Surgical Performance Analysis in a Simulated Virtual Reality Anterior Cervical Discectomy and Fusion Task

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Abstract

Introduction:

Multiple studies have demonstrated the effectiveness of virtual reality (VR) simulators in surgical skills training and assessment. Anterior cervical discectomy and fusion (ACDF) is among the most common spine procedures and requires trainees to master a broad spectrum of surgical techniques. The Sim-ortho VR simulator provides a validated anterior cervical discectomy and fusion (ACDF) simulated task. This validated tool can be used in the evaluation and assessment of surgical skill.

Objective

This thesis aims to analyze the three-dimensional data recorded by the Sim-Ortho VR simulator platform during the discectomy component of the ACDF task. We aim to use the generated data to develop novel metrics to assess the performance of participants with different levels of expertise.

Hypothesis

We hypothesize that the results of this analysis would establish a methodology to develop novel metrics that can identify performance variability between different groups of expertise and provide new insights into surgical expertise.

Methods

We recruited participants with different levels of expertise to perform a standardized ACDF simulation task. The three-dimensional structural data were generated from the simulator and recorded after each step. We collected and analyzed different data including volumes of each

structure at different stages of the procedure and rate of removal of the disc. Statistical significance was set as $p < 0.05$.

Results

Twenty-seven participants were included and divided into three groups based on their surgical expertise: medical student, resident, and post-resident groups. Medical students took longer to perform the discectomy compared to the other groups and left almost three times of disc residual as the resident and post-resident groups ($p = 0.068$). During the annulotomy component, the post-resident group removed 47.4% more disc than the resident and 102% more than the medical student group ($p = 0.03$). No statistically significant differences between groups were found during the second stage of the discectomy regarding disc residual and rate of removal. The post-resident group spent 19.1% of their surgical time actively working on areas adjacent to the dura, compared to 13.7% and 5.1% in the resident and medical student groups, respectively ($p = 0.017$).

Conclusion

Expert performance is associated with higher efficiency compared to resident and medical student groups. The amount removed and rate of removal represent other features of expertise during the annulotomy stage of the discectomy. These differences expose some of the features of experts' performance that can be further studied and taught to junior trainees.

Résumé

Introduction

De nombreuses études ont démontré l'efficacité des simulateurs de réalité virtuelle (VR) dans la formation et l'évaluation des compétences chirurgicales. La discectomie cervicale antérieure et la fusion (ACDF) sont parmi les procédures de la colonne vertébrale les plus courantes et nécessitent que les stagiaires maîtrisent un large éventail de techniques chirurgicales. Le simulateur Sim-ortho VR fournit une tâche simulée validée de discectomie cervicale antérieure et de fusion (ACDF). Cet outil validé peut être utilisé dans l'évaluation et l'appréciation des compétences chirurgicales.

Objectif

Cette thèse vise à analyser les données tridimensionnelles enregistrées par la plateforme de simulateur Sim-Ortho VR lors de la composante discectomie de la tâche ACDF. Nous visons à utiliser les données générées pour développer de nouvelles métriques afin d'évaluer les performances des participants avec différents niveaux d'expertise.

Hypothèse

Nous émettons l'hypothèse que les résultats de cette analyse établiraient une méthodologie pour développer de nouvelles métriques qui peuvent identifier la variabilité des performances entre les différents groupes d'expertise et fournir de nouvelles informations sur l'expertise chirurgicale.

Méthodes

Nous avons recruté des participants avec différents niveaux d'expertise pour effectuer une tâche de simulation ACDF standardisée. Les données structurelles tridimensionnelles ont été générées

à partir du simulateur et enregistrées après chaque étape. Nous avons collecté et analysé différentes données, notamment les volumes de chaque structure à différentes étapes de la procédure et le taux de retrait du disque. La signification statistique a été fixée à $p < 0,05$.

Résultats

Vingt-sept participants ont été inclus et divisés en trois groupes en fonction de leur expertise chirurgicale : étudiants en médecine, résidents et groupes post-résidents. Les étudiants en médecine ont mis plus de temps à effectuer la discectomie par rapport aux autres groupes et ont laissé près de trois fois des résidus discaux dans les groupes résidents et post-résidents ($p = 0,068$). Au cours de la composante d'annulotomie, le groupe post-résident a retiré 47,4 % de disque de plus que les résidents et 102 % de plus que le groupe des étudiants en médecine ($p = 0,03$). Aucune différence statistiquement significative entre les groupes n'a été trouvée au cours de la deuxième étape de la discectomie en ce qui concerne le disque résiduel et le taux d'ablation. Le groupe post-résident a passé 19,1 % de son temps chirurgical à travailler activement sur les zones adjacentes à la dure-mère, contre 13,7 % et 5,1 % dans les groupes de résidents et d'étudiants en médecine, respectivement ($p = 0,017$).

Conclusion

La performance des experts est associée à une efficacité supérieure par rapport aux groupes de résidents et d'étudiants en médecine. La quantité enlevée et le taux d'enlèvement représentent d'autres caractéristiques de l'expertise pendant la phase d'annulotomie de la discectomie. Ces différences exposent certaines des caractéristiques de la performance des experts qui peuvent être étudiées plus avant et enseignées aux stagiaires débutants.

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PREFACE AND AUTHOR CONTRIBUTIONS

The presented thesis is structured in a manuscript-based format. The authors of the manuscript have contributed significantly to put this work in its final format. The author's contribution is reported here following CRediT (Contributor Roles Taxonomy) format.[1, 2] The following statements highlight each individual's contribution to this work.

Dr. Mohamad Bakhaidar has contributed to Conceptualization, Methodology, Software, Format analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization, Funding acquisition, and Project administration.

Dr. Recai Yilmaz has contributed to Conceptualization, Methodology, Software, Format analysis, and Visualization.

Dr. Ahmad Alsayegh has contributed to Conceptualization, Methodology and Project administration.

Nykan Mirchi has contributed to Conceptualization, Methodology, Software, Investigation, Format analysis, Investigation, Visualization and Project administration.

Nicole Ledwos has contributed to Conceptualization, Methodology, Software, Investigation, Format analysis, Investigation, Visualization and Project administration.

Ali Fazlollahi has contributed to Conceptualization and Methodology.

Dr. Alexander Winkler-Schwartz has contributed to Conceptualization and Methodology.

Dr. Rolando F. Del Maestro has contributed to Conceptualization, Methodology, Format analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization, Project administration and Supervision.

ABBREVIATIONS

ACDF: Anterior Cervical Discectomy and Fusion

VR: Virtual Reality

AI: Artificial Intelligence

CBME: Competency-Based Medical Education

CPD: Continuing Professional Development

CSV: Comma Separated Value

OR: Operating Room

OSATS: Objective Structured Assessment of Technical Skills

PGY: Post-Graduate Year

PLL: Posterior Longitudinal Ligament

SD: Standard Deviation

VR: Virtual Reality

Thesis Introduction

Background

Surgical Education and the Shift to the Competency-Based Curriculum.

The history of surgical education has evolved throughout the centuries.[3] Initially, no formal education was available and most practitioners of medicine were entirely self-taught or learned through apprenticing to a physician of similar background.[4] This apprenticeship would require students to spend time with a mentor observing their practice and imitating their actions to learn medicine and surgical skills.[3] Little focus was directed toward the knowledge or skills that were to be taught.[3] Until the late 19th century, this basic apprenticeship model was the only model of surgical education.[3, 4] Sir William Osler outlined the importance of the early clinical experience to medical students during his work at McGill University and John Hopkins Medical School.[5, 6] Osler supported the appointment of William S. Halsted as the chief of the Department of Surgery at Johns Hopkins Hospital.[4] Halsted brought his European surgical experience in Germany to John Hopkins Medical School and helped to develop a more advanced surgical training model that was tightly modeled on the German one.[4] Halsted's new system relied on certain principles that focuses on supervised progressive surgical training that ensures a gradual developing autonomy with enhanced responsibilities and independence.[4] Several graduates of the training model at John Hopkins went to establish training programs at various distinguished institutions.[3] Dr. Harvey Cushing, a neurosurgical pioneer, is a graduate of Halsted's training program.[7, 8] He helped establish neurosurgery as a specialty and expanded the field through many contributions.[7, 8]

