

Editorial

Voices in Orthopaedics™...The Residency Programs: From The University at Buffalo- Evaluating the Role of the Learning Curve in Orthopaedic Residency Education: A Review

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Orthopedic surgical educational strategies have rapidly advanced, driven by increasing technical complexity in the breadth of procedures within the specialty, the introduction of novel educational supplementation including simulation-based training, and the introduction of structured feedback mechanisms to encourage competency-based training. The learning curve for various common orthopedic procedures have been previously evaluated and described; however, these changes to orthopedic education need to be considered with regards to their effect on learning curve. Increased standardization of educational curricula, including case minimums and definitions of the levels of supervision at various training levels, must be additionally considered with respect to the learning curve for procedures for which orthopedic residents must become competent during training. This review underscores the need for tailored training paradigms emphasizing high-volume exposure for complex procedures and structured simulation for skill-based learning. Standardized definitions of supervision should be included in updated assessments of the learning curve to better inform orthopedic educational initiatives.

INTRODUCTION

Understanding how surgical skills develop over time is central to evaluating training in orthopedic surgery. Progression toward procedural competence is often described using the concept of a learning curve, which reflects improvements in performance with increasing experience and operative exposure. In surgical training, this is commonly quantified by the case volume needed to reach procedural competence. Across diverse surgical contexts, studies have demonstrated the existence of a learning curve. These find-

ings reflect the progression of both technical skills and operative efficiency over time, supporting the use of measurable indicators to assess training outcomes, particularly in complex cases (D'Ambrosi et al. 2024; McCulloch et al. 2021). In orthopedic surgery, performance is frequently assessed using surrogate measures, including simulation training, operative time, complication rates, intraoperative fluoroscopy time, postoperative radiographic findings, and patient-reported outcomes (D'Ambrosi et al. 2024; McCulloch et al. 2021; De Boey et al. 2020).

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The scope of orthopedic practice includes a diverse set of conditions, each associated with distinct management strategies and potential complications. Through orthopedic surgery residency training, trainees are expected to become proficient at managing these conditions. This review examines existing assessments of the learning curve within the context of modern orthopedic surgery training. Recent changes in orthopedic training include the adoption of new educational strategies, integration of emerging technologies, and influence of standardized feedback models that align with recent changes in educational policies. These developments are important in shaping future educational benchmarks in orthopedic training.

DISCUSSION

ORTHOPEDIC SURGERY TRAINING: A CHANGING LANDSCAPE

Contemporary orthopedic training is shaped by growing scrutiny and policy emphasis on patient safety, resident supervision, and operative efficiency. At the same time, subspecialization has increased, along with rapid emergence of novel instrumentation and technologies, which continue to influence residency education. The COVID-19 pandemic further disrupted surgical education, reducing operative exposure for residents in both the United States (Iqbal et al. 2021; Higginbotham et al. 2021), as well as internationally (Brouwers et al. 2023; Al-Jabir et al. 2020; Moldovan et al. 2022). As noted by De Boey et al (2020), training has shifted away from the previous model of “see one, do one, teach one” as it is no longer sufficient for preparing residents in the current orthopedic landscape (De Boey et al. 2020). Orthopedic training will require continued shifts from traditional teaching models with increasing adoption of multimodal educational approaches to optimize learning.

IMPACT OF TRAINING LEVEL ON SURGICAL OUTCOMES IN ORTHOPEDIC PROCEDURES

Within orthopedics, it has been consistently observed that junior surgeons require more time to perform surgeries and benefit from guidance by more experienced surgeons. Increased supervision by senior surgeons is associated with a reduction in reoperation rates among junior surgeons, highlighting the critical role of structured guidance during training (Palm et al. 2012), however, the definition of “supervision” remains inconsistently defined. Furthermore, a trainee’s level of experience does not fully account for differences in performance. Although more experienced surgeons tend to perform better overall, there is notable overlap, with some trainees performing at a level comparable to, or exceeding, that of fully trained surgeons. This variability suggests that experience alone is not a reliable measure of competence and highlights the need for objective performance evaluation to verify competency across all levels of training and practice (Kojima et al. 2022). Even among attending surgeons, skill levels are not uniform and additional sub-specialized training can further influence surgi-

cal ability and performance (Burnett et al. 2024; Shaath et al. 2023; Ottesen et al. 2023; Gombera et al. 2020).

