Technology-Enhanced Simulation and 3D-Enabled Learning in Orthopaedic Postgraduate Education: Challenges and Practical Priorities

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Abstract

Orthopaedic simulation is often discussed as a choice between a screen, a printed model and a virtual-reality system. That choice comes later. A teaching session first needs a clinical task, such as selecting cup landmarks, explaining an acetabular reduction sequence or keeping a drill within a safe corridor. This perspective examines recent work on virtual simulation and three-dimensional (3D) models in postgraduate orthopaedics. The evidence is encouraging for selected procedural and anatomical outcomes, but it is heterogeneous and gives limited guidance on transfer to patient care. We use the case as the unit of curriculum design. The learner interprets the images, commits to a plan, rehearses the relevant step and then accounts for errors. A subsequent case should alter something clinically important rather than repeat the same geometry. Kern's curriculum framework, deliberate practice, debriefing, validity arguments and entrustment provide reference points for planning and assessment. The practical conclusion is modest: use the least complex medium that exposes the decision or action requiring practice, and do not treat a simulator score as clinical competence.

Keywords

Orthopaedic postgraduate education; Technology-enhanced simulation; 3D-enabled learning; Competency-based education; Surgical training.

1. Introduction

Operating-room experience remains the centre of orthopaedic training, but case mix does not repeat itself on schedule. A trainee may see several routine fractures and no opportunity to plan an unusual reconstruction; another may assist in a complex case without being able to repeat the decisive step. Simulation is useful in this narrow space between explanation and patient care. It permits an attempt to be stopped, examined and repeated. Across health professions, technology-enhanced simulation has shown an overall educational benefit, although the interventions and outcome measures are notably heterogeneous [1]. Orthopaedic residents surveyed in several countries have also expressed strong support for a formal place for simulation in training [2]. Neither finding tells a department which device to buy, but both justify a closer look at programme design.

Some terminology is easily blurred. Here, technology-enhanced simulation means computer-supported practice, including virtual or augmented environments and interactive procedural simulators. The broader phrase 3D-enabled learning includes digital reconstructions and

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physical 3D-printed models. The latter originate from digital images but are not digital simulations. This distinction matters because a model held in the hand, an image rotated on a workstation and an instrument tracked in a virtual field offer different forms of learning.

This article is a perspective rather than a report of an implemented intervention. It draws on recent literature to examine three practical matters: matching a technology to an orthopaedic task, arranging practice so that it progresses beyond one demonstration, and deciding what a simulator score can reasonably mean.

2. What the Technology Can and Cannot Do

2.1. From Images to Decisions

Take preoperative planning for total hip arthroplasty. A manipulable pelvis may help the trainee see version, pelvic tilt or bone loss. That is a useful start, not the end of the exercise. The trainee still has to state which landmarks will be trusted, select a target and explain what would change if the anatomy or position were different. With an acetabular fracture model, the required output changes: identify the fragments that block reduction, choose an exposure and set out the sequence. Merely recognising the fracture after seeing it in 3D adds little to an operative plan.

Published studies support using these tools, but they do not settle every local teaching question. Reviews of virtual reality in orthopaedic and surgical training describe gains in selected procedural measures, with substantial differences in operations, comparators and endpoints [3-5]. Reviews of 3D printing report a similar pattern: complex anatomy may be easier to learn, while the underlying study designs remain varied [6,7]. Printed models have also been studied with orthopaedic trainees learning acetabular fractures [8]. A favourable review is therefore a reason to test a defined use, not proof that a particular device will improve all parts of surgical learning.

2.2. The Task Changes Across Subspecialties

Orthopaedic subspecialties share anatomy and operative discipline, but they do not ask the learner to solve the same problem. Arthroplasty planning turns on orientation, alignment and restoration of anatomy. Trauma adds a reduction sequence and a fixation construct. In spine surgery, a few millimetres may define a safe corridor; in tumour surgery, the discussion extends from resection margin to the reconstruction left behind. A platform that records a drill trajectory may therefore be valuable for one task and irrelevant to another.

This variation does not require six unrelated curricula. A common case format can still ask what the learner saw, what plan was chosen, which part was rehearsed and where the principal risk lay. The clinical content then changes with the subspecialty. Recent work combining 3D printing with case-based learning in orthopaedic residency education is useful because the model was placed within a clinical problem rather than offered as a stand-alone display [9].

2.3. What Happens After the Attempt

A simulator usually returns something measurable: time, accuracy, path length or completion of steps. Those numbers are convenient, but none interprets itself. A fast attempt may be fluent or merely hurried. An accurate trajectory may still follow a poor indication. Confidence and satisfaction may show whether trainees will accept the session, but they cannot establish retention. They belong alongside, rather than in place of, performance on a later or altered task.

Useful feedback is tied to the error just seen. If orientation was lost, the replay should stop at that moment. If two plans differ, the learner should explain the trade-off before trying again. A review of debriefing in healthcare simulation found considerable variation and no consistently superior method [12]. The format can therefore remain simple: show the discrepancy, ask the

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trainee to account for it and repeat the relevant part. A generic discussion at the end is less useful than a short correction that changes the next attempt.

