Virtual Reality Anterior Cervical Discectomy and Fusion Simulation on the Sim-Ortho Platform: Validation Studies

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ABSTRACT

Background. Spinal surgery encompasses a highly complex and multi-faceted combination of skills. Recent advancements in technology have allowed for the development of virtual reality spinal surgery simulators. Due to their ability to record large datasets, these simulators can be used as an educational tool to provide residents with opportunities to practice surgical skill without restrictions imposed by operating rooms, supervision, or patient cases. An important step in determining a simulator's potential as an educational tool is the analysis of face, content, and construct validity.

Objective. The objective of this study was to assess face, content, and construct validity of a C4-C5 anterior cervical discectomy and fusion simulation on the Sim-Ortho virtual reality platform.

Hypothesis. The anterior cervical discectomy and fusion simulation on the Sim-Ortho virtual reality platform is reflective of the real-life operative procedure and is capable of differentiating surgical skill based on level of training.

Methods. Spine surgeons, spinal surgical fellows, and neurosurgical and orthopaedic residents performed a C4-C5 anterior cervical discectomy and fusion simulation on the Sim-Ortho platform with haptic feedback using a series of instruments specified for each step assessed. Participants were grouped into 3 categories: post-resident (spine surgeons and spine fellows), senior resident, and junior resident groups. Face and content validity were evaluated using a 7-point Likert scale questionnaire. Each procedural step: disc exposure, disc removal, osteophyte removal, and removal of the posterior longitudinal ligament was considered an individual component during metric generation and analysis. Construct validity was evaluated by investigating differences between the 3 groups on a series of metrics derived from the virtual reality simulator data. The Kruskal-Wallis test was used to compare groups and the post-hoc Dunn's test with a Bonferroni correction was used to investigate differences between groups on significant metrics.

Results. Twenty-one individuals were included in the study: 9 post-residents, 5 senior, and 7 junior residents. The post-resident group rated face and content validity, median ≥4, for the overall procedure and at least one instrument in each of the 4 steps. Significant differences (p<0.05) were found between the post-resident group and junior and/or senior residents on at least one metric for each of the four steps.

Conclusions. Our study has demonstrated face, content, and construct validity for the C4-C5 anterior cervical discectomy and fusion scenario simulation on the Sim-Ortho platform. These results support the potential use of this virtual reality spine simulation for surgical training.

RÉSUMÉ

Contexte. La chirurgie spinale requiert la combinaison d'une multitude d'habiletés très complexes. De récents progrès technologiques ont permis le développement de simulateurs de chirurgie spinale en réalité virtuelle. Grâce à leur capacité d'enregister de grandes quantités de données, ces simulateurs peuvent être utilisés comme plateforme éducative pour procurer aux résidents des opportunités de pratiquer leurs habiletés chirurgicales sans les restrictions habituellement imposées par les salles d'opérations, la supervision ou les patients. Un important prérequis pour évaluer le potentiel de ces simulateurs en éducation chirurgicale est l'analyse de la validité apparente, la validité de contenu et la validité de construction.

Objectifs. L'objectif de cette étude d'évaluer la validité apparente, la validité de contenu et la validité de construction d'un scénario de simulation de discectomie cervicale antérieure et fusion au niveau C4-C5 sur la plateforme de réalité virtuelle Sim-Ortho.

Hypothèse. Le scénario de simulation de discectomie cervicale antérieure et fusion au niveau C4-C5 sur la plateforme de réalité virtuelle Sim-Ortho de réalité virtuelle reflète la procédure opératoire réelle et est capable de différencier les habiletés chirurgicales de participants en fonction de leur niveau de formation.

Méthodologie. Des chirurgiens spinaux, des fellows, des résidents en neurochirurgie et en orthopédie ont performé une discectomie cervicale antérieure et fusion au niveau C4-C5 sur la plateforme de réalité virtuelle Sim-Ortho en utilisant une série d'outils spécifiés pour chaque étape. Les participants ont été regroupés en 3 catégories : post-résidence (chirurgiens spinaux et fellows), résident « senior » et résident « junior ». Les validité apparente et de contenu ont été évalués en utilisant un questionnaire incorporant une échelle de Likert de 7 points. Chaque étape de la procédure (l'exposition du disque, le retrait du disque, le retrait des ostéophytes et le retrait du ligament longitudinal postérieur) a été considéré comme étant indépendante pendant la génération de l'analyse de mesures de performance. La validité de construction a été évaluée en recherchant les différences entre les 3 groupes sur une séries de métriques dérivées des données du simulateur de réalité virtuelle. Le test de Kruskal-Wallis a été utilisé pour comparer les groupes et le test post- hoc de Dunn avec correction Bonferroni a été utilisé pour étudier les différences entre les groups sur des métriques significatives.

Résultats. 21 personne ont été incluses dans l'étude. 9 poste-résidents, 5 « senior » et 7 « junior » résidents. Le groupe de poste-résidents a obtenu la médiane ≥4 pour l'ensemble de la procédure et ou moins un outil dans chacune des 4 étapes. Des différences significatives ont été trouvées ($p<0.05$) entre le groupe de post-résidents et les résidents juniors et/ou seniors sur au moins une métrique pour chacune des quatre étapes.

Conclusion. Notre étude a démontré la validité apparente, validité de contenu et la validité de construit pour le C4-C5 discectomie cervicale antérieure et fusion en simulation sur le Sim-Ortho plate-forme de réalité virtuelle. Ces résultats corroborent l'utilisation potentielle de cette simulation de colonne vertébrale en réalité virtuelle pour la formation en chirurgie.

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PREFACE AND AUTHOR CONTRIBUTIONS

The thesis presented in the following communication is in the form of a manuscript submitted to the Journal of Neurosurgery: Spine for review. For the purposes of thesis requirements, the manuscript has been extended to encompass a more comprehensive methodology and discussion.

The candidate took a lead role in this study including communications with OSSimTech™ to develop the data file, development of the questionnaires, participant recruitment, data collection, data analysis, result interpretation, and manuscript writing.

Nykan Mirchi and Vincent Bissonnette assisted in data collection. The code for the metrics was used in a previous study which was developed by Nykan Mirchi. This code was shortened to meet the requirements for this thesis.

Dr. Alexander Winkler-Schwartz provided a surgical perspective in the development of the ACDF simulation as well as assisted in developing the metrics recorded by the simulator. Dr. Winkler-Schwartz also assisted in the recruitment of participants and provided knowledge for data analysis.

Dr. Recai Yilmaz contributed to developing the code for the metrics and developing the methodology used in this study.

Dr. Rolando Del Maestro oversaw the entire study including the overall planning and editing of both the manuscript and thesis. Dr. Del Maestro contributed greatly to participant recruitment and provided surgical knowledge to design and improve the Sim-Ortho platform as well as develop the metrics used in this study. He also provided surgical expertise for the interpretation of the results.

ABBREVIATIONS

ACDF: Anterior Cervical Discectomy and Fusion

AE: Adverse Events

AI: Artificial Intelligence

CBME: Competency Based Medical Education

CPD: Continuing Professional Development

CSV: Comma Separated Value

MIST-VR: Minimally Invasive Surgery Trainer – Virtual Reality

MLASE: Machine Learning to Assess Surgical Expertise

OR: Operating Room

OSATS: Objective Structured Assessment of Technical Skills

PGY: Post-Graduate Year

PLL: Posterior Longitudinal Ligament

SD: Standard Deviation

TTPL: Total Tip Path Length

VR: Virtual Reality

INTRODUCTION

Deeply rooted in tradition, the foundation of post-graduate surgical education dates to the 1890s following the development of the apprenticeship based model.[34] Since then, surgical education has become a more dynamic process, diverging away from traditional methods in an effort to improve and optimize training.[46] Post-graduate medical curriculums have faced restrictions in resident work-week hours,[32,56,68] pressures to increase patient safety,[32,56,83] and a push toward competency-based medical education.[83] These issues, combined with the advent of new technology, has resulted in the development and validation of technology-based simulators as a potential adjunct to traditional training methods.

Technology-based simulators encompass a wide variety of digital platforms capable of simulating experiences with differing levels of realism. In particular, virtual reality platforms incorporate touch, auditory, and visual feedback to provide users with a holistic practicing experience.[24] The benefits of virtual reality simulators are manifold including, unrestricted practicing opportunities,[49] novel, and objective assessment measures,[75,82] opportunities for mastery learning,[59] and potential enhancements to patient safety.[8,67] Important in establishing a simulator's effectiveness as an educational device is an assessment of validity. Validation of a simulator establishes its ability to reflect real-life operative procedures and provides evidence that it is, capable of differentiating expertise that are demonstrated in the operating room.[39]

Several surgical fields, including laparoscopic surgery, have demonstrated success with virtual reality simulators for training purposes.[21,43] However, trends across all surgical fields are not universal. For example, the development and validation of spinal surgery platforms have lagged behind other specialties.[59] The need to simulate multiple anatomic structures that require a variety of manipulation techniques poses many challenges.[51,65] Developers face an uphill battle of trying to simulate the force thresholds required for such procedures while also optimizing costs and maintaining realism.[51,65] These difficulties have been contributing factors to the paucity in developing and validating spine surgery simulators.

However, spine surgery is becoming more prevalent as a result of an aging population.[18] Surgical spine procedures to correct degenerated and herniated discs of the cervical spine have been on the rise in recent years and as such, are an important procedure for residents to learn.[18] Cervical spine procedures such as the anterior cervical discectomy and fusion (ACDF) provide residents the opportunity to become proficient in understanding anatomical landmarks, manipulating different tissues, and using a variety of instruments.[62] Practicing opportunities for the anterior cervical discectomy and fusion outside of the operating room are limited to cadavers and benchtop models highlighting a potential avenue for virtual reality simulation to take.[62]

Recently, OSSimTech™ and the AO Foundation developed the first virtual reality anterior cervical discectomy and fusion simulation on the Sim-Ortho platform. The simulated scenario provides residents the opportunity to practice their technical skills outside of the operating room using a platform that is immersive. The study carried out in this thesis investigates the validity of the anterior cervical discectomy and fusion on the Sim-Ortho platform. The objective was to determine if the ACDF simulation is reflective of the real-life operative procedure through the assessment of face, content, and construct validity. As surgical education enters a new technology-based era, the validation of surgical spine simulators is of paramount importance. Studies such as this one contribute to a growing body of literature that support and demonstrate the use of virtual reality simulators as potential educational tools for technical skill training.

BACKGROUND

Surgical Education

The foundation of surgical education is based on the interwoven connection between learning and teaching. It is a lifelong process that begins with a solid training period during residency and continues throughout one's career.[47] This continued learning process is critical to adopting new innovations and delivering optimal patient care.[47] As a trainee, students are required to learn and master a highly complex and multi-faceted combination of skills.[83] Traditionally, trainees master these skills through the apprenticeship based model developed by William Stewart Halsted in 1890.[34] Halsted's approach to residency training developed from a deepening understanding of surgical education and centered around a triadic model of basic science knowledge, research, and graduated responsibility for patient care.[74] Structured around the premise "see one, do one, teach one", students learn alongside a master surgeon while receiving feedback and critically timed instruction until they acquire the competency and skill level required to perform surgeries on their own.[72] This repetitive cycle of learning and teaching has remained a cornerstone of surgical education for over a century. However, restrictions in resident work-week hours,[32,56,68] increased concerns for patient safety,[32,56,83] and a shift toward competency based medical education (CBME)[83] has highlighted a necessity for change in the current structure of residency training programs.

Instrumental in facilitating these changes was a report released by the Institute of Medicine in 2000, "To Err is Human: Building a Safer Health System" which outlined the frequency and cost of adverse events (AEs) in hospitals.[77] An AE is any event caused by healthcare management that results in unintended injury or complications leading to prolonged hospital stays, disability, or death.[23] In 2016 preventable AEs accounted for an estimated 251,000 deaths nationwide, making it the third leading cause of death in the United States.[50] The impact of preventable AE's also causes a substantial burden to the economy with costs estimated to be around $17.1 billion dollars annually.[79] Within the Canadian medical system trends are similar. Data suggests AEs occur more frequently in teaching hospitals and about 36.9% of AEs are judged to be highly preventable.[10] Investigations into medical specialties has uncovered that the most common types of errors are related to surgery and such errors are often related to technical skill.[10] These studies suggest that although AEs are costly to the economy and have an immense impact on the lives of patients, a vast majority may be preventable with appropriate training.

Furthermore, the infrastructure of surgical education underwent a shift in 2003 when the American Council for Graduate Medical Education implemented restrictions on weekly training hours for resident.[41] This mandate went into effect to circumvent accumulating evidence that a vast majority of trainees were experiencing burnout due to prolonged working hours.[3] Burnout is associated with high levels of fatigue and increased stress resulting in decrements in learning and performance and increased risks to patient safety.[16,80] In addition, sleep deprivation associated with burnout often results in adverse effects on the doctor-patient relationship.[16] Restrictions in resident work-week hours promote patient safety and improve quality of life for trainees, however, it limits operative opportunities and crucial learning experiences for surgical residents.[68]

Finally, although the longevity of the apprenticeship model demonstrates its importance and its successes in the medical community, its foundation has been built on what many consider to be a vague definition of "competence".[13,29] Traditionally, certification has been granted to students who pass technical skills examinations and have completed the length of training necessary to deem them competent.[46] This mechanism of certification tends to be subjective and lacks a universal comprehensive analysis of skills.[29] Further, research has demonstrated that a small, but significant, amount of residents graduating from traditional training programs do not feel competent in completing all surgeries required, citing a lack of exposure to certain procedures as a common problem.[37] In diverging from the apprenticeship-based model, medical educators have shifted their focus to a competency-based approach to training and assessment.[46] Rather than centering certification around the length of training and clinical experiences, competency-based medical education (CBME) analyzes the acquisition and application of surgical skills.[46] This model emphasizes clear and objective goals that are derived from the needs of both the patient and society.[29] Competence is achieved through the completion of a long series of explicitly outlined milestones, after which the resident is granted board certification.[29]

This begs an important question: how can residency programs implement competency based training and prioritize patient safety without exceeding the mandated number of working hours? One promising solution is the use of validated technology-based simulators as educational tools.