Despite this model at John Hopkins, Abraham Flexner reported in 1910 that many medical schools in U.S. and Canada are falling behind the standards in medical and surgical education, and reform of the medical schools' education curriculum was needed.[3, 6, 9, 10] The American College of Surgeons was founded in 1912 and one of its main objectives was to improve the training for surgical trainees. This involved developing a minimum standard of requirements for graduates to be allowed to perform operations independently.[3, 4] In the same year, the Medical Council of Canada initiated a nationwide standard examination for all medical school graduates in an attempt to standardize medical education.[6]

A special Act of the Canadian Parliament established the Royal College of Physicians and Surgeons of Canada (RCPSC) in 1929 to oversee postgraduate medical education in Canada.[11] The understanding of medical education has continued to evolve leading the way to the significant advancements of our current time.[3] Halsted's apprenticeship model is facing increasing challenges, making it more difficult to graduate competent surgical trainees.[12] Reduction in working hours, increasing surgical complexity, concerns about patient safety, and increased demand for operating room efficiency have resulted in less time for teaching, learning, and practice during surgical procedures.[13, 14] Competency-based Medical Education (CBME) has been proposed as a surgical education methodology to ensure that trainees are able to master the competencies required to function effectively at each level of training.[15] A major milestone in medical education was the development of the CanMEDS Competency Framework by RCPSC in 1996 with the latest updated version published in 2015.[11, 16] This framework replaced the previous post-graduation year with newer distinct stages of postgraduate training that are specified with gaining specific competencies.[11, 16] Entrustable professional activities (EPAs) are used to evaluate the competency and help promotion decisions between stages.[11] In response to the global move toward CBME, the RCPSC launched a program referred to as Competence by Design (CBD) to transform all disciplines into a competency-based education model with the expectation of a complete transition by 2022.[11, 16-18]

Simulation in Surgical Education

Resnick and MacRae reviewed the educational concepts that underpinned teaching surgical skills and divided surgical skills acquisition into three major stages.[19] When exposed to a new skill to learn, trainees usually start with a cognitive stage in an attempt to understand the surgical steps and goals of each step.[12, 19] This is followed by an integrative stage where trainees' surgical movements are getting smoother as they are more familiar with the procedure.[12] As the trainees get more experience, their performance becomes masterly with no hesitation, and they reach the autonomous stage.[19] Similarities between this model and pilot training have been proposed in the literature.[12, 20] Both training programs are based on skill development through pattern recognition, intuition, and reflection to develop surgical skills through a series of proctored events.[20]

Simulation is a technique to replace or amplify real experiences with immersive guided experiences, that evoke or replicate substantial aspects of the real world in an interactive manner.[21] Simulated events can be introduced in a simulation laboratory which permits trainees to practice surgical procedures in a relaxed and nurturing environment.[12] Furthermore, simulated scenarios can be used to evaluate the performance and objectively direct the progress of trainees.[22] Different validated tools such as Objective Structured Assessment of Technical Skills (OSATS) can be used to evaluate surgical performance.[23, 24] In an ideal world, before participating in a surgical procedure, the trainee would start with practicing the steps of the operation in a relaxed safe simulated environment. The trainee can practice, as many times as necessary, without the fear of failing or making a technical error. Once the trainee reaches a level of comfort with the operative steps being simulated and obtains a satisfactory level assessed by an appropriate evaluation tool, the learner could then start to participate in patient operative procedures.

Surgical simulators vary widely in their complexity and can range from simple bench-top simulators such as suture tying boxes to complex advanced virtual reality (VR) simulators.[12, 25] Suture tying boxes, and laparoscopic box simulators are widely available bench-top simulators.[25] Both anesthetized live animals models and ex vivo models have been used as effective surgical simulators.[12, 26, 27] These represent high-fidelity simulators that can allow practicing surgical operation in biological tissue and permit working in teams which further enhance intraoperative communications and complication management.[26] Despite the numerous benefits of these animal models, anatomical differences between animals and humans, ethical considerations, costs, and biological hazards are some of the drawbacks of using these models.[26] Human cadavers are the gold standard for surgical anatomical simulation and have been used in teaching for centuries.[26] They also have disadvantages related to ethical considerations and cost which limit their availability for training.[26]

Prompted by the gaming and entertainment industries, the rapid advancement of VR technology has led to significant interest in its possible applications in surgical education.[28] With the advancement in computational power and visual and haptic display technologies, the field of virtual surgical environments and simulators has rapidly expanded with novel tools becoming available.[12, 29] VR simulators are widely used to teach endoscopy and laparoscopy procedures.[12] The Da Vinci Surgical Skills Simulator is one of several robot-assisted VR surgical simulators that are now being used to train surgeons how to perform robotic surgery.[12, 25, 26, 30] VR surgical simulators can help trainees to gain familiarity with the surgical procedure and develop hand-eye coordination and fine motor skills through the use of surgical tools that manipulate a virtual environment.[26] With the advancement in the graphical capabilities of computers, modern VR simulators can create minute anatomical details and offer anatomically correct, high-fidelity simulations.[26] Haptic feedback technology is often incorporated in VR simulators to provide the users with realistic real-time tactile feedback.[29, 31] The combination of tactile with audiovisual feedback systems can lead to a highly immersive experience for the trainees.[26] Despite these advantages, many VR simulators are still costly, not widely available, and have limitations related to operative realism and trainee feedback systems.[26, 32] However, as technology advances, VR simulators may overcome these shortcomings.[26]

Virtual Reality Simulators and their Emerging Role in Surgical Training

The role of VR simulators in surgical education is being extensively investigated with many studies supporting the incorporation of VR simulators in surgical education.[12, 26] An increasing number of institutions and training programs have started to implement VR simulation-based curriculum in their surgical education programs.[26, 33-35] Training in a VR simulation environment can lead to enhancement in efficiency and surgical performance.[26, 36, 37] The data suggesting the transferability of surgical skills from VR simulators to real operative theaters (OR) emphasize their importance in surgical education especially if combined with a proficiency-based curriculum.[26, 36, 38, 39 40]

There are many advantages for VR simulators over other more traditional simulators.[26, 41] A major advantage to VR simulators is their ability to record a vast amount of information of surgical performance and the simulated environment.[42-44] The variables recorded are exported as a large dataset that provides a quantification of different aspects of surgical performance.[42, 44]

This feature of VR simulators provides an objective effective tool that can be used to direct feedback and monitor the progression of surgical skills acquisition.[45, 46] The VR simulator can record data regarding some aspects of performance that are difficult to measure in real-life scenarios such as force application, real-time quantification of tissue removed, and instrument movements.[42, 47] This unique attribute allows the development of many novel applications for these performance datasets.[48-50] Analyzing metrics generated by simulators can expose and quantify novel features of expertise that could not be possible to measure in real life.[42] Generation of validated teachable metrics from VR simulators can allow trainees to improve their surgical performance and obtain personalized feedback on specific aspects of their performance.[22, 42, 51] Artificial intelligence (AI) applications to these large data set are enormous and can range from trainees classification, evaluation, and even coaching and providing personalized feedback.[46, 49, 50, 52, 53] Intelligent tutoring systems such as the virtual operative assistant (VOA)[50] can utilize the power of machine learning and large datasets to accurately differentiate surgical expertise and provide feedback on operative performance.[48] With increasing limitations to traditional methods of surgical training due to working-hour restrictions, the complexity of cases, or even global pandemic such as COVID-19, VR simulators provide an unlimited opportunity to learn and practice surgical skills outside of these constraints.[48]

Spine Surgery Simulators

Simulation advancement in spinal surgery has been relatively slow compared to other specialties such as laparoscopic or robotic surgery.[54] In spine surgery, minimally invasive procedures such as vertebroplasty and pedicle screw placement comprise the majority of available simulated tasks.[54] Few spine surgery simulators are capable of simulating complex multifaceted procedures such as anterior cervical or scoliosis surgery.[54] Difficulty in simulating anatomical structures, the wide difference in force applications between soft tissues and bone, and cost-related issues are some of the main issues that face the development of spine simulation platforms.[54] Spine surgery is usually complex and requires the trainees to master a wide spectrum of skills.[55] Accurate anatomical recreation of the simulated structures and the presence of a realistic feel to bone and soft tissues are essential.[56] Skills such as drilling of bone are very important and require realistic tactile and audiovisual feedback to accurately simulate the real operative experience.[56] Advancement in technology is helping newer spine simulators platforms overcome these issues and develop highly realistic VR-based environments and scenarios.[54] Patient-specific VR simulation tools will become more available and will be used in surgical planning and perioperative practice.[54] Table 1 provides an up-to-date summary of the available interactive VR simulators in the literature.

