, external and consequential types of validity can be targeted at the later phase of the FollowThrough stage.

Although simulation program designers will use different strategies according to their particular training needs, we believe that following a systematic “way of thinking” about the design process, such as the one proposed in this paper, will help in optimizing time and resources and, most important, will assist in moving the program design task from pure application toward a research-driven activity.

References

41. Green P. The content of a college-level outdoor leadership course. Presented at: Conference of the Northwest District Association for the American Alliance for Health, Physical Education, Recreation, and Dance; 1982: Spokane, WA.