Technology-Based Surgical Simulators

The evolution of surgical simulation from rudimentary models to high fidelity simulators has largely paralleled the evolution of technology.[8] Inspired from the successes of simulators in the aviation industry, the emergence of computerized medical simulators began in the 1960s with the creation of Sim-One.[1,66] The Sim-One manikin was developed for anesthesiology and was able to breathe, have a heart rate, and blink its eyes.[1] However, the cost of Sim-One combined with little interest in surgical simulation resulted in a lack of further testing preventing the simulator from becoming established as an educational tool.[20] In the years following Sim-One, the pioneering efforts of researchers brought the development of a computerized manikin simulator able to depict physiological responses to a variety of variables including medications.[70] Computerized simulation began to change in 1989 when Jaron Lanier coined the term virtual reality.[19] Lanier's definition of virtual reality described a computer-generated environment that simulates real-life and enables participant interaction.[19,34] One of the first virtual reality simulators described was an orthopaedic simulator for an Achilles tendon repair.[25,70] Importantly, this simulator was the first VR device to be used for preoperative rehearsal.[70] Although rudimentary by today's standards, it spurred the development of numerous other technology-based simulators that have become increasingly effective and versatile tools for surgical training.[8,70] To date, one of the most influential simulators is the Minimally Invasive Surgery Trainer – Virtual Reality (MIST-VR).[86] This surgical simulator was used for training and assessment of fundamental skills in laparoscopic surgery using a box trainer with a computerized graphic image.[8] In a ground-breaking study, Seymour et al. (2002) used rigorous validation methodology to show that training on the MIST-VR improved operating room performance and decreased the number of errors in a laparoscopic cholecystectomy.[76] More recently, the Royal College of Surgeons of England gave continuing professional development (CPD) accreditation to a virtual reality platform.[26] The FundamentalVR platform which simulates a total hip replacement, can now count toward the accumulation of CPD points for practicing surgeons.[26]

Advantages to Simulation Training

Evidence for the advantages of technology-based simulators is robust. Currently, there is a proliferation of technology based simulators involving both virtual reality and augmented reality, both of which may be advantageous to both students and residency programs. Traditional simulation models include benchtop models, cadavers, and animal models.[8,56,59,63] While these models have been shown to effectively train surgeons and improve performance, common drawbacks include availability, cost, realism, and reusability.[8,56,59,63] Technology based simulators offer a direct advantage over traditional methods by providing users with unlimited opportunities for repetitive practice.[49] Through repetitive practice, learners can concentrate on learning basic mechanical skills before entering the OR. This can train residents to automatize certain techniques, ultimately freeing up cognitive space for more complex problems that may arise in the OR.[28] However, repetitive practice does not equate to expert skill nor does it necessarily lead to performance improvement.[42] It has been found that an important process in the acquisition of surgical skill is effortful and engaged practice with informative feedback, called deliberate practice.[28,38,63] Unlike cadavers or animal models, technology based simulators can provide objective and informative feedback without the need for an instructor to be present.[75,82] Simulators can supplement the apprenticeship model by enabling students to gain technical competence in a shorter period of time, thereby rendering itself a useful tool in combating reductions in surgical opportunities.[44]

Additionally, technology based simulators allow for the deconstruction of surgical procedures into independent steps for residents to practice.[51] The conceptual framework for mastery learning proposes a curriculum where the student focuses on practicing one step of a procedure until they demonstrate they have fully mastered the skills and knowledge necessary to complete the step.[84] This framework is often used in the OR to ensure residents receive appropriate practice time without disrupting the length of the surgical procedure.[35] The decomposition of operative procedures into smaller manageable steps can help reduce the lengthy learning curve associated with technical skill acquisition.[51] Numerous technology based simulators have been developed that focus on one aspect of a surgical procedure allowing residents the ability to practice without constraints and master the required set of skills without concerns to patient safety.[59]

One of the most attractive features of technology-based simulators is their ability to record large datasets during simulated surgeries.[83] Datasets recorded by the simulators often include variables about the simulated environment and the users' actions during the simulated task.[5,7,36] Expansive datasets have been used to investigate differences in psychomotor skills that distinguish board-certified surgeons from novices.[5,7,36] Although some of these metrics may be assessed in the OR, the development and analysis of novel metrics is possible with such a dataset. For example, recordings can be made regarding the velocity, force, and acceleration of a tool tip.[75] All of these metrics would be difficult to measure in the OR, but have shown that they are important in differentiating surgical skill.[40]

Furthermore, simulations provide the opportunity for a holistic practicing experience. Through the incorporation of auditory and touch (haptic) feedback, users encounter an environment that more closely replicates the OR.[65] Simulated tissues and the reconstruction of patient specific characteristics, such as bone degradation or bleeding, can be incorporated into the simulation further enhancing realism compared to traditional training models.[65] Haptic feedback in laparoscopic training has been shown to have the greatest benefit for novices in their early stages of surgical training.[60] Such feedback allows operators to identify anatomical structures and improve coordination with a better degree of accuracy.[60]

Finally, simulators may contribute to enhancing patient safety by providing residents with an environment where it is safe to fail.[2,8,67] This environment helps to foster skills for both the prevention and the correction of errors.[2,8] Rather than training residents to avoid errors, educators can teach residents how to work through errors.[2,55,61,67] Skills such as error recognition, countermeasures, and mitigation of negative consequences can be practiced and improved without the inherent risks to patient safety.[9,55,61] Moreover, technology-based simulation can be used to assess factors that may influence performance in the OR, such as sleep deprivation or stress, without the ethical concerns to patient safety.[9,59,84] For example, using a simulated brain tumor resection Bajunaid et al. (2017) found that intraoperative stress associated with uncontrollable bleeding led to a reduction in bimanual psychomotor performance.[9] Analyses such as these, give researchers the opportunity to analyze errors and assess trainee reactions to their mistakes.[9] Such knowledge may provide novel insights that can be used in educational curricula.

Validation

There are extensive advantages to using technology-based simulators. However, before such a tool can be used in surgical curriculums it first must meet several validity requirements. Validation of a simulator provides evidence for its usefulness as an educational tool and demonstrates its potential to transfer practiced skills from the simulator to the OR.[39] Without evidence for validity, a simulator should not be included in training programs and may become obsolete.[27] Traditionally, validation studies in surgical simulation are adapted from the psychological testing standards.[33] Although the standards in psychology have changed to a slightly different framework for validity, today's surgical simulation studies have commonly used the older framework for validity.[14] Categories of validity can be broken up into both subjective and objective measurements.[73] Subjective measurements include both face and content validity.[73] Both forms of validity are established through asking experts their opinions on a variety of questions pertaining to the simulator.[73] Face validity investigates the degree to which a simulator is reflective of the real-life operative procedure; it includes questions regarding the look, feel, and experience of a simulator.[73] Similarly, content validity assesses the extent to which the simulator can measure the task it purports to simulate.[6] Although both these measurements are subjective and subject to error, they can gauge the scope of realism for the simulator. On the other hand, objective measurements of validity are traditionally assessed using the datasets provided by simulators.[81] Both construct validity and predictive validity are common in surgical simulation literature and play a vital role in establishing evidence for a simulator's capability to train surgeons.[73] Construct validity is assessed by investigating if the differences in surgical skill that are seen in the operating room are also reflected in the surgical simulation.[30] The most common way to assess construct validity is by comparing an "expert" group to a "novice" group.[30] By showing differences in surgical performance between these groups, construct validity can be established.[30] Furthermore, predictive validity is another important objective measure. Predictive validity analyzes the extent to which practicing on a simulator translates to improved skills in the OR.[30] Establishing predictive validity is difficult due to problems in accurately correlating clinical outcomes with practice on surgical simulators.[69]

Simulation in Spine Surgery

As we enter a new era of surgical training, the proliferation and assessment of VR simulators in laparoscopic surgery have shown significant benefits.[21,43] However, this trend is not universal across all specialties. In spinal surgery, simulation advancements have been relatively slow.[59] For the most part, current models simulate vertebroplastys or pedicle screw placements.[59] The focus on these procedures likely comes from the fact that they are relatively challenging, but also minimally invasive making them easier to simulate.[59] The results of technology-based spinal simulators are promising. In a meta-analysis conducted by Pfandler et al. (2017), all studies that compared surgical skill performance between a group that used a simulator to those that did not showed that the simulator group performed better on at least one outcome.[59] The relative paucity in the development of VR spine simulators may be due to problems simulating the various anatomical structure. In the operative space, developers are required simulate tissues ranging from soft structures that are easy to manipulate to more dense structures that require greater force.[65] The differences in haptic manipulation and tissue deformity requirements for bone, cartilage, and ligaments within a small simulated space require significant computing power and can be costly to accurately simulate.[51,65] For example, simulations involving hard and rigid structures such as bones has been reported to give users the sensation of being spongy and slippery.[54,82] Additional problems arise in the simulation of bone drilling during spine surgery. The execution of drilling is an important skill to learn, and thus simulate, because it requires experience and dexterity in order for it to be successful.[78] Attempts at simulating drilling are constrained by force limitations of haptic devices and the relatively slow response rate of simulated tools.[82] Additionally, a majority of the available VR spine platforms fail to provide a holistic sensory experience by lacking feedback in multiple modalities (visual, sound, haptic feedback, etc.).[82] Nevertheless, continuous progress is being made to overcome these problems and demonstrable benefits have been proven for a variety of spine simulators.[59] For example, the NeuroVR is a virtual reality simulator that incorporates 3D visual, auditory, and haptic feedback providing users with an immersive experience.[24] The simulator is primarily neurosurgical focused and is capable of simulating spinal surgeries such as a hemi-laminectomy.[24] In this scenario, operators use a burr in their dominant hand and suction in their non-dominant hand to remove the lamina.[24] As the field develops, VR platforms for more complex procedures, such as the NeuroVR, may become available and help in mitigating the serious complications that can ensue from errors during spine surgery.

Anterior Cervical Discectomy and Fusion

A potentially impactful avenue to pursue for spine simulation are surgeries related to the cervical spine. Cervical spine disease has recently become a major concern for both patients and the economy.[18] The rapidly rising age of the population combined with advancements in surgical techniques have led to a significant increase in cervical spine surgery.[18] Introduced in the 1950s, a widely accepted approach to the cervical spine is through the anterior portion of the neck.[89] Amongst the most common procedures is the anterior cervical discectomy and fusion (ACDF) which saw an 8-fold increase between 1999 and 2004.[52]

The ACDF is a spinal procedure used to treat a soft disc bulge or herniation which occurs when the disc annulus becomes weakened resulting in the disc nucleus bulging out.[89] Candidates for an ACDF procedure exhibit pain, motor weaknesses, and potential reflex loss because of cervical radiculopathy.[89] In general, the ACDF tends to be a successful procedure for treating cervical spine disease, but the anterior approach is risky with complication rates as high as 20%.[53,57] The procedure is not considered to be a demanding one, however the ACDF is an important procedure during residency training because it requires residents to become proficient in a variety of areas.[62] The ACDF involves understanding and manipulating a variety of different tissues, all of which require distinct forces and methods of retraction/removal.[62] Thus, in learning the procedure, residents gain knowledge and proficiency in a broad spectrum of surgical skills.

Despite the importance of the procedure during residency training, there have been very few models developed for simulating ACDF's, with the most recent hands-on model released in 2013. The device is a benchtop model made from polyurethane and silicone.[62] Assessments of the device, performed by the Congress of Neurological Surgeons, demonstrated promising potential but lacked anatomic variability and mechanisms for measuring surgical techniques, such as force.[62] Additionally, the model did not undergo any validity testing. Given the relatively small number of simulators available coupled with increased rates of ACDF's, the development and addition of VR simulators capable of simulating such a surgery may be beneficial to residency training and potentially impact the surgical care of a large portion of the population.

Sim-Ortho

The Sim-Ortho virtual reality platform was developed by OSSimTech™ in Montreal, Quebec, Canada. This virtual reality platform has a variety of surgical procedures that can be simulated, including trauma, orthopaedic, and spinal surgery. Sim-Ortho is a stand-alone device that uses a voxel-based platform to achieve a complex and realistic intra-operative experience for the user. The custom-made haptic technology incorporates five degrees of freedom and a tracking system with six degrees of freedom, giving the operator force feedback and real-time tool tracking. In addition, three dimensional stereoscopic glasses and auditory feedback enhance the realism of the experience. Operators can select from a multitude of tools to complete the surgery. Recent validation studies on a similar model, the Sim-K platform, have been conducted using a total knee replacement scenario.[58] Questionnaires assessing face and content validity were rated positively by participants in the study with inexperienced surgeons regarding it more highly.[58] Sim-Ortho uses voxels to create its simulated environment. The use of voxels for surgical simulators is relatively new, however is has been extensively exploited in the field of computer game design as well as medical imaging.[22] In comparison to mesh-based systems that deform when contacting tools, voxels are advantageous because they are removed when interacting appropriately with a tool. This allows researchers to easily visualize the disappearance of voxels over time. One of the surgical scenarios for the Sim-Ortho platform is a C4-C5 ACDF simulation, co-developed by the AO foundation and OSSimTech™.

The following manuscript investigates the face, content, and construct validity of the ACDF simulation on the Sim-Ortho platform. To our knowledge this is the first virtual reality anterior cervical discectomy and fusion simulation.

Manuscript: Virtual Reality Anterior Cervical Discectomy and Fusion Simulation on the Novel Sim-Ortho Platform: Validation Studies

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The preceding work has been augmented with additional information and materials to reflect the requirements for thesis submission for a master of science.

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INTRODUCTION

Technological advancements combined with a shift toward competency-based surgical education has resulted in the increased development and validation of virtual reality surgical simulators for residency training.[24,39,48] Virtual reality simulators can supplement the traditional apprenticeship-based model of surgical training by providing residents with unlimited opportunities for repetitive practice in an environment that is safe to fail.[59] This has the potential to lead to the automatization of certain technical skills[28] and allow students to practice surgical skills without the limitations imposed by operating rooms (ORs), patient cases, or supervision.[17,28,59] Virtual reality simulators have the potential to deconstruct longer and more complex surgeries into manageable steps for the learner to master.[11] This allows students to skip procedural steps in which they are competent and focus on specific steps that require improvement.[35] Since simulators have the capacity to record enormous amounts of data during virtual reality task performance, these datasets can provide novel insights into surgical expertise,[71] real-time procedural guidance,[85] automated feedback,[64,85] and to inform educators in developing objective assessment measures.[75]

The validity of a simulator gives merit to its use as an educational device and is a crucial first step in determining its ability to stimulate real-life scenarios.[39] Validity assessment measures can be broken down into two principle categories: subjective and objective validity.[73] Subjective validity is generally assessed through the distribution of questionnaires asking participants their opinions about the simulated task.[73] Two types of commonly assessed subjective validity used in virtual reality surgical simulation are face and content validity.[15,31,39] The second category is objective validity, one focus of which is construct validity.[81] Construct validity measures the extent to which skill differentiation in the operating room is reflected in the simulation.[30]

A number of virtual reality simulators for spine surgery have become available and undergone validity testing.[59] The development of virtual reality simulators which can deconstruct and simulate complex multifaceted spine procedures could advance spine surgical training. Among the most common procedures is the anterior cervical discectomy and fusion (ACDF).[52] This procedure requires trainees to master a broad spectrum of surgical techniques.[62]

The objectives of this study were twofold: 1) to investigate face and content validity for a C4-C5 ACDF simulation available on the Sim-Ortho virtual reality platform and 2) to use a series of derived metrics to assess construct validity on the ACDF simulation.