The Sim-Ortho Virtual Reality Simulator

Sim-Ortho is a VR simulator that was developed by OSSimTech™ in Montreal, Canada (currently Symgery™). The simulator uses an advanced haptic feedback technology to provide a realistic feel to bone and other anatomical structures. The simulator uses voxels and three-dimensional (3D) glasses to visualize a realistic replica of the surgical environment and instruments. In addition, different sounds such as the patient cardiac monitoring and instrument sounds when interacting with different structures are provided which add to the immersive experience of the simulator. Different tools and tool handles are available and represent most of the widely used instruments in spine surgery (Figure1A). Different metrics are recorded by the simulator including force, instrument tracking, and amount of tissue removed. Different simple and complex scenarios are available through the simulator including laminectomy, pedicle screw placement, and anterior cervical discectomy and fusion (ACDF). The simulator records data every 20 milliseconds allowing a time stamping of performance. This allows the generation of new sets of metrics such as velocity, acceleration, and rate of tissue removal. In addition, the simulator records a 3D representation of structures involved in the simulated task. The latter is interesting given the many applications that this type of data could have.

Anterior Cervical Discectomy and Fusion Simulation

Cervical degenerative spinal procedures are among the most common procedures done in spine surgery with ACDF being the most frequently performed surgery for degenerative cervical disease in the US.[57] ACDF requires the trainee to gain proficiency in multiple areas, including understanding anatomical planes, appreciating the feeling of different tissues, and achieving a safe decompression of the neural elements.[55] The latter is a very important skill, giving the serious outcome if the spinal cord or nerves are injured. Ray et al. presented the first simulator for ACDF during a Congress of Neurological Surgeons (CNS) simulation course.[55] This model was not studied further and the validity and reliability of this simulator are unknown.[55] The Sim-Ortho platform provides a multi-step ACDF simulated task that has demonstrated face, content, and construct validity.[42] AI-based and machine learning algorithms were used in different studies to analyze the data of ACDF task on the Sim-Ortho platform.[46, 58] Artificial neural network, a subset of machine learning, demonstrate high accuracy in classifying participants based on their expertise and performance.[46, 58]

The rationale of The Thesis

An increasing body of evidence supports the use of virtual reality simulation in neurosurgical training.[59-61] VR simulators emerge as an effective tool that allows trainees to gain surgical skills.[59] However, before incorporating VR simulators in surgical education curriculums, the validity of each simulator based on the assessment of each simulated scenario needs to be demonstrated.[42, 59, 62] Validation is an essential step in developing simulation-based training modules as it provides evidence for whether the simulator is actually teaching or evaluating what it is intended to teach or measure.[42, 59, 63, 64] Different validation methods are available and can be divided into subjective validity as face and content validity and objective validity such as construct, concurrent and predictive validity.[65] Face validity examines the degree of realism of the simulator through evaluating the appearance, feel, and experience of the simulator.[64, 65] Content validity examines the extent to which the simulator's content can appropriately represent the knowledge or skills that have to be learned in the real environment.[64, 66] These subjective validity measurements are established through experts' opinions using a variety of questionnaires and are prone to errors.[64, 65] On the other hand, objective validity is determined using data obtained from performance on the simulators and is more challenging and time-consuming to establish.[64] Objective validity is an important measurement that plays a vital role in establishing evidence for a simulator's capability to train surgeons.[64] Through identifying the differences between expert and novice performance in a simulated surgical task, the construct validity of the simulation can be established.[42] Construct validity is one of the most valuable assessments of the simulator prior to incorporation into a competency-based curriculum.[64] Concurrent validity deals with the extent of the ability of the simulator to be used as an assessment tool compared with the "gold standard".[64, 67] Furthermore, predictive validity is a measurement of the transferability of surgical skills from the simulator to the real operative theater.[64, 65, 67] Establishing concurrent and predictive validities is challenging as it requires the development of gold standard performance metrics to which the performance on the simulator could be reliably compared with.[64] Research focusing on developing validated metrics of VR simulators will lead to the development of a robust framework for the use of VR in education.[59]

Virtual reality-based surgical simulators can record a large amount of data related to surgical performance. This provides an objective measurement of performance that can be used in validity testing.[42] The Sim-Ortho platform is equipped with the ability to record 3D data of the structures involved in the simulated task. This can provide information concerning the structural changes during different stages of the simulated operation. For example, in an ACDF task, the 3D data can give information regarding the location of the residual disc material, the rate of disc removal, and the spatial relationship between the force applied by an instrument and the location and amount of tissue removed. The 3D data recorded by the Sim-Ortho simulator platform concerning the discectomy component of the ACDF has not been investigated previously.

Thesis Hypothesis and Objectives

This study hypothesizes that utilizing 3D data generated by the Sim-Ortho virtual reality simulator platform employing the ACDF discectomy simulated task, we can establish a methodology to develop novel performance metrics that can differentiate between skilled and less-skilled participants and provide new insights into surgical expertise.

The objectives of this study are 1) to develop a methodology to extract 3D data recorded by the Sim-Ortho virtual reality simulator platform associated with the discectomy component of the ACDF simulation, 2) to utilize this methodology to accurately reconstruct and quantitate disc dimensions and volumes, 3) to develop a series of novel metrics to assess simulated disc removal including efficiency metrics, volume removal and rate of disc removal and 4) to assess the performance of skilled and less-skilled participants utilizing these metrics.

Manuscript

Performance in a Simulated Virtual Reality Anterior Cervical Discectomy and Fusion Task: Disc Residual, Rate of Removal and Efficiency Analyses.

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Manuscript abstract

Background:

Anterior cervical discectomy and fusion (ACDF) is among the most common spine procedures. The Sim-Ortho virtual reality simulator provides a validated anterior cervical discectomy and fusion (ACDF) simulated task. We aim in this study to describe a methodology to study the three-dimensional data of the discectomy component of the task and analyze different performance metrics across participants with different levels of surgical expertise.

Methods

We recruited participants with different levels of expertise to perform a standardized ACDF simulation task. The three-dimensional structural data recorded by the simulator were extracted after each step. We collected and analyzed other data including performance duration, disc volumes, and rate of removal.

Results

Twenty-seven participants were included and divided into three groups: medical student, resident, and post-resident groups. The post-resident group spent 61.8% of their surgical time actively working on disc, compared to 53% and 30.2% in the resident and medical student groups, respectively ($p = 0.01$). Medical students left almost three times of disc residual as the resident and post-resident groups ($p = 0.068$). During the annulotomy component, the post-resident group removed 47.4% more disc than the resident and 102% more than the medical student groups ($p = 0.03$).

Conclusion

Expert performance is associated with higher efficiency compared to resident and medical student groups. The amount removed and rate of removal represent other features of expertise observed during the annulotomy stage of the discectomy. These differences expose some of the features of experts' performance that can be further studied and taught to junior trainees.

Introduction

Surgical educational paradigms are evolving to include new methods of assessment and training associated with a shift from the current apprenticeship model to a competency-based curriculum.[52] Studies have demonstrated the effectiveness of surgical simulators in surgical skills evaluation and training along with the transferability of acquired surgical skills to patient operative environment.[22, 46, 52, 68-71] Surgical simulation has the potential to effectively train residents to gain surgical skills outside the constraints of the operating room.[55] The use of validated metrics of performance in addition to the simulated model can result in a tool that is able to not only assess surgeons' performance but can help improve their skills.[63, 72, 73] The use of such a model has shown superiority in helping surgical trainees achieve proficiency benchmarks when compared to the standard model of surgical education.[63]

Virtual reality (VR) surgical simulation is an evolving tool that can be used in training surgical trainees and assessing their surgical performance.[73, 74] Several VR simulators for spine surgery are available and have undergone validity testing.[13, 54] However, only a few VR platforms can deconstruct and simulate complex, multifaceted spine procedures.[42] The Sim-Ortho VR simulator platform utilizes three-dimensional (3D) visual, auditory, and haptic feedback to provide the user with an immersive experience. Anterior cervical discectomy and fusion (ACDF) is among the most common neurosurgical procedures.[75] This procedure requires the trainee to gain proficiency in multiple areas, including understanding anatomical planes, appreciating the feeling of different tissues, and achieving a safe decompression of the neural elements.[55]

One of the main advantages of VR simulators is their ability to record a huge amount of data during a simulated task.[50, 76] This can be used to develop validated metrics of performance, an essential step in developing simulation-based training models.[63, 76] These metrics can provide the learner with a quantitative performance benchmark to work toward and can provide feedback to meet specific proficiency benchmarks.[63] The Sim-Ortho VR platform records a large amount of data of each user performance including a constructed 3D representation of each simulated structure after each step of the simulated surgical procedure. Data obtained from the simulator were used to obtain face, content, and construct validity of the ACDF task on the Sim-Ortho virtual reality platform.[42] In addition, artificial neural network algorithms, a subset of machine learning, were used to accurately classify surgical performance on the ACDF task and identify the importance of specific performance metrics in surgical expertise.[46, 58] However, the 3D data generated by the simulator has not been investigated before.