QUANTIFYING SURGICAL PERFORMANCE

Measuring surgical performance is inherently complex, as common metrics don’t fully encapsulate true technical ability. Learning curves are commonly evaluated using estimated blood loss (EBL), fluoroscopy time, operating room time, and complication rates. However, these metrics are not without limitations, as they are indirect representations of skill and influenced by multiple external factors. Within orthopedics, blood loss is commonly used to measure performance and is particularly important in procedures where higher volumes of blood loss are expected, however, reporting is often inconsistent and inaccurate. It has been found that various OR team members, including surgeons, anesthesiologists, nurses, and technicians, demonstrated errors greater than 25% when it comes to reporting EBL, with only 27% showing consistent reporting across various OR settings (Rothermel and Lipman 2016). This variability indicates that numeric estimations can be highly subjective and unreliable, and the use of categorical ranges, such as minimal, moderate, and large, may be a better scale for reporting EBL.

Fluoroscopy use is another metric used to assess surgical ability, which reflects technical performance and radiation exposure to the patient. Within orthopedic education, simulation training in the setting of wire navigation in supracondylar humerus fracture fixation resulted in fewer numbers of images taken and less time to complete wire placement (Thomas et al. 2023). Similarly, a performance improvement program focused on standardizing intraoperative imaging views in the setting of peritrochanteric fractures and found decreased fluoroscopy time, as well as improved fracture reduction quality and implant positioning accuracy (Rikli et al. 2018). Virtual reality-based training has also been found to reduce operative time and radiation exposure in lateral lumbar interbody fusion procedures (Zaki et al. 2024). Collectively, these findings demonstrate that targeted educational interventions can enhance efficiency, optimize imaging use, and improve technical performance of surgeons in the operating room.

Complication rates provide an outcome-based measure of surgical performance and are frequently used to evaluate progression along the learning curve. Similarly to fluoroscopy time, targeted educational interventions have been effective in improving complication rates (Waterman et al. 2016). Multiple studies have analyzed outcomes such as complications, revision rates, operative duration, and systemic complications to assess the impact of resident involvement on patient safety. While attending presence has been associated with better overall outcomes (Kashner et al. 2023), resident involvement alone does not increase the risk for major complications (Mitchell et al. 2016; Cvetanovich et al. 2015), although it may lead to longer operative times (Khazi et al. 2021; N. J. Lee et al. 2018; Gulbrandson et al. 2020; Lebedeva et al. 2021). A large multi-center retrospective cohort study assessing 7,125 total joint replacements found no difference in surgical site complica-

tions, revision rates, or mortality between cases involving residents versus those performed by attending surgeons alone. However, a slight increase in systemic complications was observed in cases involving residents, most commonly related to urologic issues rather than surgical technique, and likely attributable to prolonged operative times (Bron et al. 2021). These findings indicate that operative time is not just a measure of efficiency, but also a measure that is linked to complication risk.

Despite widespread use of these measures, accurately capturing surgical performance remains challenging, as no single metric fully reflects surgical skill. Commonly used metrics, including those contributing to the establishment of surgical learning curves, often fall short of a true and full consideration for the nuance associated with surgical skill and their correlation to patient outcomes.

COMPARING LEARNING CURVES IN ORTHOPEDIC SURGERY: CASE VOLUME, PROFICIENCY TIMELINES, AND TARGETED TRAINING STRATEGIES

The number of cases required to achieve proficiency in orthopedic procedures varies widely depending on the operation being performed. For example, thoracic pedicle screw placement in scoliosis correction requires approximately 60 screw insertions to achieve competency comparable to experienced surgeons (Gang et al. 2012). In total knee arthroplasties (TKA), a detailed analysis of 67 procedural steps demonstrated that junior trainees commit significantly more errors than senior surgeons, suggesting that this procedure has a steeper learning curve (Hafez et al. 2023).

Hip arthroscopy has likewise been found to have a steeper learning curve compared to other arthroscopic procedures, which may be attributed to factors such as relative novelty, less established training frameworks, limited validation of simulation-based training, and challenging anatomy (De Boey et al. 2020; Haipeng et al. 2021; Kautzner et al. 2018). Despite these challenges, evidence suggests improvement with experience, specifically with portal placements, which has shown that fewer complications occur with increasing case volume. After a surgeon has performed 100 cases, there are likely to be fewer complications, decreased operative time, and improved patient outcomes (Konan et al. 2011; Kautzner et al. 2018). While it is believed that residents will achieve basic competency for hip arthroscopy after performing 20 cases (Lee et al. 2013), a more realistic estimate of full proficiency is likely to be closer to 100 cases (Kautzner et al. 2018).