MATERIALS AND METHODS

Participants

A total of 27 neurosurgeons, orthopaedic surgeons, surgical fellows, neurosurgical and orthopedic residents were recruited for this study. None of the participants had previous experience using the Sim-Ortho platform to perform an ACDF simulation. Three left-handed participants were excluded since the Sim-Ortho virtual reality platform is only optimized for right-handed users. Two neurosurgeons and one fellow were also excluded as their practice and/or training was not primarily spine surgery. The remaining 21 participants were grouped into 3 categories: post-resident (neurosurgical and orthopaedic spine surgeons and spine fellows), senior, and junior resident groups. The senior resident group consisted of both neurosurgical (PGY 4-6 years) and orthopaedic (PGY 4-5) residents while the junior resident group included neurosurgical (PGY 1-3) and orthopaedic (PGY1-3) residents (Table 1). All participants signed an informed consent approved by the Research Ethics Board at McGill University. Demographic data regarding age, sex, level of training, and previous experience with VR simulators was collected prior to completing the simulation task. Participants answered a 5-point Likert scale questionnaire regarding their knowledge (1= minimal, 5= expert) and comfort level (1= not at all, 5= very comfortable) of an ACDF prior to the task.

Virtual Reality Simulator Platform

This study utilized the Sim-Ortho virtual reality simulator platform (Figure 1A) developed by OSSimTech™ (Montreal, Quebec, Canada) and the AO Foundation (Davos, Switzerland). Sim-Ortho uses a voxel-based platform to achieve a complex and realistic intraoperative experience for the user.[67] The simulator incorporates haptic technology that provides the user with touch feedback and real-time tool tracking as the individual interacts with different simulated structures (Figure 1A-C). Users are equipped with 3D stereoscopic glasses and receive auditory feedback throughout the procedure (Figure 1C). Participants can select from a variety of instruments and instrument sizes to complete each component of the simulation.

Anterior Cervical Discectomy and Fusion Simulation Experience

The anterior cervical discectomy and fusion simulation is segmented into 7 units: 3 animated sections and 4 interactive sections (Table 2). Operators could not interact with the simulated scenario during the animated sections of the procedure. The 4 interactive sections of the procedure included: disc exposure, discectomy, osteophyte removal, and posterior longitudinal ligament removal. The four interactive sections were designed to be distinct steps of the operative procedure, each with a different instrument(s) and different objectives which allowed each individual step to be assessed and taught independently. Participants were allowed unlimited time to complete the procedure. Once the participant felt that a step was satisfactorily completed, they proceeded to the next step and could not return to any previous steps. During the interactive steps of the procedure, participants could interact with any simulated anatomical structures: C4 and C5 vertebrae, the disc annulus and nucleus, the posterior longitudinal ligament, and the spinal dura. Although participants could select from a variety of instruments to perform the ACDF simulation, operators were limited to specific instruments and instrument sizes for each step for standardization purposes. Prior to starting the ACDF simulation, operators were given verbal and written instructions on how to complete the 4 interactive sections of the procedure, including a careful demonstration of the instruments they could choose from. No questions were allowed once the procedure was underway.

The task began with an animated dissection of a transverse incision from the midline followed by a 2.5cm lateral retraction to expose the disc. The first step to be completed by the user was to expose the disc annulus by making a 2cm transverse box incision at the center of the exposed disc using a No.15 blade scalpel (Figure 2A). This was followed by the animated insertion of the distraction pins and the application of a 2mm distraction. The next step the participant had to complete was a C4-C5 discectomy using a disc rongeur, curette, and/or 2mm 45º pituitary rongeur (Figure 2B & C). Participants could use any of the instruments interchangeably throughout this step based on preference. Participants were then required to use a 3mm diamond burr to remove the osteophytes on the C4 and C5 vertebrae until the endplates were flat and the PLL was fully exposed (Figure 2D). For the final interactive step of the procedure, operators used a 3mm right-angled nerve hook to lift the posterior longitudinal ligament anteriorly and then remove the posterior longitudinal ligament using a 1mm kerrison (Figure 2E & F). The ACDF simulation ended with an animation depicting the insertion of the interbody spacer, removal of distraction pins, and retractors and the closure of the patient. All steps are outlined in table 1.

Face and Content Validity

Following completion of the ACDF simulation, participants answered a series of questions regarding the realism of the simulated scenario and its potential use as an educational tool to assess face and content validity. These questionnaires were given in the form of a 7-point Likert scale with 1 being completely unrealistic and 7 being completely realistic. It was considered appropriate to ask participating spine surgeons and spine fellows (post-resident group) who had consistent exposure to patient ACDF procedures, to assess face and content validity of the simulation. In the absence of consensus in the surgical simulation literature on an median value to determine face and content validity we used a median rating of ≥4.0 on the 7-point Likert scale for this purpose.[73]

Construct Validity

Construct validity was assessed using a series of metrics, established a priori, for each of the 4 steps. Given that each of the steps can be completed and taught independently and involve different instruments and surgical techniques, the developed metrics and subsequent analysis were carried out independently for each step. Participant data was recorded by the Sim-Ortho platform and the dataset was separated based on the instrument employed and saved as a comma separated value (CSV) file. The data file consisted of multiple variables including time, forces on each structure, and volume of anatomical structures removed. The metrics for each step were based on a previous model developed by our group where metrics are categorized into two tiers for each of the procedural steps.[4,5,7] Tier 1 metrics included: number of voxels removed and time spent in contact with each anatomical structure. Tier 2 metrics included maximum and average force applied to each of the anatomical structures and total tip path length for each instrument utilized. Total tip path length measures the distance travelled by the tip of the instrument and is a measure of efficiency.[4] A complete list of metrics for each step is provided in Tables 3-6. For each step, all three of the groups' performances were compared on each metric to assess construct validity.

Statistical Analysis

Raw data from each participant was imported into MatlabR2018b for data manipulations to develop metrics. Metrics were removed from the initial dataset if less than 30% of individuals did not contribute to them. Statistical assessment was completed in SPSS (version 26.0, SPSS Inc.). Normality assessment was conducted with a Shapiro-Wilk test which showed that data was not normally distributed ($p<0.05$). As such, a Kruskal-Wallis test was used to investigate statistical differences, results are presented in Tables 3-6. Dunn's pairwise comparison with a Bonferroni correction ($p<0.05$) was used post-hoc to analyze between-group differences on significant metrics.

RESULTS

Participants

Demographic data on the 21 participants included in the trial can be seen in Table 1. Group ratings related to expert level textbook and surgical knowledge are also present in Table 1. The post-residency group rated themselves as having expert level textbook (median = 5.0; range= 0.0) and surgical knowledge of the ACDF procedure (median = 5.0; range= 4.0 - 5.0) suggesting they were well acquainted with the procedure. Furthermore, data was collected regarding each individuals' perceptions of virtual reality surgical simulators (table 7). Overall, VR surgical simulation is perceived positively by all 4 groups, with the highest ratings on the Likert-scale coming from the post-resident group.

Face and Content Validity

Median scores of face and content validity are outlined in Table 8**.** The post-residency group rated the overall realism of the ACDF simulation to be realistic with a median of 4.0 (range= 2.0 – 6.0). For each of the interactive steps, assessment of the realism associated with each instrument is displayed in Table 8. Results indicated that all four steps were valid for at least one instrument (median ≥4). However, median scores on face validity for the curette and kerrison did not reach the cut-off for sufficient validity. For the discectomy component of the ACDF simulation, all individuals used the curette and 8 out of 9 (89%) of the participants used the pituitary rongeur. The median score for using the disc rongeur to remove the disc was 5.0 (range 2.0 – 5.0), however only 4 out of 9 (44%) people in the post-resident group used the disc rongeur to complete the discectomy, thus further testing is required to establish validity of this instrument. Removing the osteophytes on C4 and C5 was assessed by the post-resident group to be the most realistic step of the procedure with a median of 6.0 (range = 5.0 – 7.0). The overall scores for Sim-Ortho as a training tool were positive, with most participants in the post-resident group (66%) agreeing with the statement that they would use the ACDF simulation scenario for training technical skills (median=4.0; range 1.0 - 5.0). Additionally, 67% of all individuals responded "yes" when asked if they would recommend integrating virtual reality simulation training into surgical programs after using the Sim-Ortho platform. Overall satisfaction, personal analysis of performance, and assessment of task difficulty for each of the three groups are outlined in Table 9. All 3 groups found the task to be moderately difficult with a median score of 4.0.

Construct Validity

There was a significant difference between groups on 5 metrics for step one, 2 metrics for step two, 4 metrics for step three, and 3 metrics for step four (Tables 3-6). Pairwise comparison of significant metrics for each of the four steps are presented in Figures 3-13. During step 1 of the procedure, the post-resident group spent significantly more time in seconds (29.0 ± 9.3) interacting with the disc nucleus compared to the junior resident group (14.8 ± 9.1) and removed more voxels (a measure of tissue mass removed) from the disc nucleus (18095 ± 7597) compared to junior residents (9215.57 ± 4836.65) (Figure 3&4). The post-resident group had a significantly longer total tip path length compared to junior residents while contacting the disc annulus (526.5 ± 273.2 versus 948.1 ± 321.8) and disc nucleus (558.6 ± 306.7 versus 1108.5 ± 382.6) (Figure 5&6). For the discectomy step of the procedure, the post-resident group demonstrated a significantly higher maximum force on the disc annulus (0.08±0.03) compared to senior (0.04 ± 0.01) and junior residents (0.04 ± 0.01) (Figure 7). There was no significant difference between groups on the maximum force applied to the spinal dura after post-hoc testing however the median value for the junior resident group was quite low (Figure 8). When removing the osteophytes with the burr during step 3, the post-resident group applied significantly lower average force with the burr on C4 (0.004 ± 0.001) compared to senior residents (0.005 ± 0.001) (Figure 9). The post-resident group spent less time in contact with C5, although this metric was not significant after post-hoc testing (Figure 10). The post-resident group also removed significantly less voxels from C5 (3209.8 ± 2556.7) compared to junior residents (10485.7 ± 6389.0) (Figure 11) and had a significantly shorter total tip path length while contacting C5 (674.8 ± 445.3) compared to junior residents (1763.8 ± 752.0) and senior residents (1686.8 ± 445.3) (Figure 12). Analysis of step 4 of the procedure demonstrated one significant metric (Figure 13). While using the kerrison, senior residents spent significantly less time (s) in contact with the posterior longitudinal ligament (36.7 ± 35.8) compared to the post-resident groups (116.8 ± 68.4) (Figure 13).

DISCUSSION:

Summary

Virtual reality simulators offer advantages to traditional surgical training methods and provide an opportunity to enhance educational curriculums.[59] The anterior cervical discectomy and fusion simulation on the Sim-Ortho platform demonstrates face, content, and construct validity. This provides an important step in establishing this virtual reality simulator as a potential educational tool. The anatomical, color, and overall realism were rated positively by the post-resident group indicating that participants felt the simulator was reflective of the real-life procedure. Importantly, the steps of the procedure that were rated highly on face validity were also the steps of the procedure that had the most differentiating metrics between groups.

Face and Construct Validity

Disc Exposure: Analysis of face and construct validity for this step of the procedure demonstrated that the Sim-Ortho virtual reality platform was reflective of the operative procedure and able to differentiate between groups using four metric parameters. Our results are consistent with the concept that the post resident group compared to the junior resident group both contacts and removes more disc nucleus with the scalpel secondary to an increased total tip path length when using this instrument. This may be related to the post-resident group having a better understanding of the safe use of this instrument in this anatomical location. These results are consistent with other studies which demonstrate that skilled participants focus on safety and have a longer total tip path length compared to less skilled groups.[4,71]

Disc Removal: Results from this step of the procedure indicated that the pituitary rongeur, but not the curette were reflective of the operative procedure. Feedback from participants indicated that the curette could be improved by a more accurate display of the actual disc pieces removed during the procedure. Construct validity assessments revealed that the maximum force applied by the instruments to the disc annulus differentiated groups consistent with the results in step 1, suggesting that skilled participants have adapted their force application consistent with safe application[71] The lack of other differentiating metrics may be a result of collapsing multiple instruments into one overall score. It is possible that instrument preferences selected for the discectomy portion of the procedure may be an important metric for understanding differences between varying levels of expertise. Further studies using larger numbers of participants are required to establish construct validity for the individual instruments used in this step.

Osteophyte Removal: Using the burr for osteophyte removal was rated highly on face validity and displayed construct validity on three metrics. In line with previous studies involving a brain tumor resection task, tier 2 metrics demonstrated that the post-resident group demonstrated a shorter burr total tip path length when contacting C5 compared to the other groups indicating a more efficient approach to removing osteophytes[4,71] The removal of significantly less voxels from the C5 vertebra by the post-resident group compared to the junior resident group suggests that the post-resident group was better able to accurately identify and remove osteophytes when utilizing the burr. This combination of significant metrics for tier 1 and tier 2 is indicative of greater focus on safety and efficiency of burr utilization for the post-resident group which is consistent with previous studies.[4,71]

Posterior Longitudinal Ligament Removal: This step demonstrated sufficient face validity for the nerve hook but not for the kerrison. Construct validity analysis demonstrated validity for 1 metric, indicating that the post-resident group spent significantly more time in contact with the posterior longitudinal ligament. This step of the ACDF simulation was challenging for all groups suggesting the need for further development of this simulated component.

Sim-Ortho as an Educational Tool

The development of psychomotor skills for surgery is complex. Operating procedures involving different types of technical skills can be deconstructed into major steps so that residents can master a particular part of the procedure before learning another.[35] This decomposition allows residents to focus on one manageable portion of the procedure at a time without being overwhelmed by the multitude of other steps.[35] It has been suggested that surgical simulators should focus on adopting modular paradigms whereby the simulators isolate important surgical steps to give residents sufficient exposure and practice before operating on patients.[51] Although participants in our study completed the steps sequentially, each step and its associated metrics were developed and analyzed independently of the other steps. The metrics developed for the Sim-Ortho platform can be used to assess and teach the technical skills required for one step of the procedure while skipping over parts of the procedure that residents have mastered. The Sim-Ortho platform contains the first virtual reality ACDF simulation with haptic feedback. Studies have indicated that haptic feedback is important in complex procedures that require interaction of multiple structures.[60] These results indicate that this Sim-Ortho virtual reality simulation may be an important educational resource for residents but further concurrent and prospective validation studies are needed to define its role in educational paradigms.

Limitations

First, the advanced gaming engine incorporated into the Sim-Ortho virtual reality surgical simulator allows improved color and tissue visualization scenarios but does not simulate the complex ever-evolving environment in the operating room. The simulator utilized is one-handed and has been developed only for right-handed users which limits its usefulness for left-handed participants and for quantification of bimanual skills. In virtual reality trials left and right handed ergonomics have been shown to be different and may need to be assessed independently.[71] Second, to simplify the interpretation of participants' surgical performance multiple variables were controlled including the number and type of instrument employed which is not reflective of patient operative procedures. Third, the study involved small participant groups from a single institution limiting our ability to obtain information by further subdividing our groups and the generalizability of our results. The authors believe that increasing the number of participants and institutions involved may provide further insights into the usefulness of the metrics of performance utilized in this study.