The objectives of this study are 1) to develop a methodology to extract 3D data recorded by the Sim-Ortho virtual reality simulator platform associated with the discectomy component of the ACDF simulation, 2) to utilize this methodology to accurately reconstruct and quantitate disc dimensions and volumes, 3) to develop a series of novel metrics to assess simulated disc removal including efficiency metrics, volume removal and rate of disc removal and 4) to assess the performance of skilled and less-skilled participants utilizing these metrics.

Methodology

Participants

Thirty-three spine neurosurgeons and orthopedic surgeons, spine fellows, and neurosurgical and orthopedic residents, and medical students were recruited. Experience using the Sim-Ortho platform to perform the ACDF simulation was an exclusion criterion. One fellow and two neurosurgeons were excluded since their training and/or practice was not spine-focused. As the Sim-Ortho VR platform is optimized for right-handed users, three left-handed participants were excluded. The remaining 27 participants were a priori categorized into 3 groups: post-resident (neurosurgical and orthopedic spine surgeons and spine fellows, n=9), resident (senior and junior neurosurgical and orthopedic residents, n=12) and medical student (n=6) groups. Participants signed a consent form approved by the McGill University Health Centre Research Ethics Board, Neurosciences-Psychiatry before trial participation. They provided demographic data regarding age, gender, level of training, and VR simulator experience.

The virtual reality simulator

Sim-Ortho is a virtual reality simulator platform that uses 3D stereoscopic glasses, advanced haptic technology, audio feedback, and realistic simulated structures to help achieve an immersive simulated experience (Figure 1).[42, 46] In addition, the simulator collects a vast amount of information during the simulated task that includes instrument tip position, instrument angulation, number of contacts of each simulated structure, force applied to, and the amount removed from each structure. This information is collected every 20 milliseconds, which allows the generation of a new set of information such as the rate of tissue removal.

The simulated ACDF task

The C4-C5 ACDF simulated task on the Sim-Ortho platform has been shown to have face, content, and construct validity.[42] The task consists of three animated and four interactive steps including annulotomy, discectomy, osteophyte removal, and posterior longitudinal ligament (PLL) removal. During the annulotomy step, participants use a simulated number 15 scalpel to make a box-like incision to expose the disc. The participant then uses a set of different tools to complete the discectomy down to the PLL. These tools include a bone curette, a disc Kerrison rongeur, and a 2mm pituitary rongeur.[42, 46, 58] After completion of the discectomy, a simulated 3mm burr is employed for osteophyte removal and a simulated Kerrison rongeur is used to remove the PLL. This study focuses on the annulotomy and discectomy components of the simulated task.

Participants were provided with standardized verbal and written instructions along with a demonstration of simulated instruments and their use. Each step is distinctive and once completed the participant proceeds to the next step and is not allowed to revisit previous steps. The segmentation of the simulated task aims to allow each step to be evaluated and taught separately. No time limit was set for the procedure and no questions were allowed once the simulated procedure commenced.

Three-dimensional Disc Structure

The Sim-Ortho platform outlines the simulated disc as an anterior annulus and a posterior disc component representing the nucleus pulposus (Figure 2 A, B, and C). We processed the three-dimensional data generated by the simulator using 3D slicer software (version 4.10.2; https://www.slicer.org/), an open-source platform for the analysis of medical imaging information and similar data sets.[77] We used the segmentation tool to extract the 3D structures from their background. An automated thresholding method (Otsu's thresholding) was used in our segmentation process.[78] The information generated was further edited through Meshmixer (3.5 version, http://www.meshmixer.com, Autodesk Meshmixer (RRID:SCR_015736)), an open-source 3D modeling software that has a variety of tools to deal with 3D meshes. The baseline volumes of the anterior annulus and remaining posterior disc were determined. Previous studies demonstrated variation in surgical performance when users interact with a critical part of the simulated surgical tissue.[42, 43] The disc was further subdivided into 3 areas based on the anteroposterior disc diameter (the depth of the disc) with each area having an anterior-posterior diameter of 0.51cm (Figure 2D). This division aims to assess each region separately and allows for the detection of performance differences especially in areas closer to the dura.

Quantification of disc volumes and rate of disc removal

We recorded the baseline volumes of the disc (V), including the anterior disc annulus (V_A) and posterior disc nucleus (V_N). In addition, we have recorded the volumes of the same structures after the first (V_1, V_{A1}, V_{N1}) and the residual (V_2, V_{A2}, V_{N2}) after the second step of the simulated task. We used the equation $\Delta V = V - V_2$ to determine the volume of disc removed during the total discectomy task (ΔV). In addition, we calculated the volume removed during the first step (ΔV_1) and the second step (ΔV_2) using the following equations $\Delta V_1 = V - V_1$ and $\Delta V_2 = V_1 - V_2$. Following the same methodology, we calculated the volume removed during both stages for both the annulus and nucleus. (Table 2)

The total duration of the procedure (d) and the duration of the first (d_1) and seconds (d_2) stages were calculated. Using the volumes calculated and durations, we were able to calculate the rate of removal. The rate is calculated by dividing the volume removed by the duration. For example, to calculate the rate of removal of the disc during the whole discectomy task we used the following equation: Rate = $\Delta V/d$. Similarly, the rate of removal of each disc component during each stage of the simulated task was calculated.

We as well reported an efficiency metric called the efficiency index (EI). EI is a measurement of time spent in active contact with simulated structures over the total time expended.[44, 79] EI of each area of the disc was calculated using the time spent with the instrument tip present in the areas studied. Table 2 summarizes the abbreviations and equations used to calculate the volumes and rate of disc removals.

Statistical analysis

The data were analyzed using R software version 4.0.2 (The R Foundation for Statistical Computing http://www.r-project.org/). Due to the small size of the groups, we used Kruskal–Wallis test to compare the groups' means. Dunn's Multiple Comparison Test was used to perform a post hoc analysis of the groups. Values are outlined as means (SD) and statistical significance was set as $p < 0.05$.

Results

Participants:

Demographic data and VR experience of the 27 trial participants included are outlined in Table 3.

Disc Measurements and Volumes

The C4-C5 disc (including the anterior annulus and posterior nucleus) in the ACDF simulation investigated had a maximum transverse diameter of 2.13 cm, an anteroposterior diameter (depth) of 1.53 cm, and a height of 0.76 cm (Figure 2B and 2C). The total simulated disc volume was 1.029 cm^3, with a disc annulus measuring 0.0654 cm^3 and the disc nucleus measuring 0.9605 cm^3. The calculated volumes of areas 1, 2, and 3 were 0.289, 0.448, and 0.292 cm^3, respectively (Figure 2D).

Procedure Duration and Efficiency

The medical student group took 563.26 (234.74) seconds to perform the task while the post-resident and resident groups took a mean of 474.56 (180.44) and 474.19 (147.95) seconds, respectively. The difference between the groups was not statistically significant (p = 0.67). The EI for the post-resident group was 0.62 (0.16) for the total discectomy task (annulotomy and discectomy), while residents and medical students had an EI of 0.53 (0.19) and 0.30 (0.09), respectively. This difference between groups was found to be statistically significant (p = 0.01) with post hoc analysis showing a statistically significant difference between the post-resident and the medical student group (p = 0.01). The largest difference in EI between groups is seen in area 2 of the disc during the first stage of the simulated task. The post-resident group spent 21.5% (0.08) of their time in active contact with the disc compared to 9.97% (0.05) for resident and 10.2% (0.07) for the medical student groups. The difference between the groups shows a statistically significant difference (p = 0.003). Post hoc analysis demonstrated a statistically significant difference between the post-resident and both the resident (p = 0.004) and the medical student (p = 0.04) groups. Table 4 details the groups' performance in terms of duration and efficiency index.