3. Building a Workable Programme

3.1. Start with a Case, Not a Device

Curriculum design starts before the simulator is switched on. Kern's six-step approach offers a familiar order for describing the problem, the learners, objectives, teaching method, delivery and evaluation. Its use in health-systems science shows that it can be applied to a defined curricular component rather than only to a whole course [10]. In an orthopaedic module, the starting problem might be quite specific: trainees recognise a deformity on CT but cannot translate it into a reproducible plan, or they lose orientation when a safe corridor is viewed from an unfamiliar angle. Writing the problem at this level makes the choice of medium easier.

An interactive reconstruction suits a problem of spatial interpretation. A physical model is better when hand position, access or the relation of an implant to bone must be explored. A tracked virtual task becomes worthwhile when repeated attempts and an objective error measure matter. Sometimes none is needed; a disputed indication can be taught better through a case conference. Fidelity earns its cost only when it preserves the feature on which the learner's judgement depends.

3.2. Progression Without More Hardware

One demonstration can introduce a technique; it cannot show that the trainee can use it again. Deliberate practice is relevant because it couples an observed attempt with focused feedback and another attempt. Rapid-cycle formats have produced favourable immediate learner outcomes, although a scoping review found variable implementation and limited evidence of superiority over other simulation approaches [11]. The important feature is not the label attached to the cycle, but whether repetition addresses an identified weakness.

Cases can be made more difficult by changing one feature at a time. The first task may use labelled anatomy and a conventional solution. The next can change version, bone stock, fracture line or a structure at risk. Later, the trainee may have to choose between two defensible plans and state the trade-off. This is more informative than repeating an unchanged model until the route is remembered.

3.3. Scores, Competence and Entrustment

A simulation record can support competency assessment, but it needs more than a completion time. Direct observation and feedback remain central to competency-based assessment [13]. For a planning task, the record might include image interpretation, choice of approach, proposed steps and the response when new information is introduced. For an instrument task, essential safety steps can be checked while overall fluency is rated separately. Agreement between observers remains a property of the assessment process, not of the hardware.

Problems arise when a precise measurement is given an imprecise meaning. A deviation of two degrees may be measured reliably, yet the task may still represent only one small part of the operation. Messick's and Kane's validity frameworks prompt questions about content, response process, reproducibility and consequences [14]. Those questions become more important if the score will influence progression. Before setting a pass mark, educators should be able to say what the score supports and what it does not.

Entrustable professional activities place the question back in clinical work: how much supervision does this trainee need for this activity? A national pilot in general surgery found EPA implementation feasible but variable across programmes [15]. Simulation may inform that judgement by exposing gaps in planning or execution. It cannot establish independent clinical

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readiness on its own, because it does not reproduce the full patient, team or operating-room context.

3.4. Keep Implementation Feasible

A programme can fail for ordinary reasons: the workstation is unavailable, the model takes too long to prepare, or no faculty member has time to review the attempt. A short library of reusable case formats is likely to be easier to maintain than a collection of unrelated demonstrations. Each case needs enough information for another teacher to run it: the learner's task, likely errors, the points worth discussing and the basis for judging the response.

Budget discussions are easier when each item is linked to a teaching function. A synthetic model may be sufficient for orientation or instrument handling. A virtual platform has a clearer role when it permits repeated attempts, captures a meaningful error or represents a hazard that a simpler model cannot. Initial evaluation should stay close to what was delivered: completion, feasibility, consistency between raters and change on the defined task. Claims about operating-room transfer require a different design and longer follow-up.

4. Discussion

Technology is the visible part of a simulation programme, so it tends to dominate its description. The consequential decisions are less visible: which error is being made, what representation exposes it and what the learner must do differently on the next attempt. A department may therefore build a strong session around a modest model. An expensive system can add little if the task ends with passive viewing or an uninterpreted score.

Transfer is the uncomfortable test. Improvement on one saved case may reflect genuine learning, growing familiarity with the interface or memory of that particular geometry. An altered case is a useful check, and a delayed attempt is better still. Fidelity raises a related problem. Visual realism can be impressive while preserving little of the decision under study; conversely, a simplified model may retain the critical landmark or hazard. The relevant question is not how closely the model resembles an operation in general, but which part of the operation it represents well enough for the intended lesson.

For these reasons, reports of orthopaedic simulation would be more useful if they described the original educational difficulty, the feedback and the intended interpretation of the outcome with the same care given to the hardware. Local programmes also need room to adapt. Faculty time, case availability and training requirements differ, and a design that cannot be repeated in its own setting has limited educational value.

5. Conclusion

Technology-enhanced simulation and 3D-enabled learning are most useful when each is given a specific job. A reconstruction may make anatomy visible, a printed model may make access tangible, and a virtual procedure may permit a step to be repeated. None replaces the clinical judgement required to choose and adapt an operation.

The practical sequence is straightforward even when the case is not: begin with the learning problem, observe what the trainee does, discuss the error, and test the same principle in another case. Simulation can prepare a trainee for supervised clinical work and show where further practice is needed. Responsibility for patient care must still be judged in clinical settings and over time.

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