Although data from our questionnaire displays differences between the three groups in terms of procedural exposure, ACDF knowledge, and operating room experience, the segmentation of groups based on year of residency training may bias results. Future studies may benefit from adopting an approach based on surgical competence. The subjective Likert-scale questionnaires used show a wide variation for some assessment questions. However, this scale was chosen as it has been an important tool in assessing the validity of surgical simulators.[12,39] Content validity was investigated for the overall procedure and not for each individual step of the procedure. In future studies it may be useful to assess content validity for each step of the simulation.

CONCLUSIONS

Our study established face, content, and construct validity for all steps of the ACDF simulation on the Sim-Ortho virtual reality platform supporting the potential use of this virtual reality spine simulation for surgical training. The segmentation of the surgical procedure into four distinct steps provides an opportunity for residents to be assessed and practice surgical skill for individual procedural steps. The large number of metrics that can be assessed by the OSSimTech™ simulator may be useful in providing further insights on the surgical psychomotor skill involved with performing spine procedures.

SUMMARY

Research on the development, use, and impact of virtual reality surgical simulation as an educational tool has been steadily growing over the last two decades. Rigorous efforts are required to grasp a thorough understanding of the effectiveness of virtual reality simulation over traditional simulation methodology currently used in curriculums. Validation of a simulator is an important first step and is paramount to establishing its ability to reflect the operative procedure and discriminate novices from experts.[39] The establishment of metrics that are capable of distinguishing expertise on the simulator have the potential to be used to train novices in novel ways.

This thesis provides evidence for face, content, and construct validity of an ACDF simulation on the Sim-Ortho virtual reality platform. The evaluation of face and content validity as rated by experienced surgeons indicates the ACDF simulation is similar to the operative procedure and thus, could play a role in exposing novice surgeons to the anatomical and technical aspects of an ACDF before entering the OR. More importantly, the demonstrated differences between levels of expertise on several metrics establishes that variation in technical skill in the OR, due to experience, is also reflected in the simulated scenario. The segregation of the ACDF simulation into a 4-step procedure allowed the independent development and analysis of metrics for each step. These metrics have the potential to be used as training devices and objective assessment measures for residents.

FUTURE DIRECTIONS

One of the greatest challenges to researchers investigating the validity of virtual reality surgical simulators is the lack of a standardized methodology for assessment. With VR becoming more prominent in surgery, educators and researchers should seek to establish clear and concise guidelines for the validation of simulators. The establishment of a gold-standard for validity assessment would also provide a more accurate way for surgical educators to compare simulators that are available on the market. Looking forward, adjustments should be made to the Sim-Ortho platform to enhance the operative experience. The addition of another handle as well as alterations to the location of the operator would be beneficial for user experience. Future validity studies should be carried out on the Sim-Ortho platform with a specific focus on the steps mentioned previously and closer analysis of content validity for each of the four steps. These investigations should also seek to increase the number of participants and expand their studies to incorporate multiple institutions. Additionally, current assessment methods use the objective structured assessment of technical skills (OSATS) to assess a trainee's capabilities on a set of tasks.[88] Although this method is widely accepted, it has been demonstrated that rating scales are unable to accurately grasp important aspects of surgical performance including force and volume of anatomical structures removed.[88] Going forward, it has been suggested that educators seek to establish more rigorous assessment methodologies that use a hybrid system with both OSATS and virtual reality simulation.[88]

Moreover, studies in surgical simulation have started to apply artificial intelligence (AI) methodologies to exploit the large datasets that are recorded by simulators.[75] Specifically, a subset of AI known as machine learning, can be employed to identify hidden patterns in large datasets.[45] Currently, machine learning is being used in surgical simulation to provide objective assessment measures and classify participants based on their performance on a series of metrics.[75] Recently, the Machine Learning to Assess Surgical Expertise (MLASE) checklist has been developed to help researchers ensure quality methodology and reporting when using machine learning for surgical expertise.[87] This study marks an important first step in standardizing machine learning literature in medicine.[87] Given the multitude of variables recorded by the Sim-Ortho platform, future studies should integrate machine learning methodologies into their analysis. These results would be important in providing novel insights on surgical skill and could be used to further support the metrics found in this study.

Ultimately, the use of VR in surgical education starts by building a foundation through validity studies. The results of this thesis add to a growing body of literature that demonstrates VR simulators can be realistic and differentiate surgical skill.[4,5,7,36,71] Sim-Ortho offers safe and unconstrained opportunities for residents to practice and improve surgical skills in an environment that allows opportunities to make mistakes. Their ability to record large datasets affords novel insights on surgical skill and can facilitate the shift toward competency-based surgical education. As such, virtual reality simulators, like the Sim-Ortho platform, may enhance surgical education by providing an adjunct to the traditional apprenticeship model in surgery.

REFERENCE LIST

1. Abrahamson S, Denson JS, Wolf RM: Effectiveness of a simulator in training anesthesiology residents. **J Med Educ 44:**515-519, 1969
2. Agha RA, Fowler AJ: The role and validity of surgical simulation. **Int Surg 100:**350-357, 2015
3. Ahmed N, Devitt KS, Keshet I, Spicer J, Imrie K, Feldman L, et al: A systematic review of the effects of resident duty hour restrictions in surgery: impact on resident wellness, training, and patient outcomes. **Ann Surg 259:**1041-1053, 2014
4. Alotaibi FE, AlZhrani GA, Mullah MA, Sabbagh AJ, Azarnoush H, Winkler-Schwartz A, et al: Assessing bimanual performance in brain tumor resection with NeuroTouch, a virtual reality simulator. **Neurosurgery 11 Suppl 2:**89-98; discussion 98, 2015
5. Alotaibi FE, AlZhrani GA, Sabbagh AJ, Azarnoush H, Winkler-Schwartz A, Del Maestro RF: Neurosurgical Assessment of Metrics Including Judgment and Dexterity Using the Virtual Reality Simulator NeuroTouch (NAJD Metrics). **Surg Innov 22:**636-642, 2015
6. Alsalamah A, Campo R, Tanos V, Grimbizis G, Van Belle Y, Hood K, et al: Face and content validity of the virtual reality simulator 'ScanTrainer(R)'. **Gynecol Surg 14:**18, 2017
7. Azarnoush H, Alzhrani G, Winkler-Schwartz A, Alotaibi F, Gelinas-Phaneuf N, Pazos V, et al: Neurosurgical virtual reality simulation metrics to assess psychomotor skills during brain tumor resection. **Int J Comput Assist Radiol Surg 10:**603-618, 2015
8. Badash I, Burtt K, Solorzano CA, Carey JN: Innovations in surgery simulation: a review of past, current and future techniques. **Ann Transl Med 4:**453, 2016

9. Bajunaid K, Mullah MA, Winkler-Schwartz A, Alotaibi FE, Fares J, Baggiani M, et al: Impact of acute stress on psychomotor bimanual performance during a simulated tumor resection task. **J Neurosurg 126:**71-80, 2017

10. Baker GR, Norton PG, Flintoft V, Blais R, Brown A, Cox J, et al: The Canadian Adverse Events Study: the incidence of adverse events among hospital patients in Canada. **CMAJ 170:**1678-1686, 2004

11. Bartlett JD, Lawrence JE, Stewart ME, Nakano N, Khanduja V: Does virtual reality simulation have a role in training trauma and orthopaedic surgeons? **Bone Joint J 100-B:**559-565, 2018

12. Bauer DE, Wieser K, Aichmair A, Zingg PO, Dora C, Rahm S: Validation of a Virtual Reality-Based Hip Arthroscopy Simulator. **Arthroscopy 35:**789-795, 2019

13. Bhatti NI, Cummings CW: Competency in surgical residency training: defining and raising the bar. **Acad Med 82:**569-573, 2007

14. Borgersen NJ, Naur TMH, Sørensen SMD, Bjerrum F, Konge L, Subhi Y, et al: Gathering Validity Evidence for Surgical Simulation: A Systematic Review. **Ann Surg 267:**1063-1068, 2018

15. Brewin J, Nedas T, Challacombe B, Elhage O, Keisu J, Dasgupta P: Face, content and construct validation of the first virtual reality laparoscopic nephrectomy simulator. **BJU Int 106:**850-854, 2010

16. Brown SD, Goske MJ, Johnson CM: Beyond substance abuse: stress, burnout, and depression as causes of physician impairment and disruptive behavior. **J Am Coll Radiol 6:**479-485, 2009

17. Bugdadi A, Sawaya R, Olwi D, Al-Zhrani G, Azarnoush H, Sabbagh AJ, et al: Automaticity of Force Application During Simulated Brain Tumor Resection: Testing the Fitts and Posner Model. **J Surg Educ 75:**104-115, 2018

18. Buser Z, Ortega B, D'Oro A, Pannell W, Cohen JR, Wang J, et al: Spine Degenerative Conditions and Their Treatments: National Trends in the United States of America. **Global Spine J 8:**57-67, 2018

19. Coleman J, Nduka CC, Darzi A: Virtual reality and laparoscopic surgery. **Br J Surg 81:**1709-1711, 1994

20. Cooper JB, Taqueti VR: A brief history of the development of mannequin simulators for clinical education and training. **Qual Saf Health Care 13 Suppl 1:**i11-18, 2004

21. Cosman PH, Hugh TJ, Shearer CJ, Merrett ND, Biankin AV, Cartmill JA: Skills acquired on virtual reality laparoscopic simulators transfer into the operating room in a blinded, randomised, controlled trial. **Stud Health Technol Inform 125:**76-81, 2007

22. Crassin C, Neyret F, Lefebvre S, Eisemann E: GigaVoxels: ray-guided streaming for efficient and detailed voxel rendering, in **Proceedings of the 2009 symposium on Interactive 3D graphics and games.** Boston, Massachusetts: ACM, 2009, pp 15-22

23. de Vries EN, Ramrattan MA, Smorenburg SM, Gouma DJ, Boermeester MA: The incidence and nature of in-hospital adverse events: a systematic review. **Qual Saf Health Care 17:**216-223, 2008

24. Delorme S, Laroche D, DiRaddo R, Del Maestro RF: NeuroTouch: a physics-based virtual simulator for cranial microneurosurgery training. **Neurosurgery 71:**32-42, 2012

25. Delp SL, Loan JP, Hoy MG, Zajac FE, Topp EL, Rosen JM: An interactive graphics-based model of the lower extremity to study orthopaedic surgical procedures. **IEEE Trans Biomed Eng 37:**757-767, 1990

26. Downey A: VR surgical simulator first to receive Royal College accreditation, in **Digital Health.** London, United Kingdom: Digital Health Intelligence Limited, 2019

27. Evgeniou E, Loizou P: Simulation-based surgical education. **ANZ J Surg 83:**619-623, 2013

28. Fahad E. AlOtaibi GAZ, Khalid Bajunaid, Alexander Winkler-Schwartz, Hamed Azarnoush, Muhammad A.S. Mullah, Abdulraham Sabbagh, Rolando F. Del Maestro: Assessing Neurosurgical Psychomotor Performance- Role of Virtual Reality Simulators, Current and Future Potential. **SOJ Neurol 2:**1-7, 2015

29. Frank JR, Mungroo R, Ahmad Y, Wang M, De Rossi S, Horsley T: Toward a definition of competency-based education in medicine: a systematic review of published definitions. **Med Teach 32:**631-637, 2010

30. Gallagher AG, Ritter EM, Satava RM: Fundamental principles of validation, and reliability: rigorous science for the assessment of surgical education and training. **Surg Endosc 17:**1525-1529, 2003

31. Gallagher K, Bahadori S, Antonis J, Immins T, Wainwright TW, Middleton R: Validation of the Hip Arthroscopy Module of the VirtaMed Virtual Reality Arthroscopy Trainer. **Surg Technol Int 34**, 2019

32. Gasco J, Patel A, Ortega-Barnett J, Branch D, Desai S, Kuo YF, et al: Virtual reality spine surgery simulation: an empirical study of its usefulness. **Neurol Res 36:**968-973, 2014

33. Goldenberg M, Lee JY: Surgical Education, Simulation, and Simulators-Updating the Concept of Validity. **Curr Urol Rep 19:**52, 2018

34. Gorman PJ, Meier AH, Krummel TM: Simulation and virtual reality in surgical education: real or unreal? **Arch Surg 134:**1203-1208, 1999

35. Grantcharov TP, Reznick RK: Teaching procedural skills. **BMJ 336:**1129-1131, 2008

36. Gélinas-Phaneuf N, Choudhury N, Al-Habib AR, Cabral A, Nadeau E, Mora V, et al: Assessing performance in brain tumor resection using a novel virtual reality simulator. **Int J Comput Assist Radiol Surg 9:**1-9, 2014

37. Haji FA, Steven DA: Readiness for practice: a survey of neurosurgery graduates and program directors. **Can J Neurol Sci 41:**721-728, 2014

38. Holmboe ES: Realizing the promise of competency-based medical education. **Acad Med 90:**411-413, 2015

39. Huang C, Cheng H, Bureau Y, Agrawal SK, Ladak HM: Face and content validity of a virtual-reality simulator for myringotomy with tube placement. **J Otolaryngol Head Neck Surg 44:**40, 2015

40. Hung AJ, Chen J, Che Z, Nilanon T, Jarc A, Titus M, et al: Utilizing Machine Learning and Automated Performance Metrics to Evaluate Robot-Assisted Radical Prostatectomy Performance and Predict Outcomes. **J Endourol 32:**438-444, 2018

41. Jagannathan J, Vates GE, Pouratian N, Sheehan JP, Patrie J, Grady MS, et al: Impact of the Accreditation Council for Graduate Medical Education work-hour regulations on neurosurgical resident education and productivity. **J Neurosurg 110:**820-827, 2009

42. Jowett N, LeBlanc V, Xeroulis G, MacRae H, Dubrowski A: Surgical skill acquisition with self-directed practice using computer-based video training. **Am J Surg 193:**237-242, 2007

43. Kanumuri P, Ganai S, Wohaibi EM, Bush RW, Grow DR, Seymour NE: Virtual reality and computer-enhanced training devices equally improve laparoscopic surgical skill in novices. **JSLS 12:**219-226, 2008

44. Kim DH, Kim Y, Park JS, Kim SW: Virtual Reality Simulators for Endoscopic Sinus and Skull Base Surgery: The Present and Future. **Clin Exp Otorhinolaryngol 12:**12-17, 2019

45. Kotsiantis SB, Zaharakis I, P. P: Supervised machine learning: A review of classification techniques. **Emerging Artificial Intelligence applications in Computer Engineering 160:**3-24, 2007

46. Long DM: Competency-based residency training: the next advance in graduate medical education. **Acad Med 75:**1178-1183, 2000

47. Luc JGY, Antonoff MB: Active Learning in Medical Education: Application to the Training of Surgeons. **J Med Educ Curric Dev 3**, 2016