Volume and Rate of Disc removal

During the annulotomy component of the discectomy, a trend was observed for more disc removal at a higher rate with an increase in the level of expertise (Table 5). The post-resident group removed 22.25% of disc (mean volume of 0.23 cm^3 (0.0846)) compared to the residents 15.25% (mean volumes 0.16 cm^3 (0.0809)) and the medical students 10.98% (mean volume 0.113 cm^3 (0.0792)). A statistically significant difference between means was identified (p = 0.03) and on post hoc analysis, a statistically significant difference was found only between the post-resident and medical student groups (p = 0.029).

During the annulotomy, the post-resident group removed the disc at a higher rate with an average of 2.52 mm^3/s (1.15 mm^3/s) compared to the resident and medical student groups (1.71 mm^3/s

(0.86 mm^3/s) and 1.03 mm^3/s (0.56 mm^3/s), respectively). A statistically significant difference was found when comparing the group means ($p = 0.018$). On post hoc analysis, only the post-resident and medical student groups were significantly different ($p = 0.015$).

During the second stage of the discectomy, the post-resident and resident groups removed disc at a higher rate with less residual disc compared to the medical student group, but no statistically significant difference was found between the groups (Table 5). For the total discectomy procedure (both stages), the post-resident group removed the disc at a mean rate of 2.24 (0.605) mm^3/s, the resident group at 2.27(0.670) mm^3/s and the medical student group at 1.66 (0.597) mm^3/s. The difference between groups was not statistically significant ($p = 0.15$). The mean total disc removed by the post-resident group was 94.27% (mean volume of 0.97 cm^3 (0.068)) while the resident group and medical student group removed 96.21% (mean volume 0.99 cm^3 (0.068)) and 85.5% (mean volume 0.88 cm^3 (0.28)) of the disc, respectively. The difference was not statistically significant ($p = 0.78$).

Residual location

During the first stage of the discectomy, a decrease in the amount of the residual disc at all three areas of the disc is associated with the increase of the level of expertise. A statistically significant difference between groups only exists in area 2 ($p = 0.035$).

Looking at the areas of the residual disc at the end of the procedure, we found a trend of increasing residual as we move toward the deeper areas of the disc. Residual disc in area 3 is almost double the residual in area 2 for both the resident and post-resident groups. No statistically significant difference exists between the groups when comparing the average residual per area (Table 6).

Figure 3 highlights some of the main findings of this study through boxplot graphs.

Discussion

In this study, we analyzed data generated from a validated simulated ACDF procedure on the Sim-Ortho platform to explore different aspects of performance during the annulotomy and discectomy components of the simulated ACDF procedure. We described a methodology to extract 3D data from the simulator and obtain disc measurements and volumes. The open-source platforms used in this study were useful in achieving the objectives of this study. We were able to obtain and quantitate the volume of the simulated 3D structures. The obtained data permitted a more granular assessment of metrics including disc volume removed, rates of disc removal, and efficiency metrics. We used these metrics to describe some of the performance differences between the groups exposing some of the features associated with expert performance.

Our results are consistent that during the annulotomy component of the procedure, the post-resident group removed more total disc and inner disc volumes and at a higher rate than the other groups, but this was only significant between the post-resident and medical student groups. The standardized preprocedural information instructs participants to make a box-like incision in the annulus but did not give specific details about the depth of the incision or how much total disc to remove during this part of the procedure. It can be suggested that the post-resident group procedural knowledge allowed this group to initially make larger and deeper incisions with the scalpel and remove more overall volume during the annulotomy. Since it is safe to do so, the metric of making a larger incision with removal of more disc underneath the annulus at a faster rate during the annulotomy is consistent with being associated with increased expertise. The area analysis results demonstrated a statistically significant difference in area 2 of the disc. The post-resident group used their instruments significantly more in the deeper portion of the disc, mainly area 2, to remove disc tissue while residents and medical students tend to spend more time in the superficial part of the disc (area 1). The post-resident group had a statistically significantly higher EI in area 2 compared to the two other groups. EI is used to assess efficiency, in the form of cognitive-motor skills that focus on decision-making abilities related to next step planning while performing the task.[45] This difference between the groups could indicate a feature of expertise that is associated with scalpel use in the annulotomy stage. Medical students and residents may not be as aware of the anatomy and how to use the scalpel safely and efficiently. Most medical students' incisions during this stage were line-like incisions in the annulus compared to larger incisions that went deeper and extend to the endplates that are seen with more expert performance (Figure 4).

Looking at the residual disc and rate of removal during the whole discectomy task, no statistically significant difference exists between the groups. It is interesting that while residents removed the disc at a slightly higher rate and ended up with a slightly smaller residual than the post-resident group, the resident group has a lower EI in area 2 and area 3 of the disc when compared to the post-resident group. This could be explained by the possibility that the post-resident group might tend to favor safety over efficiency. The post-resident group spent more time actively removing disc tissues while trying to decrease the risk of injuring important structures. The validation study of this ACDF procedure has demonstrated a statistically significant difference between the groups related to force application, with senior residents applying the most amount of force.[42] It is possible that the post-resident group traded the slightly higher rate of removal with lower force application to decrease the risk of injury to important structures. Future studies could assess instrument force application in different parts of the disc to further explore its role in defining surgical expertise.

The application of our presented methods can extend to other different simulated scenarios using the Sim-Ortho and other VR simulation platforms. Valuable information such as the location of the entry point and the course of a pedicle screw and the amount of facet joint removed during a laminectomy could be produced from the raw data recorded by the simulator. These data could be further studied to develop new performance metrics. In addition, combining these 3D data with other data such as force and instrument tracking might expose some hidden features of performance associated with expertise. Artificial intelligence and machine learning algorithms were able to classify participants based on their surgical expertise.[46, 49, 53] AI-based tutor systems can analyze performance instantly and provide feedback to participants.[50] It is possible to integrate 3D data with other AI-derived personalized feedback systems to build a better model to teach surgical expertise and improve surgical performance.

Limitations

The Sim-Ortho VR surgical simulator faces some limitations in simulating the complexity of the realistic ACDF procedure. The platform's simulation of the annulus does not extend further than the anterior disc and needs to be improved. In addition, this simulator is optimized for right-handed participants preventing comment on left-handed individuals and limits the ability to assess bimanual performance.[43, 47] The recruitment of small numbers of participants from one institution limited our ability to find significant differences and comment on the generalizability of the results. Future studies should involve other national and international institutions and take advantage of national or international meetings to improve recruitment.[55]

Conclusions

This study demonstrated a methodology to assess the 3D virtual reality structures and provide novel insights into surgical performance. The annulotomy stage of the discectomy may be one differencing metric useful in formative and summative assessment educational paradigms.

Thesis Summary

We were able in this work to demonstrate the feasibility of our methods to extract 3D data from the Sim-Ortho VR platform. We were able to calculate the dimensions of the disc and quantify the volumes. We used the data obtained to assess some novel metrics of performance that were not studied before. In addition, we described some features of expertise related to the annulotomy stage that could be used in surgical training. The application of our presented methods can extend to other different simulated scenarios using the Sim-Ortho platform. Using 3D data from the simulator, valuable information such as the entry point of a cervical lateral mass screw, the course of the pedicle screw, and the amount of facet joint removed during a laminectomy could be produced from the raw data recorded by the simulator. In addition, combining these 3D data with other data such as force and instrument tracking might expose some new features of performance associated with expertise.

We have studied different aspects of performance using a combination of 3D data and other metrics. We found that the increase in the amount of inner disc material removed and a higher rate of removal in the initial stage of the discectomy to be associated with expertise. This finding exposes a feature of expertise that could be taught up front to medical students to help improve their surgical performance.

Another interesting finding of this work is that despite that the most expert group showed a higher EI, especially in areas adjacent to the dura, no difference exists between the groups when looking at the rate of removal and amount of disc residual left at the end of the procedure. This might be explained by the fact that experts favor safety over efficiency, and they use a lower amount of force especially in the areas adjacent to the dura. Future studies can investigate the relationship between force application and expertise especially in areas next to important structures such as dura and nerves.

Future directives

Future studies can focus on analyzing different areas of instrument force application during the discectomy task to help better understand the results of this study. Identifying statistically significant differences in performance might help expose some of the features of expertise that can be further studied and taught to junior trainees.