Procedures with steeper learning curves, particularly those involving newer technologies, may benefit from simulation training as a supplement to real surgical experience, especially when case volume is limited or procedures are technically difficult. Advances in simulation, including the incorporation of haptic feedback to mimic tactile sensation and enhance realism, allow for better translation to the operating room (De Boey et al. 2020). In hip arthroscopy training, virtual reality simulations demonstrate an increase in performance after as few as three sessions, however, performance metrics plateau after approximately six sessions (Bartlett et al. 2020). Similarly, an 8-week struc-

tured curriculum used in microvascular surgery showed a decrease in procedure time (37 to 24 minutes) and an increase in patency rates (50% to 92%) (Selber et al. 2012). Structured and simulation-based training helps to speed up early skill development, eventually improving efficiency and outcomes, while also reducing the reliance on high case volumes in order to achieve competency.

Not all procedures are equally complex to learn, as some have shorter learning curves with proficiency achieved early in training. For example, femoral intramedullary nailing requires approximately 20 cases to achieve proficiency, with associated reductions in both operative time and blood loss (Li et al. 2017; Altintas et al. 2014). In the setting of nondisplaced femoral neck fixation, the learning curve is minimal, as outcomes are consistently successful, suggesting that proper technique is more important than case volume (Y. K. Lee et al. 2018). In studies that compared differences between junior and senior residents in hip fracture fixation, there is no significant difference in complication rates, but junior residents demonstrated both increased operative time and fluoroscopy use compared to seniors (Haslhofer et al. 2023). For procedures with shorter learning curves, early trainees can achieve safe outcomes under supervision, as patient safety is not volume-dependent, whereas efficiency is likely to improve with accumulated experience.

ENHANCING ORTHOPEDIC SURGICAL TRAINING: EFFECTIVE EDUCATIONAL STRATEGIES AND COMPETENCY-BASED MODELS

As orthopedic surgery continues to evolve, effective educational strategies are needed to address constraints in training, including the work-hour restrictions. One learning strategy that has proven to be effective is known as active retrieval, which is when a learner actively recalls and documents procedural steps. A randomized trial compared active retrieval to passive studying in the setting of fracture fixation training and found that although the passive group had a better initial performance, they demonstrated a decline in recall of procedural steps and in correct instrument identification over time. In contrast, the active retrieval group showed 80-90% retention after one-week (Ndoja et al. 2022). These findings demonstrate that active retrieval improves long-term retention and supports procedural competency.

Orthopedic surgeons practice in diverse settings, necessitating tailored educational models to meet the demands of different subspecialties. For instance, trauma surgery requires a different skill set than clinical sports medicine. To address this, newer educational approaches have shifted away from assigning residents based solely on service needs toward allocating cases based on educational value. This model has been shown to increase the number of procedures performed by trainees, as well as the number of cases where trainees had the opportunity to be the primary surgeon, indicating that intentional case allocation improves training experiences (Morris et al. 2016). A second model highlights the importance of real-time, standardized, predictable feedback systems. One example is the Image-based Decision Error Analysis (IDEA) score, which was used to

evaluate residents based on imaging-related decision-making during wire navigation in hip fractures, which demonstrated an inverse relationship between experience level and decision errors (Long et al. 2021). This scoring system provides trainees with specific areas for improvement as well as a structured framework to self-reflect on their skills. Together, these models enhance training efficiency and allow for targeted skill development.

Orthopedic education has shifted towards competency-based education with the goal of improving resident assessment and progression. The traditional time-based training model consists of a fixed duration, typically five years, with progression tied to time rather than skill. In contrast, the competency-based training model emphasizes progression based on ability, rather than time spent in training. The American Board of Orthopaedic Surgery (ABOS) is the governing body that sets the standards for orthopedic training, and has recently initiated the Knowledge, Skills, and Behavior Program. This initiative tracks resident development through standardized assessments, provides real-time feedback, and focuses on readiness for independent practice (Van Heest et al., n.d.). Competency-based models improve assessment quality, allow individualized progression, and enhance training outcomes.

EVOLVING TRENDS IN ORTHOPEDIC RESIDENCY EDUCATION AND THEIR IMPACT ON EARLY ATTENDING PREPAREDNESS

The current climate of orthopedic education has changed due to evolving methods and major disruptions, such as the COVID-19 pandemic. The ongoing evolution of training has resulted in variation in experience, affecting both autonomy and confidence. Notably, differences in case volume persist, with residents in the 90th percentile performing significantly more cases than those in the 10th percentile, suggesting that differences in exposure may impact both confidence and technical skill at the time of independent practice (Morrisey et al. 2024). An analysis of 3,146 resident case logs from ACGME-accredited orthopedic programs between 2018 and 2022 demonstrated a temporary decline in case volume during the peak of the pandemic in 2020, particularly in arthroscopic procedures, however, overall case volume increased across the study period (Morrisey et al. 2024). These findings indicate that although overall surgical exposure was largely maintained, the reduction in elective procedures necessitated supplementation through alternative training methods. Despite the pandemic affecting caseloads, total procedural exposure per resident increased significantly from approximately 1764 in 2018-2019 to 1899 in 2021-2022, reflecting successful efforts to maintain training volume (Morrisey et al. 2024).