48. Luciano CJ, Banerjee PP, Sorenson JM, Foley KT, Ansari SA, Rizzi S, et al: Percutaneous spinal fixation simulation with virtual reality and haptics. **Neurosurgery 72 Suppl 1:**89-96, 2013

49. Mabrey JD, Reinig KD, Cannon WD: Virtual reality in orthopaedics: is it a reality? **Clin Orthop Relat Res 468:**2586-2591, 2010

50. Makary MA, Daniel M: Medical error-the third leading cause of death in the US. **BMJ 353:**i2139, 2016

51. Malone HR, Syed ON, Downes MS, D'Ambrosio AL, Quest DO, Kaiser MG: Simulation in neurosurgery: a review of computer-based simulation environments and their surgical applications. **Neurosurgery 67:**1105-1116, 2010

52. Marawar S, Girardi FP, Sama AA, Ma Y, Gaber-Baylis LK, Besculides MC, et al: National trends in anterior cervical fusion procedures. **Spine (Phila Pa 1976) 35:**1454-1459, 2010

53. Mayo BC, Massel DH, Bohl DD, Long WW, Modi KD, Singh K: Anterior Cervical Discectomy and Fusion: The Surgical Learning Curve. **Spine (Phila Pa 1976) 41:**1580-1585, 2016

54. Mediouni M, Volosnikov A: The trends and challenges in orthopaedic simulation. **J Orthop 12:**253-259, 2015

55. Mittal VK: Simulation Training-a Necessity for Future Surgeons. **Indian J Surg 77:**258-259, 2015

56. Morgan M, Aydin A, Salih A, Robati S, Ahmed K: Current Status of Simulation-based Training Tools in Orthopedic Surgery: A Systematic Review. **J Surg Educ 74:**698-716, 2017

57. Nanda A, Sharma M, Sonig A, Ambekar S, Bollam P: Surgical complications of anterior cervical diskectomy and fusion for cervical degenerative disk disease: a single surgeon's experience of 1,576 patients. **World Neurosurg 82:**1380-1387, 2014

58. Newman S, Gulati V, Bahadori S, Wainwright T: Content and Face Validity Assessment of the Sim-K Haptic-Feedback Enhanced Total Knee Replacement Virtual Reality Simulator. **The Internet Journal of Orthopedic Surgery 27:**1-6, 2019

59. Pfandler M, Lazarovici M, Stefan P, Wucherer P, Weigl M: Virtual reality-based simulators for spine surgery: a systematic review. **Spine J 17:**1352-1363, 2017

60. Pinzon D, Byrns S, Zheng B: Prevailing Trends in Haptic Feedback Simulation for Minimally Invasive Surgery. **Surg Innov 23:**415-421, 2016

61. Rall M, Dieckmann P: Simulation and Patient Safety: The use of simulation to enhance patient safety on a systems level. **Current Anaesthesia & Critical Care 16:**273-281, 2005

62. Ray WZ, Ganju A, Harrop JS, Hoh DJ: Developing an anterior cervical diskectomy and fusion simulator for neurosurgical resident training. **Neurosurgery 73 Suppl 1:**100-106, 2013

63. Reznick RK, MacRae H: Teaching surgical skills--changes in the wind. **N Engl J Med 355:**2664-2669, 2006

64. Rhienmora P, Haddawy P, Suebnukarn S, Dailey MN: Intelligent dental training simulator with objective skill assessment and feedback. **Artif Intell Med 52:**115-121, 2011

65. Roitberg B: Virtual Reality Simulation for the Spine, in Alaraj A (ed): **Comprehensive Healthcare Simulation: Neurosurgery.** Cham: Springer International Publishing, 2018, pp 245-255

66. Rosen KR: The history of medical simulation. **J Crit Care 23:**157-166, 2008

67. Ruikar DD, Hegadi RS, Santosh KC: A Systematic Review on Orthopedic Simulators for Psycho-Motor Skill and Surgical Procedure Training. **J Med Syst 42:**168, 2018

68. Ryu WH, Chan S, Sutherland GR: Supplementary Educational Models in Canadian Neurosurgery Residency Programs. **Can J Neurol Sci 44:**177-183, 2017

69. Satava R, Gallagher A: Next generation of procedural skills curriculum development: Proficiency‑based progression. **Journal of Health Specialties 3:**198-205, 2015

70. Satava RM: Historical review of surgical simulation--a personal perspective. **World J Surg 32:**141-148, 2008

71. Sawaya R, Bugdadi A, Azarnoush H, Winkler-Schwartz A, Alotaibi FE, Bajunaid K, et al: Virtual Reality Tumor Resection: The Force Pyramid Approach. **Oper Neurosurg (Hagerstown) 14:**686-696, 2018

72. Schlich T: 'The Days of Brilliancy are Past': Skill, Styles and the Changing Rules of Surgical Performance, ca. 1820-1920. **Med Hist 59:**379-403, 2015

73. Schout BM, Hendrikx AJ, Scheele F, Bemelmans BL, Scherpbier AJ: Validation and implementation of surgical simulators: a critical review of present, past, and future. **Surg Endosc 24:**536-546, 2010

74. Sealy WC: Halsted Is Dead: Time for Change in Graduate Surgical Education. **Current Surgery 56:**34-39, 1999

75. Sewell C, Morris D, Blevins NH, Dutta S, Agrawal S, Barbagli F, et al: Providing metrics and performance feedback in a surgical simulator. **Comput Aided Surg 13:**63-81, 2008

76. Seymour NE, Gallagher AG, Roman SA, O'Brien MK, Bansal VK, Andersen DK, et al: Virtual reality training improves operating room performance: results of a randomized, double-blinded study. **Ann Surg 236:**458-463; discussion 463-454, 2002

77. Stefl ME: To Err is Human: Building a Safer Health System in 1999. **Front Health Serv Manage 18:**1-2, 2001

78. Tsai MD, Hsieh MS, Tsai CH: Bone drilling haptic interaction for orthopedic surgical simulator. **Comput Biol Med 37:**1709-1718, 2007

79. Van Den Bos J, Rustagi K, Gray T, Halford M, Ziemkiewicz E, Shreve J: The $17.1 billion problem: the annual cost of measurable medical errors. **Health Aff (Millwood) 30:**596-603, 2011

80. van Vendeloo SN, Godderis L, Brand PLP, Verheyen KCPM, Rowell SA, Hoekstra H: Resident burnout: evaluating the role of the learning environment. **BMC Med Educ 18:**54, 2018

81. Varoquier M, Hoffmann CP, Perrenot C, Tran N, Parietti-Winkler C: Construct, Face, and Content Validation on Voxel-Man Simulator for Otologic Surgical Training. **International Journal of Otolaryngology 2017:**8, 2017

82. Vaughan N, Dubey VN, Wainwright TW, Middleton RG: A review of virtual reality based training simulators for orthopaedic surgery. **Med Eng Phys 38:**59-71, 2016

83. Vedula SS, Ishii M, Hager GD: Objective Assessment of Surgical Technical Skill and Competency in the Operating Room. **Annu Rev Biomed Eng 19:**301-325, 2017

84. Weigl M, Stefan P, Abhari K, Wucherer P, Fallavollita P, Lazarovici M, et al: Intra-operative disruptions, surgeon's mental workload, and technical performance in a full-scale simulated procedure. **Surg Endosc 30:**559-566, 2016

85. Wijewickrema S, Ma X, Piromchai P, Briggs R, Bailey J, Kennedy G, et al: Providing Automated Real-Time Technical Feedback for Virtual Reality Based Surgical Training: Is the Simpler the Better?, in**.** Cham: Springer International Publishing, 2018, pp 584-598

86. Wilson MS, Middlebrook A, Sutton C, Stone R, McCloy RF: MIST VR: a virtual reality trainer for laparoscopic surgery assesses performance. **Ann R Coll Surg Engl 79:**403-404, 1997

87. Winkler-Schwartz A, Bissonnette V, Mirchi N, Ponnudurai N, Yilmaz R, Ledwos N, et al: Artificial Intelligence in Medical Education: Best Practices Using Machine Learning to Assess Surgical Expertise in Virtual Reality Simulation. **Journal of Surgical Education 76:**1-11, 2019

88. Winkler-Schwartz A, Marwa I, Bajunaid K, Mullah M, Alotaibi FE, Bugdadi A, et al: A Comparison of Visual Rating Scales and Simulated Virtual Reality Metrics in Neurosurgical Training: A Generalizability Theory Study. **World Neurosurg**, 2019

89. Zdeblick T: Anterior Cervical Discectomy and Fusion. **Operative Techniques in Orthopaedics 3:**201-206, 1993

APPENDIX

FIGURE 1. The virtual reality platform used to perform the anterior cervical discectomy and fusion simulation. (A) The Sim-Ortho virtual reality platform with the 3D stereoscopic glasses and multitude of instrument handles to complete a variety of simulated operations. (B) An operator holding the instrument handle in their dominant right-hand while receiving haptic feedback as they interact with the anatomical structures. (C) An operator performing an anterior cervical discectomy and fusion simulation with 3D glasses.

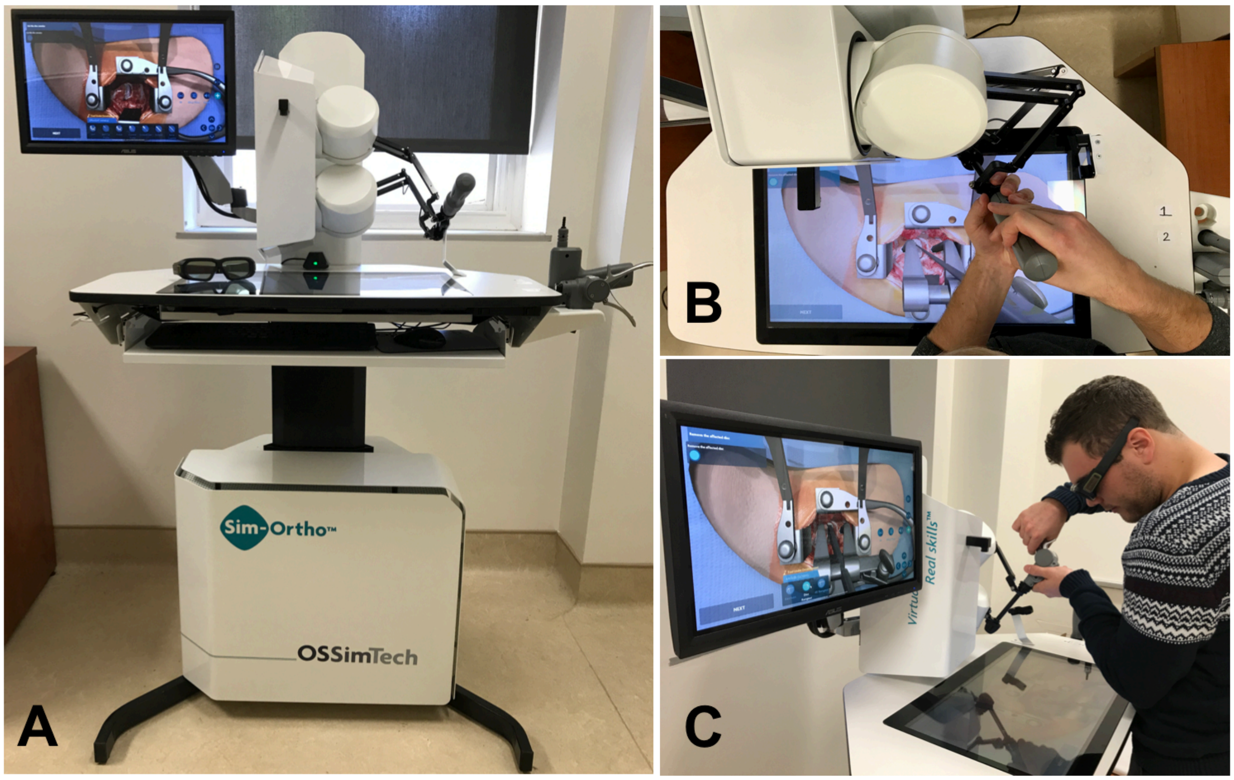


FIGURE 2: Each step and the accompanying instrument during the anterior cervical discetomy and fusion simulation. (A) Scalpel making a transverse box incision on the center of the exposed disc. (B) Pituitary rongeur removing the disc. (C) Curette removing the disc. (D) Burr removing the disc. (E) Nerve hook hooking the PLL. (F) Kerrison removing the PLL.

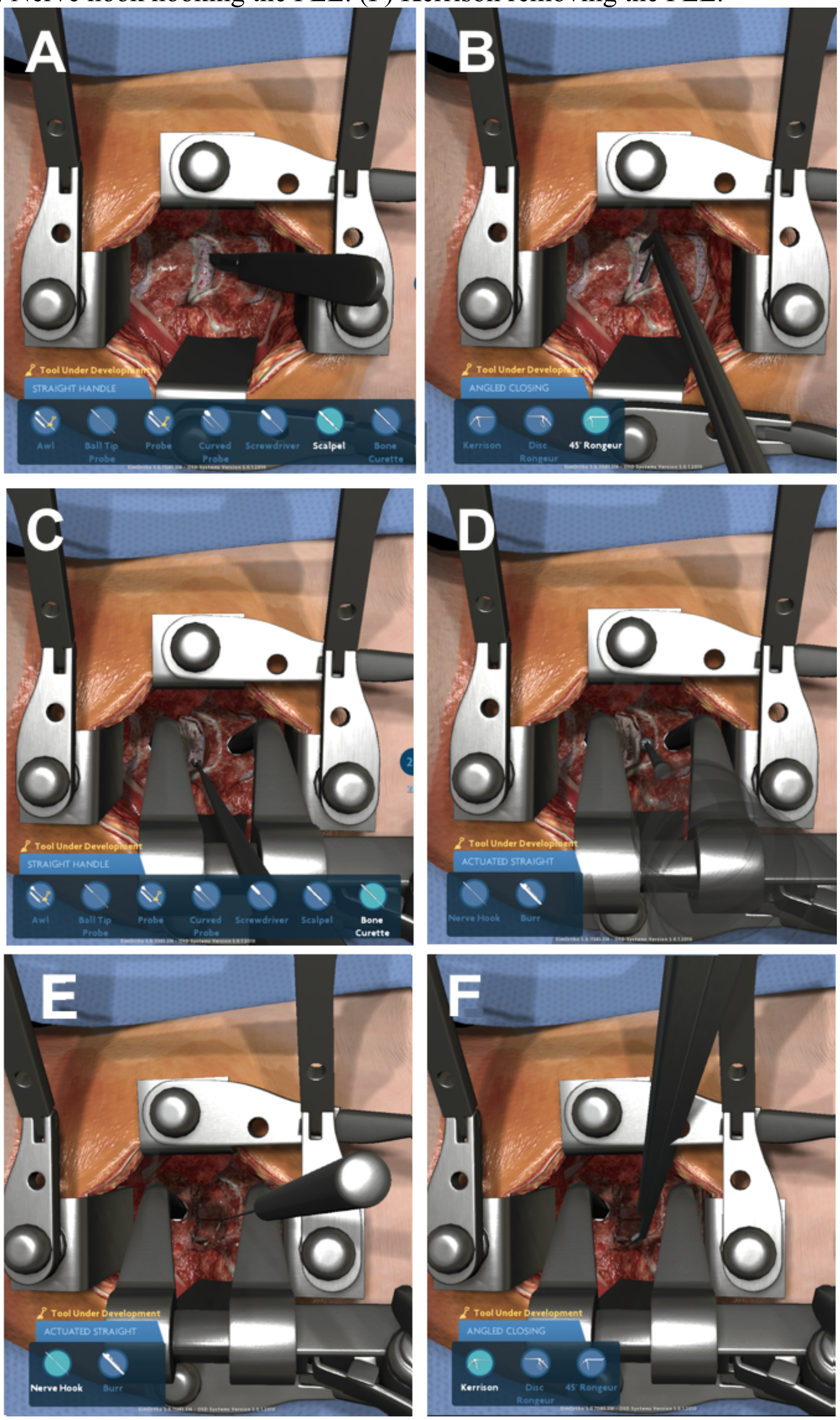


TABLE 1. Demographic data for each of the three groups performing the ACDF simulation on the Sim-Ortho platform.