In addition, three-dimensional data generated by our methodology could be explored further. Artificial intelligence and machine learning algorithms were able to classify participants based on their surgical expertise.[46, 49, 53] AI-based tutor systems can analyze performance instantly and provide feedback to participants.[50] Moreover, machine learning and AI algorithms can be used in visual pattern analysis.[80] Incorporating 3D data into the different AI-based algorithms, might help in improving their performance. In addition, they might expose some novel metrics of performance that were not studied before

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Sim-Ortho™
OSSimTech

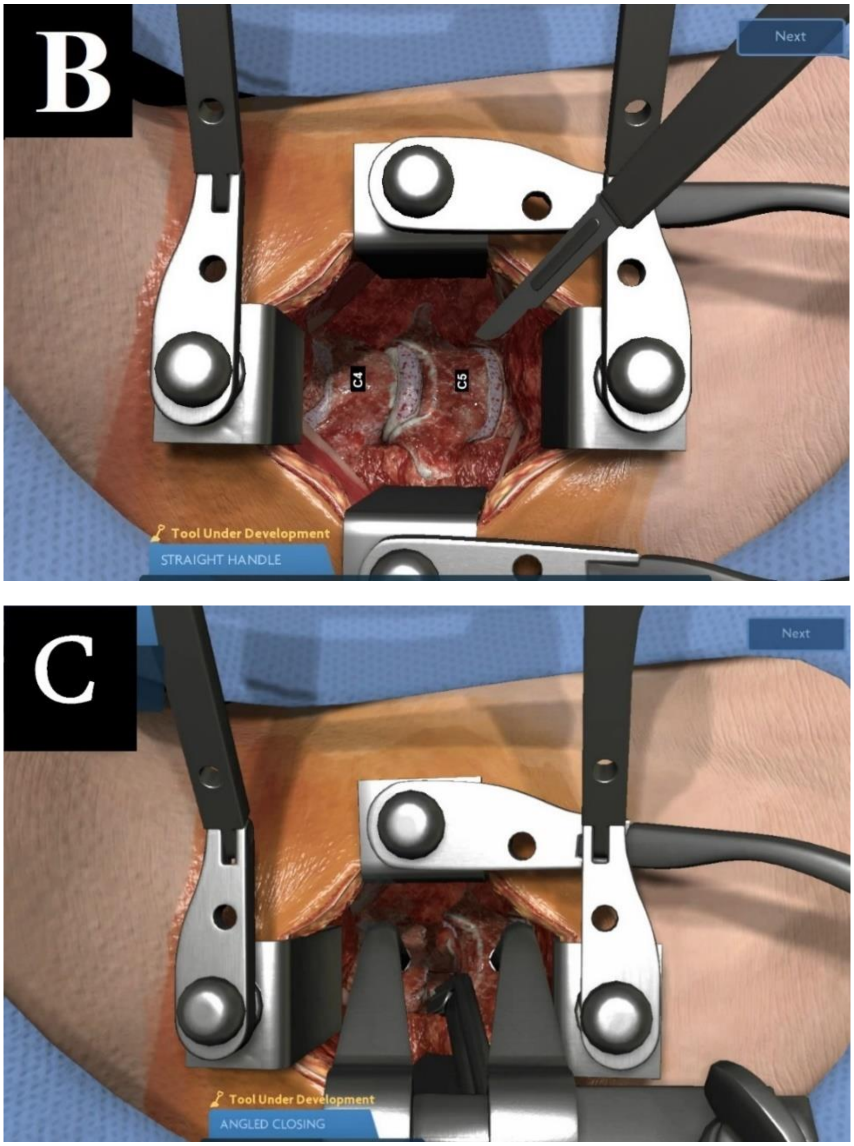


Figure1. (A) Sim-Ortho VR simulator showing the (1) robotic arm that employs an advanced haptic feedback technology to provide tactile feedback to the user. (2) Different tools' handles that can be used in the simulated scenario, (3) 3D glasses, (4) 3D monitor, and (5) Secondary monitor. (B) The surgical view prior to starting the simulated C4-5 ACDF procedure showing the surgical field and a number 15 blade. (C) The simulated task at the end of the discectomy, showing a pituitary rongeur removing the last piece of the simulated disc.

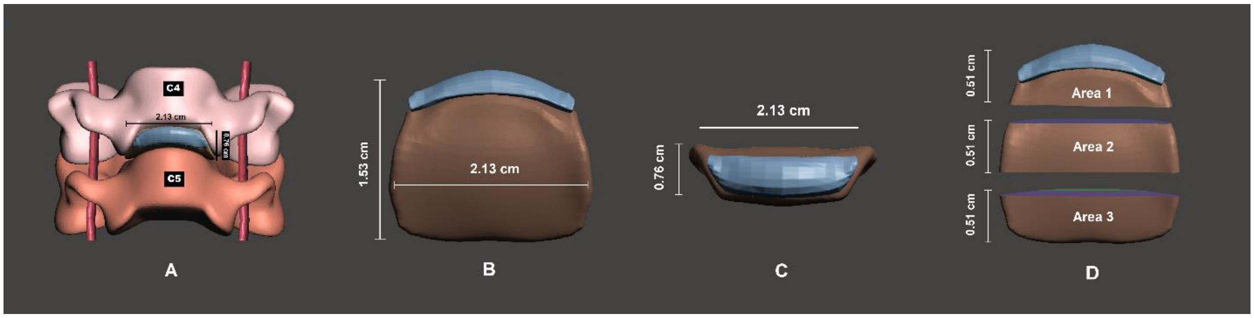
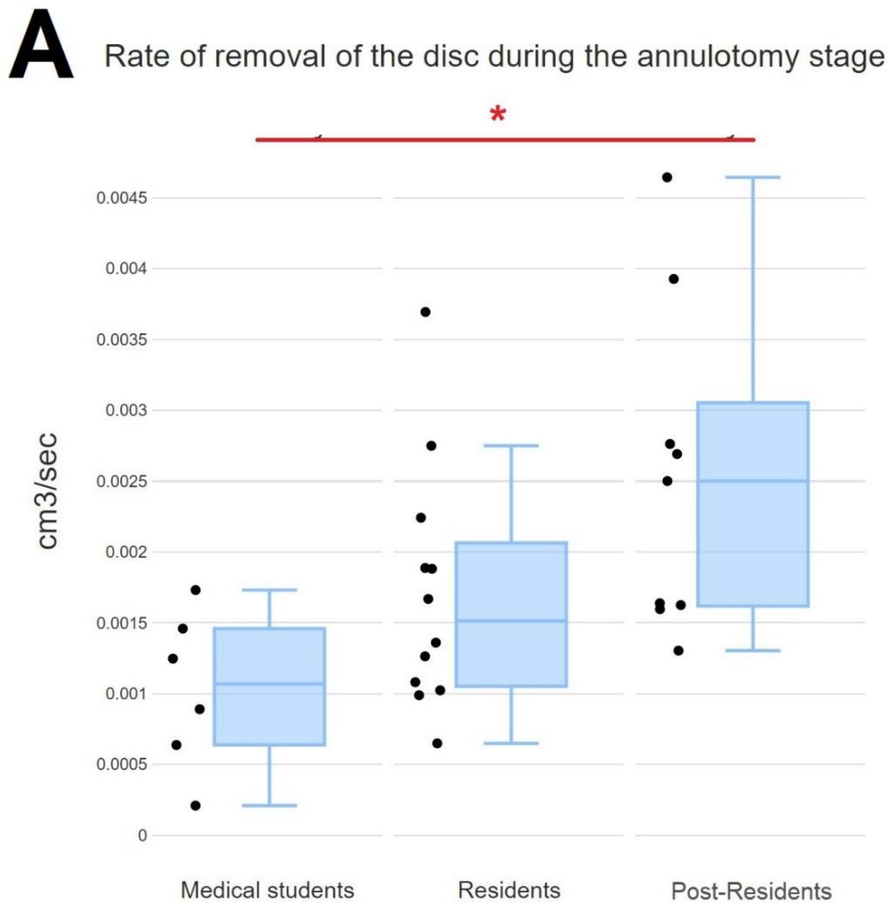


Figure2. Three-dimensional reconstructions of the simulated disc and surrounding structures. (A) Disc in relationship with the C4 and C5 vertebral bodies along with the vertebral arteries. (B) Superior view of the disc outlining the transverse and anteroposterior disc measurements. (C) Anterior view of the disc with height and transverse measurements (D) The three different disc areas are divided on the basis of depth with each area measuring 0.51 cm in the anteroposterior diameter.