Transitioning from residency to independent practice is associated with a rapid increase in surgical autonomy. However, this shift may not be fully supported by training experiences, as resident operative exposure is limited due to greater patient awareness, increased patient safety concerns, and expanding training experiences outside of the OR (De Boey et al. 2020). Simulation-based training has been developed to supplement skill acquisition while avoid-

ing patient risk, demonstrating improved technical skills outside of the OR (Logishetty et al. 2019). In terms of the validity of simulation-based training, it has been demonstrated that skills transfer well to the OR, particularly in procedures with steep learning curves, such as arthroscopy (Bartlett et al. 2018). The COVID-19 pandemic accelerated the implementation of educational strategies such as virtual learning, web-based teaching, and surgical video review, which has contributed to reduced OR exposure. While these learning models increase participation in discussion-based settings such as didactics and journal clubs, they cannot replace hands-on training (Ehrlich et al. 2020). Surgeons who trained during this period have reported decreased confidence in their technical abilities and decreased perceived readiness as attendings, which they attribute to limited exposure to complex elective cases (Ehrlich et al. 2020). Although learning tools such as simulations and virtual tools are helpful and becoming increasingly necessary, they cannot replace real operative experience. Balanced integration of novel tools while maintaining hands-on exposure will be essential for developing competent and confident orthopedic surgeons.

EVALUATING CASE MINIMUMS IN ORTHOPEDIC SURGERY RESIDENCY: BALANCING QUANTITY, QUALITY, AND SUPERVISION

The Accreditation Council for Graduate Medical Education (ACGME) is the governing body that determines the minimum case requirements for orthopedic surgery residents to ensure adequate surgical exposure prior to graduation (Accreditation Council for Graduate Medical Education 2024). These benchmarks, which are derived from analyses of resident case logs, are intended to provide both breadth and depth of experience necessary for independent practice. However, procedural learning curves must be taken into account when determining if the current case requirements are both sufficient and appropriate. While research shows that case volume is important for skill development, additional factors such as the quality of supervision and case complexity are also critical (Palm et al. 2007). With the recent increase of modern training tools such as simulation, competency-based frameworks, and new educational tools, skill acquisition is no longer limited to live surgical cases (Long et al., n.d.). As a result, traditional assessment of procedural learning curves may not fully reflect the current training landscape. Although case minimums remain a useful benchmark, they do not provide a comprehensive measure of surgical competency, which is also influenced by the degree of resident involvement and quality of supervision during training.

While the ACGME and ABOS both provide a baseline structure for orthopedic training, gaps still exist in defining the quality of training. In particular, there is limited research on how levels of supervision at different stages of training affect competency. There is currently no standardized definition of levels of supervision, limiting consistency across training programs. One proposed approach is to define supervision along a graded spectrum based on attending presence and level of involvement, similar to the feed-

back framework used in ABOS competency-based assessments (Van Heest et al., n.d.). Further research is needed to evaluate how supervision impacts surgical learning curves, as this may help refine minimum case requirements and inform how supervision is structured by governing bodies.

CONCLUSION

Orthopedic education is rapidly evolving, driven in part by increasing technical complexity and the integration of new training methods. This review highlights the need to reevaluate learning curves across common orthopedic procedures, including the metrics used to define competency, the role of simulation, the use of structured feedback, and the range of educational strategies. Greater standardization is needed to improve consistency across training curricula, particularly in defining levels of supervision. Training approaches should be procedure-specific rather than uniform, with complex procedures requiring higher case volumes and technical skill development supported by simulation. Ongoing performance evaluation, optimized case distribution, competency-based education models, and clearly defined supervision frameworks with graduated autonomy will be essential. Ultimately, continued advancement in orthopedic education will rely on evidence-based strategies aimed at developing competent and confident surgeons.

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EL, DC contributed to the study design and conception. EL, DC, TR MG and ZT contributed to literature review and drafting of the initial manuscript. EL, DC, TR MG and ZT contributed to final edits. All authors read and approved the final manuscript.

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