	Junior Residents	**Senior Residents**	**Post-Residents**
No. of participants	7 (33%)	5 (24%)	9 (43%)
Mean age ± SD	27.4 ± 1.4	30.6 ± 2.3	44.2 ± 13.2
Sex			
Male	5 (71%)	4 (80%)	9 (100%)
Female	2 (29%)	1 (20%)	0 (0%)
No. of individuals in each group who:			
Have previous experience using a surgical simulator	5 (71%)	4 (80%)	7 (78%)
Assisted on an ACDF in the last month	1 (14%)	3 (60%)	N/A
Performed an ACDF solo in the last month	1 (14%)	1 (20%)	7 (78%)
Median self-rating on 5-point Likert scale (range):			
Textbook knowledge of an ACDF	3.0 (1.0 – 4.0)	3.0 (2.0 – 4.0)	5.0 (0.0)
Surgical knowledge of an ACDF	3.0 (1.0 – 3.0)	3.0 (3.0 – 4.0)	5.0 (4.0 - 5.0)
Comfort level performing an ACDF with a consultant in the room	3.0 (1.0 – 4.0)	3.0 (2.0 - 5.0)	N/A
Comfort level performing an ACDF solo	1.0 (1.0 – 3.0)	3.0 (2.0 – 4.0)	5.0 (3.0 - 5.0)

ACDF = Anterior cervical discectomy and fusion
No. = Number
SD = Standard deviation

TABLE 2. Each of the animated and interactive steps of the C4-C5 anterior cervical discectomy and fusion simulation on the Sim-Ortho Virtual Reality Platform.

Step	Objective	Instrument Required	Type
Dissection	Transverse incision from the midline. Using 2 blade retractors, retract tissues laterally 2.5cm to expose the disc	N/A	Animated
Step 1: Disc Exposure	Expose the disc annulus by making a 2cm transverse box incision at the center of the exposed disc	No.15 blade scalpel	Interactive
Distractor Pin Insertion	Screw two 14mm distraction pins at center of vertebral body and apply a 2mm distraction	N/A	Animated
Step 2: Disc Removal	Remove disc annulus, nucleus and cartilage until vertebral body endplates are exposed and cleaned	Disc rongeur Curette 2mm pituitary rongeur	Interactive
Step 3: Osteophyte removal	Remove osteophytes until endplates are flat and posterior longitudinal ligament is fully exposed	3mm diamond burr	Interactive
Step 4: Posterior Longitudinal Ligament Removal	Plunge through posterior longitudinal ligament and lift it 0.5mm anteriorly, then remove the posterior longitudinal ligament	3mm right-angled nerve hook 1mm kerrison	Interactive
Closure	Insertion of cervical interbody spacer, removal of distracting pins and retractors, close patient	N/A	Animated

TABLE 3. Tier 1 and tier 2 metrics for step 1 of the ACDF simulation.

Step Number (instrument used)	Tier	*p* value†
Step 1 (scalpel)		
Disc annulus removed	1	.07
Disc nucleus removed	1	.03*
Disc annulus contact time	1	.05
Disc nucleus contact time	1	.03*
Avg. force on disc annulus	2	.61
Avg. force on disc nucleus	2	.93
Max. force on disc annulus	2	.13
Max force on disc nucleus	2	.36
TTPL while contacting disc annulus	2	.03*
TTPL while contacting disc nucleus	2	.02*

Avg. = Average
† *p*-value for Kruskal-Wallis, non-parametric test
* Significant *p*-value for Kruskal-Wallis, non-parametric test ($p<0.05$)
TTPL = Total tip path length

TABLE 4. Tier 1 and tier 2 metrics for step 2 of the ACDF simulation.

Step Number (instrument used)	Tier	*p* value†
Step 2 (overall: pituitary rongeur, disc ronguer, curette)		
Disc annulus removed	1	.80
Disc nucleus removed	1	.09
Disc annulus contact time	1	.28
Disc nucleus contact time	1	.28
Avg. force on disc annulus	2	.18
Avg. force on disc nucleus	2	.31
Avg. force on spinal dura	2	.10
Avg. force on posterior longitudinal ligament	2	.70
Max force on disc annulus	2	< .01*
Max force on disc nucleus	2	.23
Max force on spinal dura	2	.04*
Max force on posterior longitudinal ligament	2	.41
TTPL of curette while touching disc annulus	2	.35
TTPL of curette while touching disc nucleus	2	.15
TTPL of pituitary while touching disc annulus	2	.30
TTPL of pituitary while touching disc nucleus	2	.27

Avg. = Average
† *p*-value for Kruskal-Wallis, non-parametric test
* Significant *p*-value for Kruskal-Wallis, non-parametric test ($p<0.05$)
TTPL = Total tip path length

TABLE 5. Tier 1 and tier 2 metrics for step 3 of the ACDF simulation.

Step Number (instrument used)	**Tier**	***p* value†**
Step 3 (burr)		
C4 removed	1	.93
C5 removed	1	.01*
C4 contact time	1	.98
C5 contact time	1	.04*
Avg. force on C4	2	< .01*
Avg. force on C5	2	.23
Avg. force on posterior longitudinal ligament	2	.87
Max force on C4	2	.14
Max force on C5	2	.09
Max force on posterior longitudinal ligament	2	.17
TTPL while touching C5	2	< .01*
TTPL while touching C4	2	.83

Avg. = Average
† *p*-value for Kruskal-Wallis, non-parametric test
* Significant *p*-value for Kruskal-Wallis, non-parametric test ($p<0.05$)
TTPL = Total tip path length

TABLE 6. Tier 1 and tier 2 metrics for step 4 of the ACDF simulation.

Step Number (instrument used)	Tier	*p* value†
Step 4 (nerve hook and kerrison)		
Posterior longitudinal ligament removed with kerrison	1	.18
Posterior longitudinal ligament contact time with kerrison	1	.02*
Posterior longitudinal ligament contact time with nerve hook	1	.79
Avg. force on posterior longitudinal ligament with nerve hook	2	.87
Avg. force on posterior longitudinal ligament with kerrison	2	.2
Avg. force on spinal dura with nerve hook	2	.27
Avg. force on spinal dura with kerrison	2	.29
Max force on posterior longitudinal ligament with nerve hook	2	.30
Max force on posterior longitudinal ligament with kerrison	2	.05
Max force on spinal dura with nerve hook	2	.96
Max force on spinal dura with kerrison	2	.14
TTPL with kerrison	2	.05
TTPL with nerve hook	2	.80

Avg. = Average
† *p*-value for Kruskal-Wallis, non-parametric test
* Significant *p*-value for Kruskal-Wallis, non-parametric test ($p<0.05$)
TTPL = Total tip path length

TABLE 7. Median score on a 7-point Likert scale regarding perceptions of virtual reality as an educational tool.

Statement	Median score (range)		
	Junior Residents	Senior Residents	Post-Residents
Resident use of virtual reality simulators to practice techniques will improve operating room skills	4.0 (2.0 - 7.0)	6.0 (3.0 - 7.0)	6.0 (1.0 - 7.0)
Virtual reality simulators would be useful for attending surgeons	4.0 (1.0 - 6.0)	4.0 (2.0 - 7.0)	6.0 (1.0 - 7.0)
Virtual reality simulation could assist in preparation for complex cases	6.0 (3.0 - 7.0)	6.0 (2.0 - 7.0)	6.0 (1.0 - 7.0)
Virtual reality simulators could provide objective measurement of surgical skill	4.0 (2.0-6.0)	6.0 (2.0-7.0)	6.0 (1.0 -7.0)
In the future, virtual reality simulators could be used to practice techniques that will help to improve patient safety	5.0 (1.0-7.0)	6.0 (5.0-7.0)	7.0 (1.0-7.0)

TABLE 8. Median score on a 7-point Likert scale for face and content validity for the post-resident group after completing the ACDF simulation.

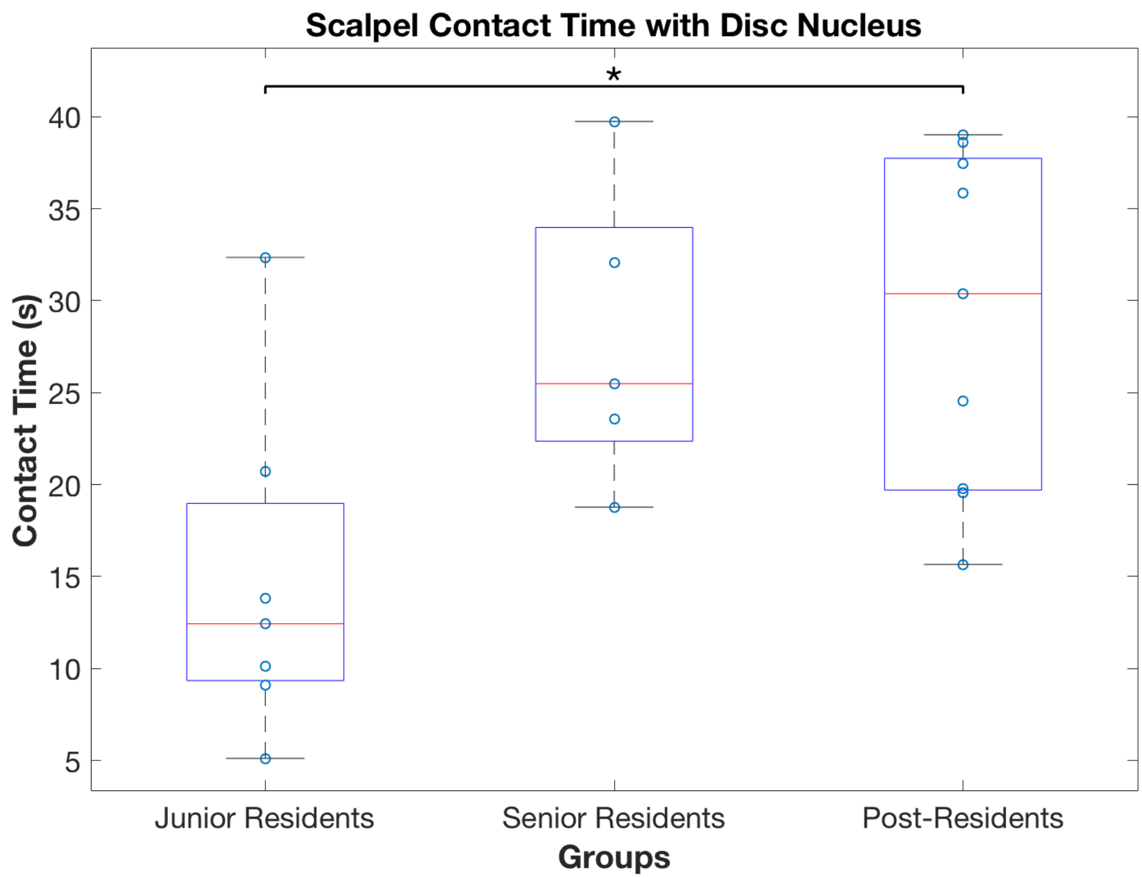
Validity Statements	**Median Score for Post-Resident Group**	**Range**
Overall Realism	4.0	2.0-6.0
Anatomical Realism	6.0	2.0-6.0
Overall realism of the color for the simulated anatomical structures	5.0	2.0-6.0
Using a scalpel to make a transverse box incision at the center of the exposed disc	5.0	3.0-7.0
Using a pituitary rongeur to remove the disc	4.0	2.0-5.0
Using a curette to remove the disc	3.0	2.0-6.0
Using a disc rongeur to remove the disc	5.0	2.0-5.0
Using a burr to remove the osteophytes	6.0	5.0-7.0
Using a nerve hook to lift the posterior longitudinal ligament	4.0	1.0-6.0
Using a kerrison, remove the posterior longitudinal ligament	3.5	1.0-5.0
If this simulator was available in your program, you would use this simulation scenario for training of the technical skills simulated.*	4.0*	1.0-5.0*

*Question assessed using a 5-point Likert Scale

TABLE 9. Median score on a 7-point Likert scale for difficulty, satisfaction, and performance for each of the three groups after performing the ACDF simulation.