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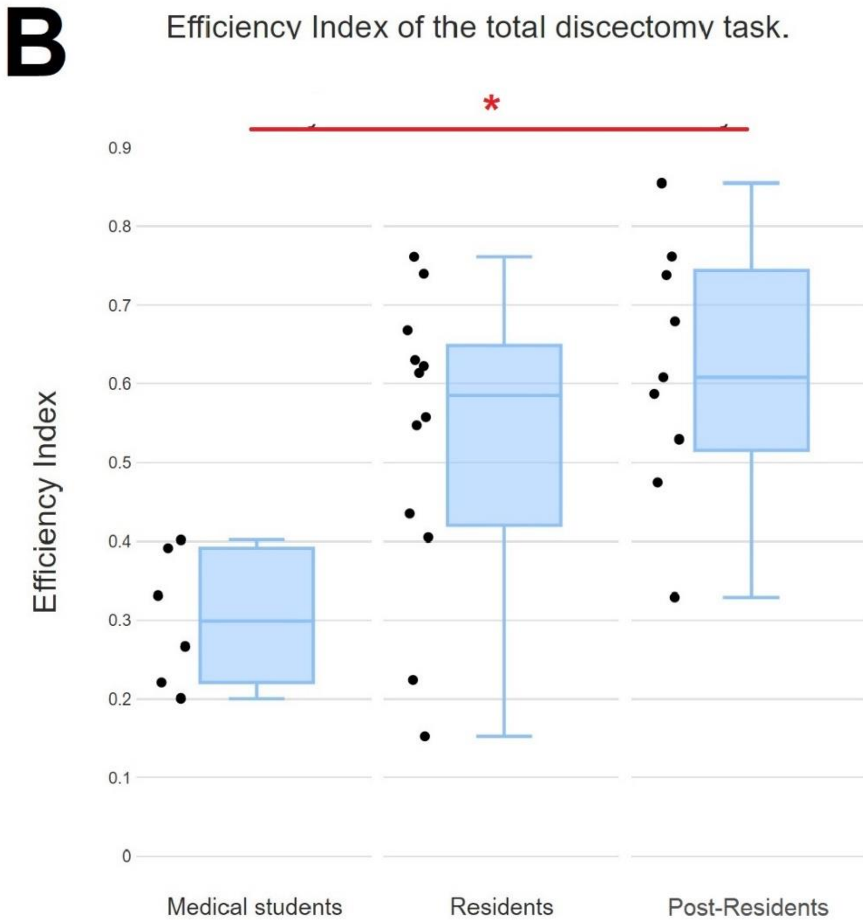

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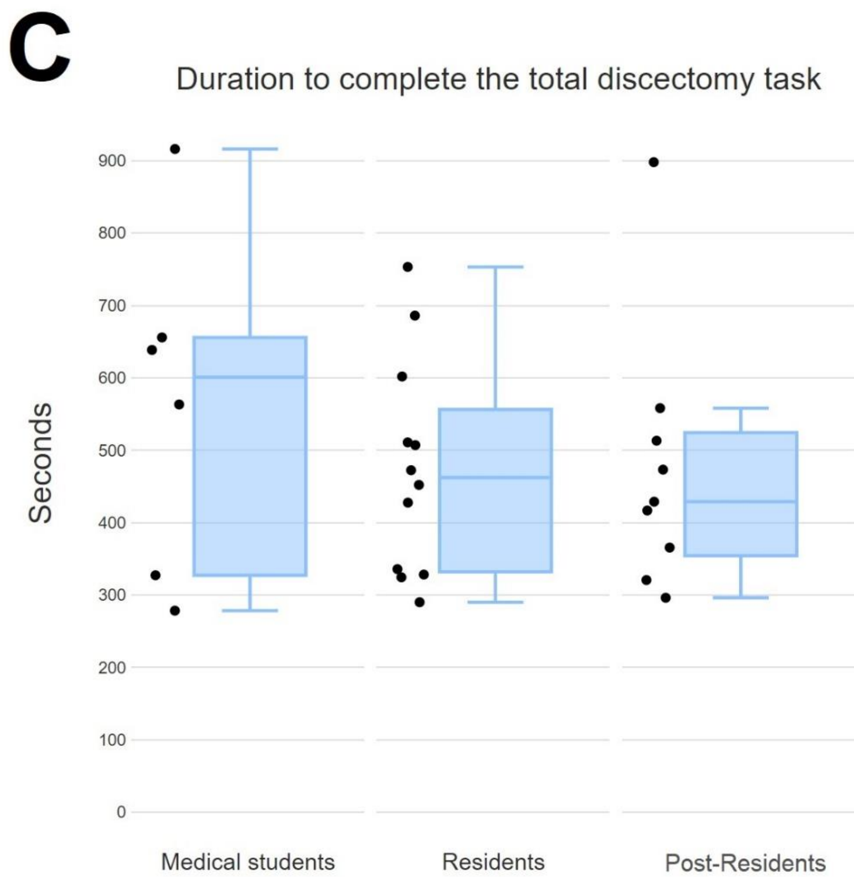

Figure 3. Boxplot graphs of study findings. Figure 3A shows the rate of removal of the disc during the annulotomy component of the discectomy between the different groups. Figure3B shows the efficiency index during the total discectomy task. Figure 3C shows the total duration to complete the task.

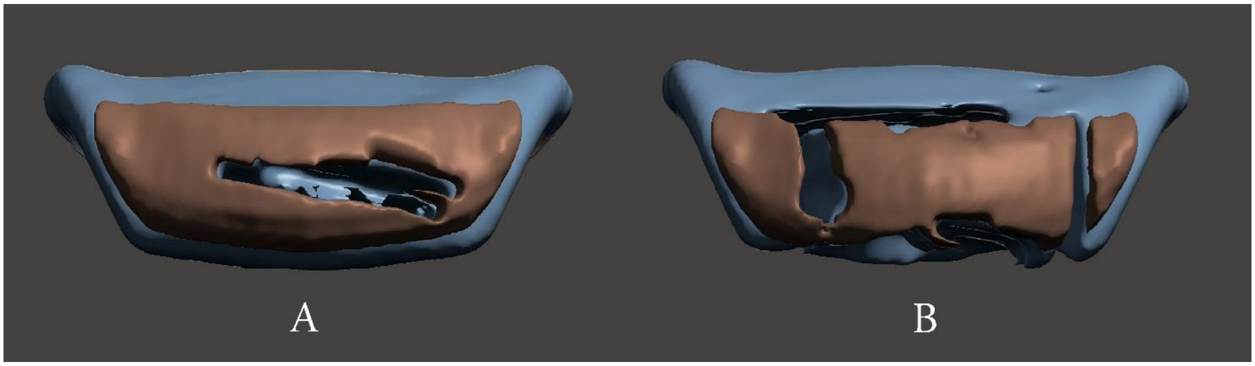

Figure 4. Medical students (A) and post-resident group (B) performance during annulotomy stage. The Post-resident group tends to make a larger box incision that reaches the endplates.

Table 1: Summary of interactive VR spine surgical simulators available in the literature

No.	Key Publications (year)	Simulator	Simulator description and Simulated Procedure(s)	Advantages & disadvantages of the simulator
1	Luciano et al (2005,2011)[81, 82] Alaraj (2013)[83] Roitberg et al (2013)[84] Gasco et al (2014)[85]	ImmersiveTouch®	ImmersiveTouch® is one of the first systems to provide an integrated high-resolution stereoscopic display and haptic feedback. The VR simulator uses head and hand tracking through robotic arms to compute the user's perspective and movements around the virtual environment. The system can be used to simulate many spinal surgery scenarios that	**Advantages:** • The simulator provides an immersive experience by providing both visual and haptic feedback. • The simulator can record performance data that allows for skill level assessments and validation studies. • The simulator is capable of importing patient-specific imaging studies into the simulation training. • The simulator can simulate multiple spinal procedures. • The simulator is available and one of

			include pedicle screw placement, vertebroplasty, and lumbar puncture.	the most widely studied spine simulators. **Disadvantages:** • No audio feedback. • No validation studies of the spine procedures were carried out.
2	Mostafa et al (2017)[86] Ryu et al (2017)[87]	NeuroSimVR®	The NeuroSimVR® is a 3D stereoscopic VR simulator that uses a single robotic hand and VR glasses to simulate the pedicle screws insertion procedure. The simulator visualizes the 3D structure of the bony spine and the	**Advantages:** • The simulator utilizes stereoscopic glasses and haptic feedback to provide a realistic simulated experience. • Face and content validity testing were attempted. The authors tried to compare the simulator with immersive touch®.[86]

			surrounding structures as well as X-ray views to guide the user interaction during the simulated task. Haptic feedback is provided through the robotic handle.	**Disadvantages:** • The simulator lacks audio feedback which can affect the immersive simulation experience. • The attempted validation study is limited by the number of participants (only 6 physicians) which affected the ability to do a quantitative statistical analysis. • Haptic feedback is not realistic as per the validation study. • No clear description of what raw data is recorded by the simulator. • Utilizing a single handle might pose some difficulties in carrying out validation studies.