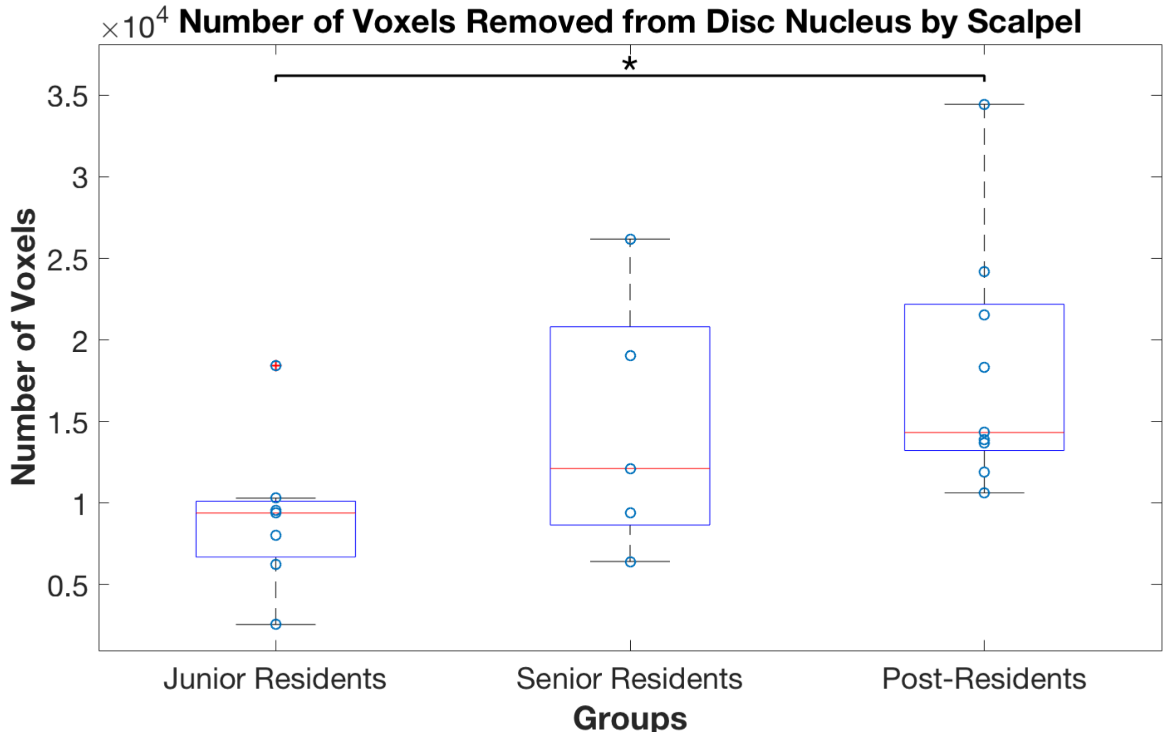
Statement	**Median score (range)**		
	Junior Residents	**Senior Residents**	**Post-Residents**
Overall difficulty of the scenario	4.0 (2.0 - 5.0)	4.0 (2.0 - 5.0)	4.0 (2.0 - 6.0)
Overall satisfaction	4.0 (1.0 - 5.0)	4.0 (1.0 - 6.0)	4.0 (2.0 - 6.0)
Personal rating of performance	4.0 (1.0 - 6.0)	2.0 (1.0 - 6.0)	4.0 (1.0 - 7.0)

FIGURE 3. Dunn's pairwise comparison of significant differences between groups for scalpel contact time with disc nucleus.



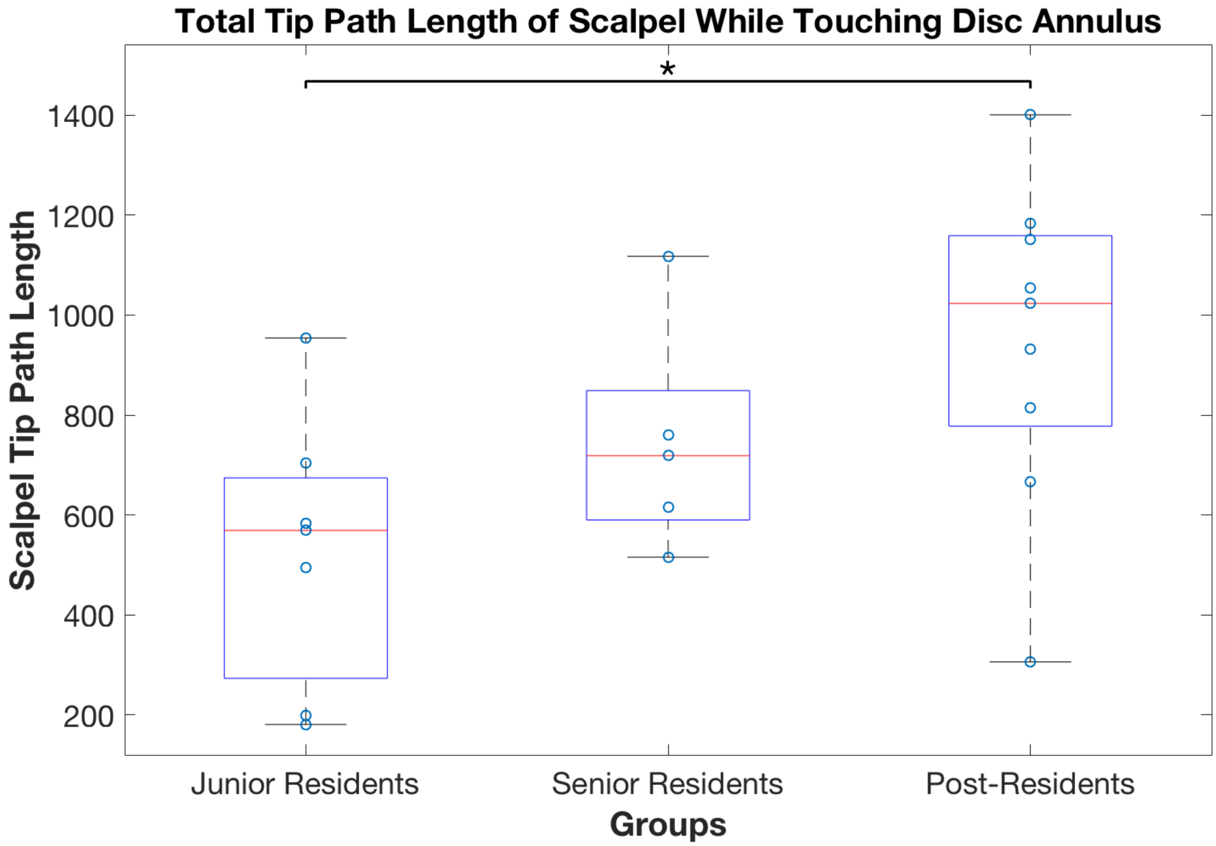
*Denotes a significant difference ($p<0.05$) between groups after Bonferroni correction
+ Outlier
Central mark (red line) indicates the median value for the group
Top and bottom edges of the box represent the 25th and 75th percentiles, respectively

FIGURE 4. Dunn's pairwise comparison of significant differences between groups for number of voxels removed from the disc nucleus by the scalpel.



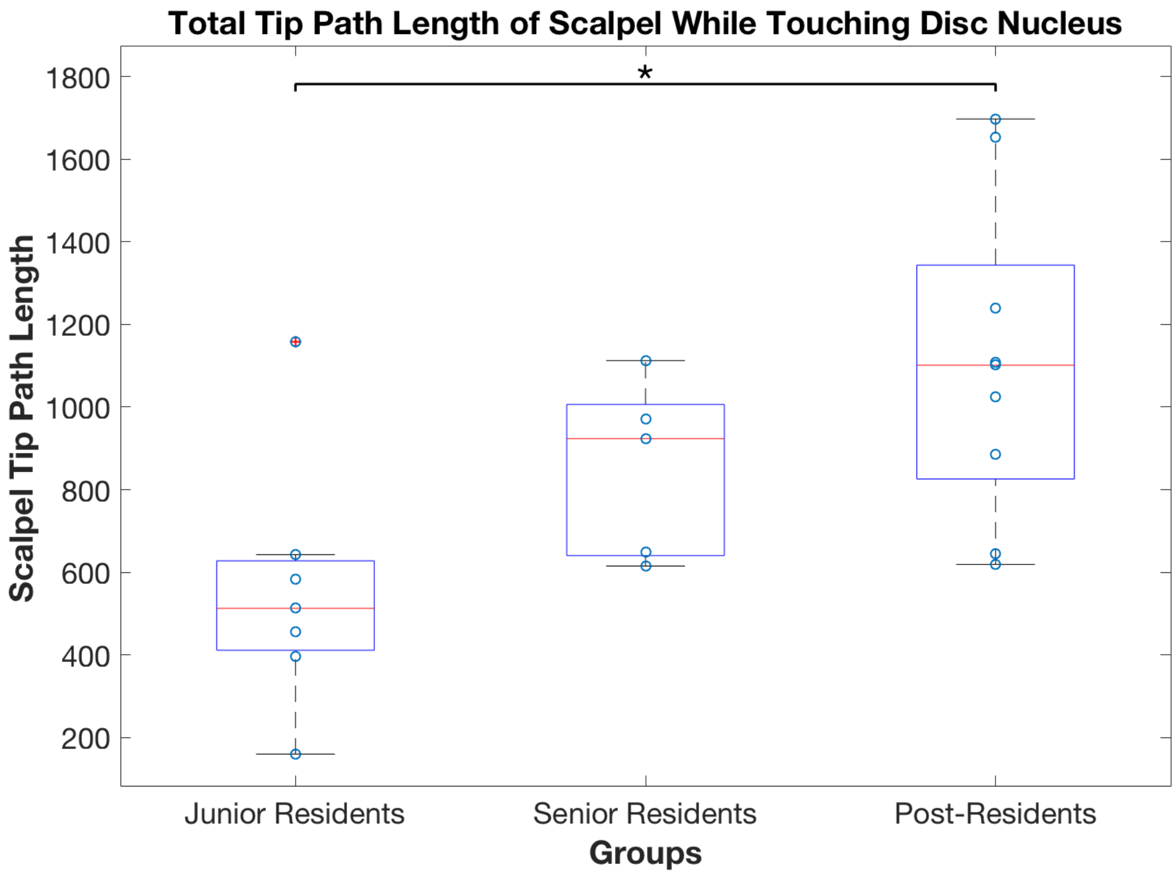
*Denotes a significant difference (*p*<0.05) between groups after Bonferroni correction
+ Outlier
Central mark (red line) indicates the median value for the group
Top and bottom edges of the box represent the 25th and 75th percentiles, respectively

FIGURE 5. Dunn's pairwise comparison of significant differences between groups for scalpel total tip path length while contacting the disc annulus.



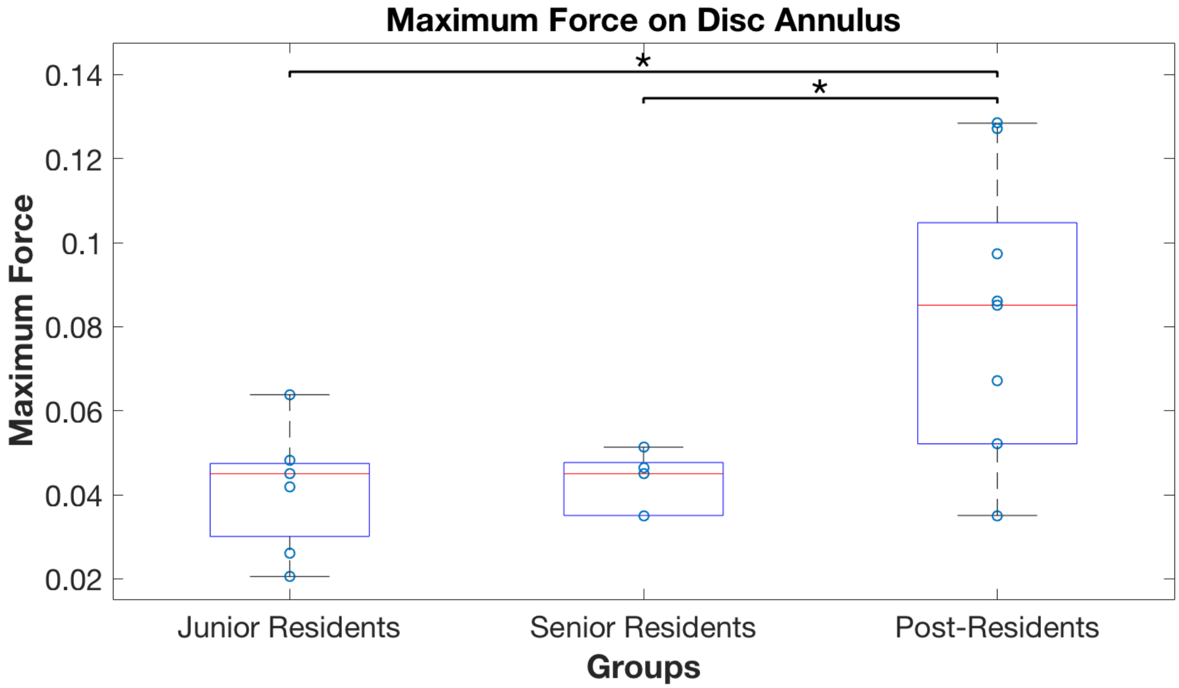
*Denotes a significant difference ($p<0.05$) between groups after Bonferroni correction
+ Outlier
Central mark (red line) indicates the median value for the group
Top and bottom edges of the box represent the 25th and 75th percentiles, respectively

FIGURE 6. Dunn's pairwise comparison of significant differences between groups for scalpel total tip path length while contacting the disc nucleus.



*Denotes a significant difference (p<0.05) between groups after Bonferroni correction
+ Outlier
Central mark (red line) indicates the median value for the group
Top and bottom edges of the box represent the 25^{th} and 75^{th} percentiles, respectively

FIGURE 7. Dunn's pairwise comparison of significant differences between groups for maximum force on the disc annulus while performing the discectomy.



*Denotes a significant difference ($p<0.05$) between groups after Bonferroni correction
+ Outlier
Central mark (red line) indicates the median value for the group
Top and bottom edges of the box represent the 25th and 75th percentiles, respectively

FIGURE 8. Dunn's pairwise comparison of significant differences between groups for the amount of voxels removed from C5 with the burr.

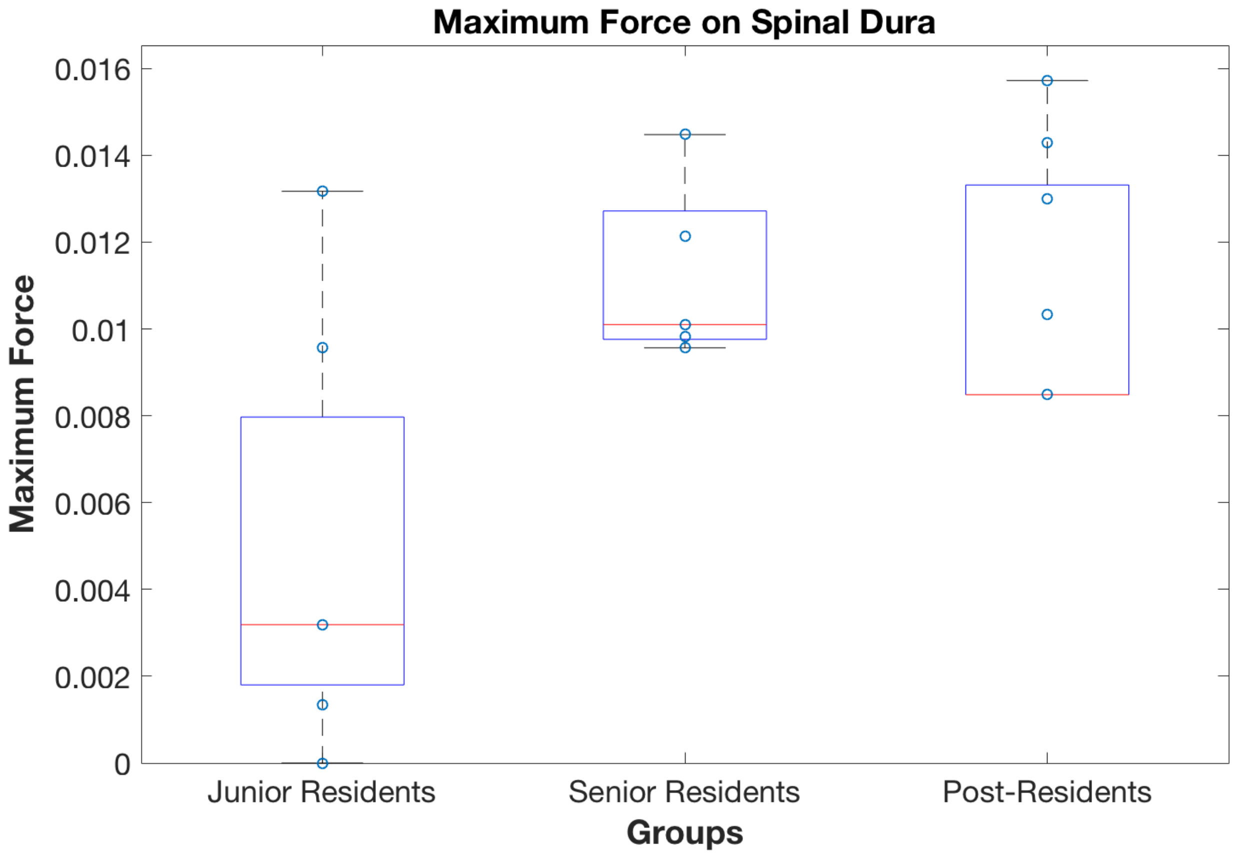
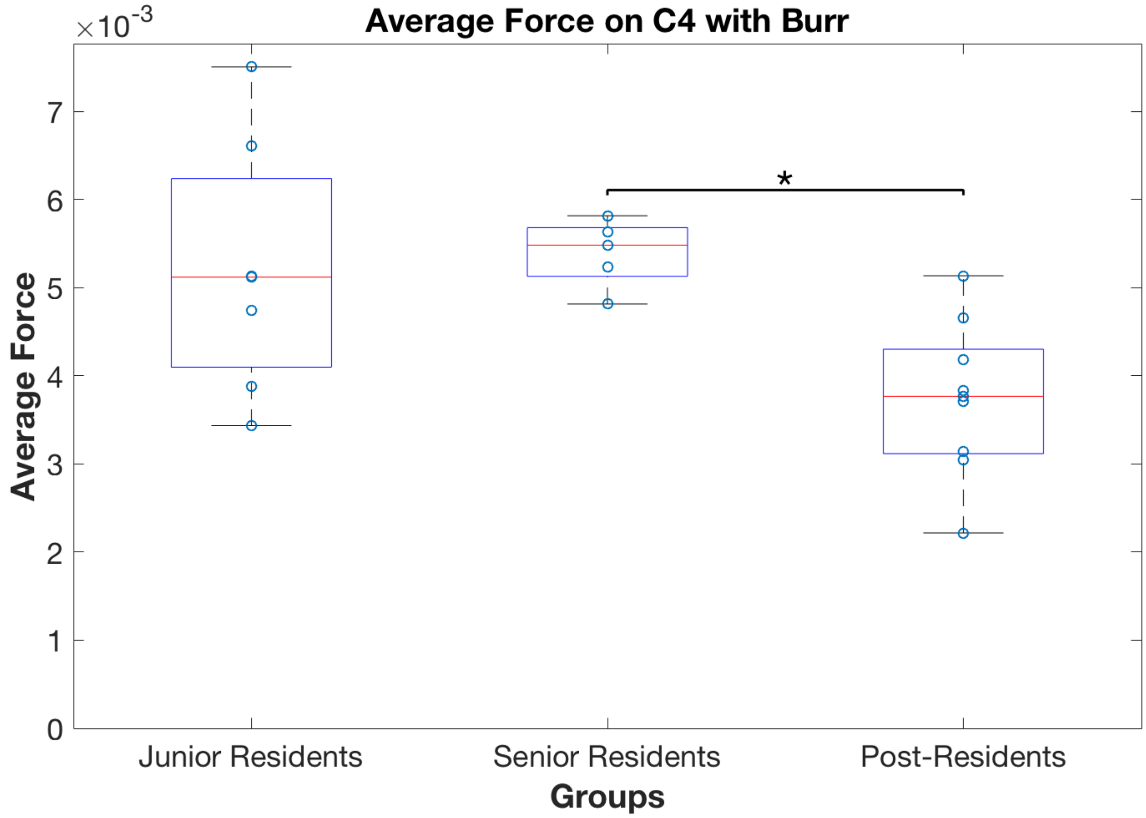
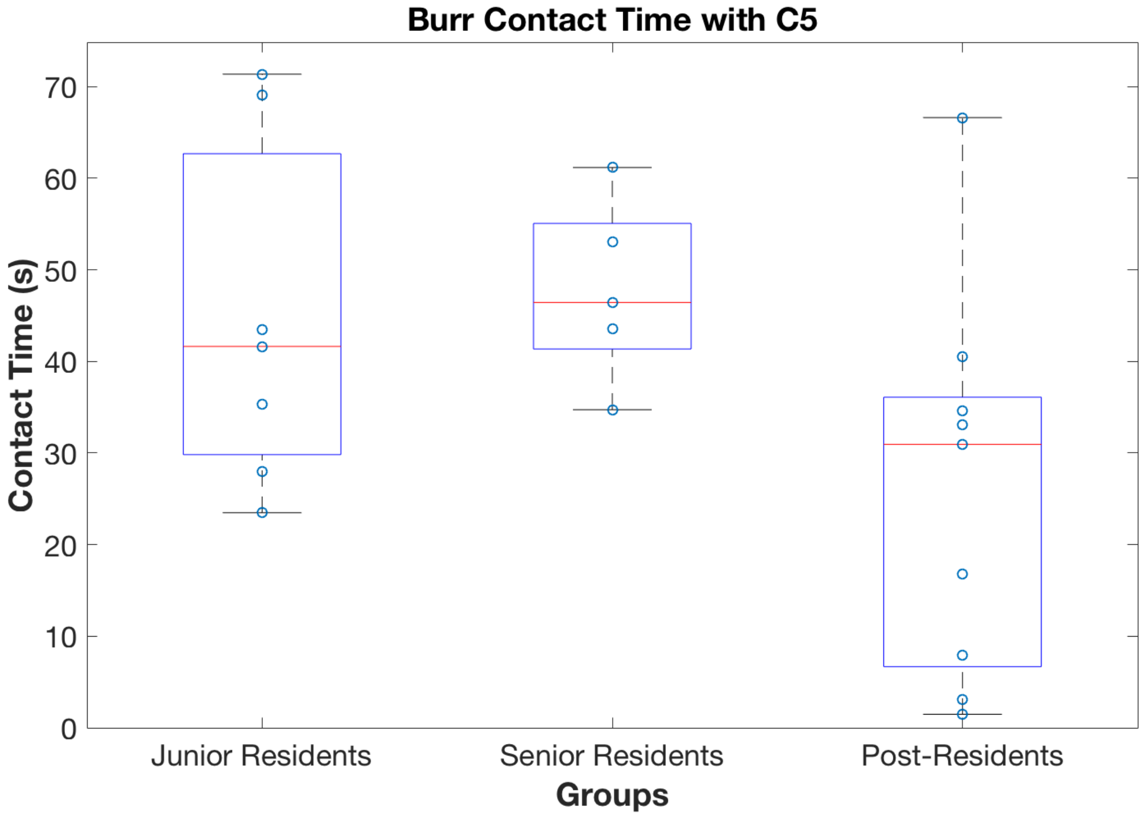


FIGURE 9. Dunn's pairwise comparison of significant differences between groups for average force on C4 with the burr.



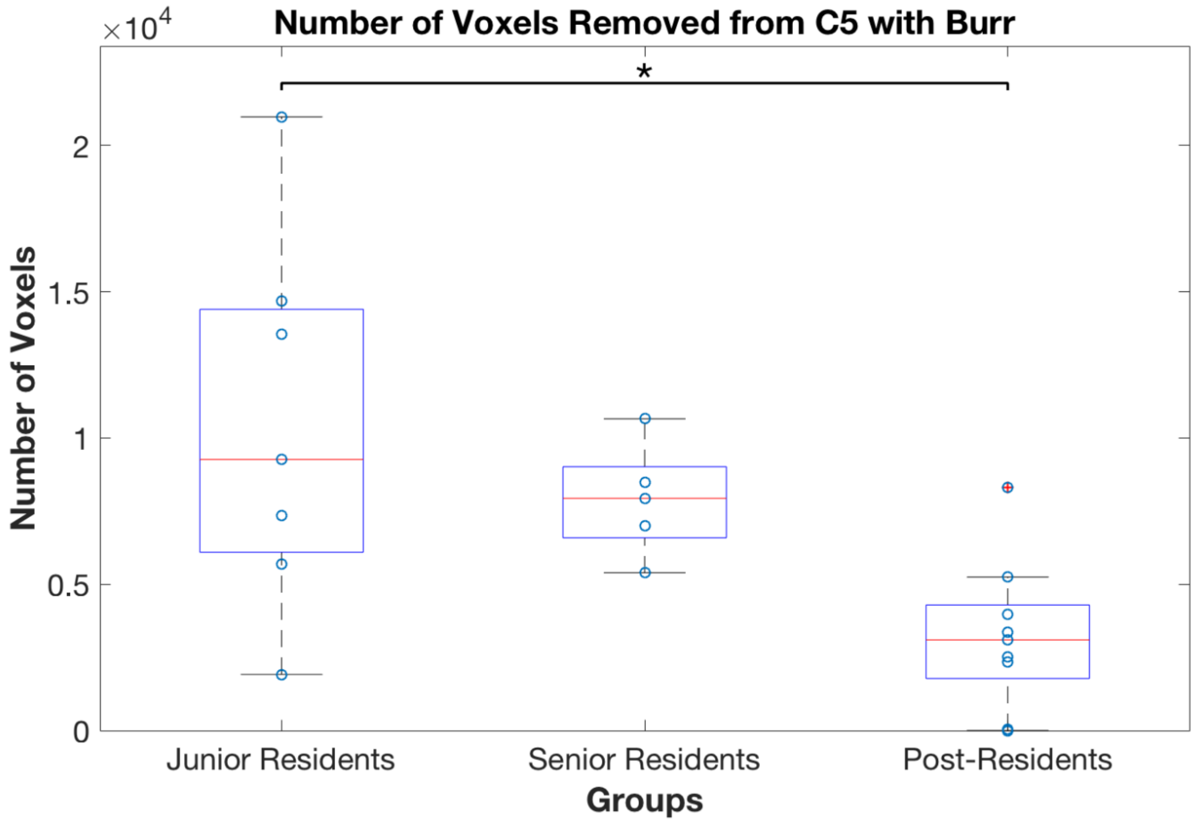
*Denotes a significant difference ($p<0.05$) between groups after Bonferroni correction
+ Outlier
Central mark (red line) indicates the median value for the group
Top and bottom edges of the box represent the 25th and 75th percentiles, respectively

FIGURE 10. Dunn's pairwise comparison of significant differences between groups for the amount of voxels removed from C5 with the burr.



*Denotes a significant difference ($p<0.05$) between groups after Bonferroni correction
+ Outlier
Central mark (red line) indicates the median value for the group
Top and bottom edges of the box represent the 25th and 75th percentiles, respectively

FIGURE 11. Dunn's pairwise comparison of significant differences between groups for the amount of voxels removed from C5 with the burr.

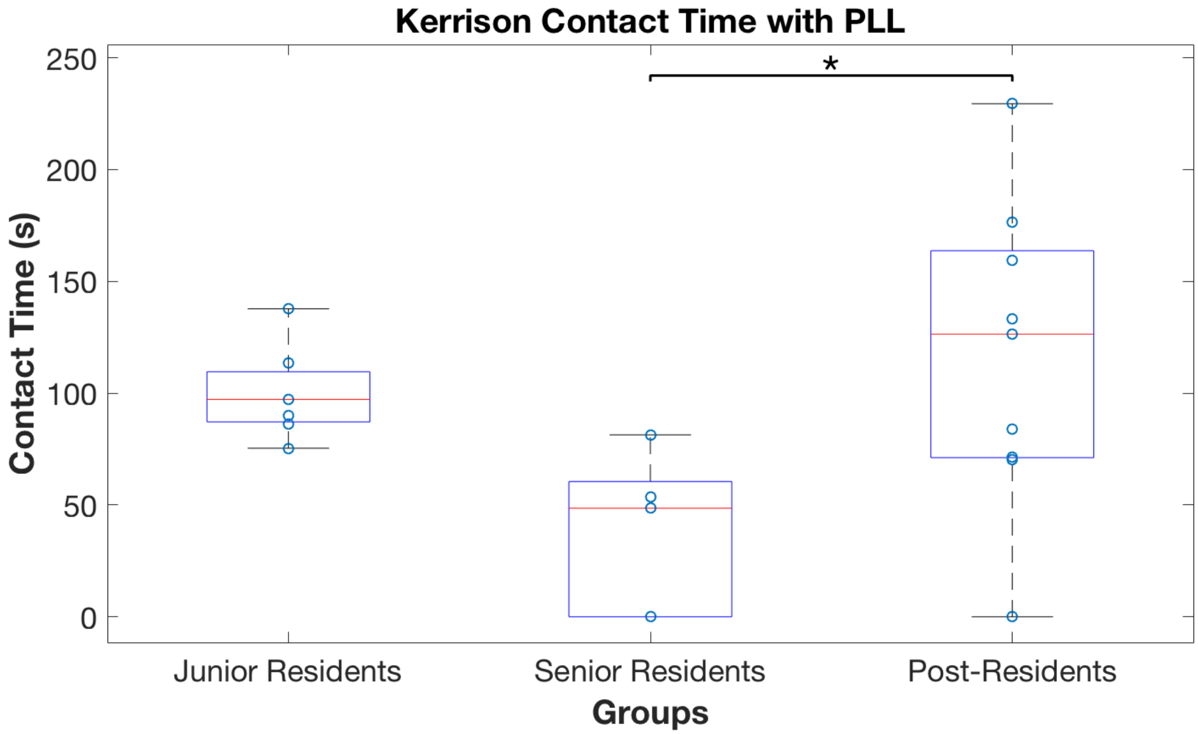


*Denotes a significant difference (p<0.05) between groups after Bonferroni correction
+ Outlier
Central mark (red line) indicates the median value for the group
Top and bottom edges of the box represent the 25th and 75th percentiles, respectively

FIGURE 12. Dunn's pairwise comparison of significant differences between groups for total tip path length while contacting C5 with the Burr.

*Denotes a significant difference (*p*<0.05) between groups after Bonferroni correction
+ Outlier
Central mark (red line) indicates the median value for the group
Top and bottom edges of the box represent the 25th and 75th percentiles, respectively

FIGURE 13. Dunn's pairwise comparison of significant differences between groups for amount of time spent touching the PLL with the kerrison.



*Denotes a significant difference (*p*<0.05) between groups after Bonferroni correction
+ Outlier
Central mark (red line) indicates the median value for the group
Top and bottom edges of the box represent the 25th and 75th percentiles, respectively