3	Hou 2018[88, 89]	Virtual Surgical Training System (VSTS)	The VSTS is a VR simulator that aims to simulate cervical spine drilling and thoracic pedicle screw placement. The simulator uses a screen and a robotic arm for haptic feedback.	**Advantages:** • The spine model in the simulated VR scenario is obtained from a normal human spine. • Validation studies were attempted.[88] **Disadvantages:** • No face, content, or construct validity studies were done. • The simulator uses a two-dimensional screen with a 3D representation of tissues. • No audio feedback. • No available information regarding whether performance data is recorded by the simulator.

4	Alsideri, G (2018)[51] Bissonnette et al (2019)[90]	NeuroVR®	The NeuroVR® (formally known as NeuroTouch®) is a VR platform that incorporates haptic and audiovisual feedback. The simulator uses a microscopic view of the spine to complete a simulated left L3 hemilaminectomy. Each participant uses a simulated drill in the dominant hand and a simulated suction in the non-dominant hand to complete the task.	**Advantages:** • The simulator provides an immersive experience by providing audiovisual and haptic feedback. • The simulator records a vast amount of data that allowed the conduct of a validation study[51] and implementation of machine learning algorithms to assess surgical expertise.[90] **Disadvantages:** • This simulator does not represent the multifaceted situations encountered in the operating room during the complex spinal procedure. • The validation study focused only on

				the drilling part of the laminectomy. • The simulated task allows for the use of the drill only to complete the simulated laminectomy task. The simulator does not simulate a Kerrison rongeur. • The simulated model does not provide a realistic haptic differentiation between the deeper portion of the lamina and ligamentum flavum. • The validation study only incorporated a small number of participants.

5	Xin (2019,2020)[91, 92]	The immersive virtual reality surgical simulator for pedicle screws placement. (IVRSS-PSP)	The IVRSS-PSP is a VR platform that is designed to simulate pedicle screw placement. It utilizes a heads-on display (HUD) unit to visualize the simulated surgical procedure and operative environment. A robotic arm is used to provide haptic feedback. The simulated handle was 3D printed according to the real surgical instrument.	**Advantages:** • The simulator integrates a HUD and haptic feedback to provide an immersive experience by simulating the surgical procedure and the surrounding operative environment. • The spine model in the simulated VR scenario is obtained from a normal human spine. • The simulated handle was 3D printed according to the real surgical instrument. • Validation studies were attempted[92] **Disadvantages:** • No face, content, or construct validity studies were done.

				• No available information about what data could be recorded by the simulator. • Simulation is limited to screw placement with no clear description of the simulated steps or available tools.

6	Lohre (2020)[93]	PrecisionOS Technology®	This simulator is a VR simulator that uses a HUD unit and haptic controllers to simulate multiple orthopedics and spine procedures including spinal endoscopic surgical training.	**Advantages:** • The HUD display provides an immersive experience by simulating the surrounding surgical environment. • The simulator has been studied for shoulder arthroplasty and demonstrated superior learning efficiency, knowledge, and skill transfer.[94] **Disadvantages** • The spine simulated scenarios are still new and have not been studied or validated. • The controllers do not provide realistic haptic feedback. • No data on what information is

				recorded by the simulator.

7	Ledwos et al (2019,2021)[42, 95] Mirchi et al (2020)[46] Alkadri et al (2021)[58] Reich et al (in-press)[96]	Sim-Ortho®	Sim-Ortho is a voxel-based VR simulator that uses stereoscopic 3D glasses and provides haptic and auditory feedback. The simulator has many simulated scenarios that include ACDF, lumbar discectomy, lumbar laminectomy, lumbar and thoracic pedicle screw insertion, and cervical lateral mass screws insertion. It allows the use of a wide range of simulated instruments.	**Advantages:** • The simulator can record a large amount of data including 3D data of each user performance. • The simulator can simulate multifaceted procedures as ACDF. • The simulator can simulate multiple spinal procedures. • The ACDF scenario has been validated (face, content, and construct) and studied through AI-based algorithms. **Disadvantages:** • Only a single robotic arm. • The simulator is optimized for right-handed users.

				• Other spinal procedures have not been validated yet.

8	Chen 2021[97]		This VR simulator consists of a HUD headset (that provides audio-visual simulation) and two controllers to interact with the simulated structures. The simulator is designed to simulate pedicle screws placement. The user can use different tools to interact with soft tissue and bone.	**Advantages:** • The spine model in the simulated VR scenario is obtained from a normal human spine. **Disadvantages:** • No face, content, or construct validity studies were done. • No 3D data representation or audio feedback. • Limited to drilling and pedicle screw placement. • No information if data is recorded by the simulator.
9	Charalambou (2021)[98]	TraumaVision®	This is a VR orthopedic simulator that uses a robotic arm to provide haptic	Unfortunately, no available literature to comment on the advantages or disadvantages of the simulator.

			feedback. It has a model for pedicle screw placement.	

Table 2: Summary of some abbreviations and equations used in this study.

Disc Removal: Annulus and Nucleus	
V, V_A, V_N	Basic volumes for disc (V), disc annulus (V_A), and disc nucleus (V_N).
V_1, V_{A1}, V_{N1}	Volumes of the disc and its components at the end of the first stage.
V_2, V_{A2}, V_{N2}	Volumes of the disc and its components at the end of the Second stage.
$\Delta V_1 = V - V_1$ $\Delta V_2 = V_1 - V_2$ $\Delta V = V - V_2$	ΔV_1, ΔV_2, and ΔV represent the volume of the disc (in cm^3) that was removed during the first stage, the second stage of the discectomy, and the total discectomy task, respectively. Similar equations were used to calculate the volumes of the disc components (annulus and nucleus) at the end of each stage.
Duration & Efficiency Index (EI)	
d, d_1, d_2	d represents the total duration of the discectomy task. d_1 and d_2 represent the duration of the first stage and second stage, respectively.
Efficiency Index (EI)	This is calculated by dividing the amount of time spent actively removing tissues by the total amount of time spent to complete the task.
Rate of removal	
Rate, $Rate_A$, $Rate_N$	Rate: The rate of removal of the disc during the discectomy procedure. It is calculated as $\Delta V/d$ and reported as cm^3/sec. $Rate_A$ and $Rate_N$ are calculated similarly (volume removed/time) and represent the rate of removal of the annulus and nucleus during the discectomy procedure, respectively.

Table 3: Participants Demographics

Groups	Medical students	Residents		Post-residents	
	Medical students	**Junior residents**	**Senior residents**	**Fellows**	**Spine surgeons**
Number of participants	6	7 (3 neurosurgery, 4orthopedics)	5 (3 neurosurgery, 2 orthopedics)	5 (5 neurosurgery, 2 orthopedics)	4 (2 neurosurgery and 2 orthopedics)
Mean age (SD)	23.67 (1.03)	27.4 (1.4)	30.6 (2.3)	36.2 (3.19)	54.3 (14.48)
Gender (n, %)	Female (1, 16.67%) Male (4, 66.67%) Non-binary (1,16.67%)	Female (2, 28.57%) Male (5, 71.43%)	Female (1, 20%) Male (4, 80%)	Male (5, 100%)	Male (4, 100%)
Previous VR simulation experience	5 (83.33%)	5 (71.43%)	4 (80%)	3 (60%)	4 (100%)

Table 4: Summary of the duration and EI of the groups.

	Medical students (n=6)	**Residents (n=12)**	**Post-residents (n=9)**	**P value (Kruskal–Wallis test)**
Duration				
Duration of first stage in seconds (SD)	109.14 (28.02)	91.32 (20.08)	95.41 (17.99)	0.25
Duration of second stage in seconds (SD)	454.12 (216.96)	382.87 (145.87)	379.15 (172.17)	0.71
Mean total duration in seconds (SD)	563.26 (234.74)	474.19 (147.95)	474.56 (180.44)	0.67
EI (first stage - annulotomy)				
EI of first stage (SD)	0.25 (0.13)	0.35 (0.17)	0.48 (0.15)	0.024*
EI of area 1 (SD)	0.098 (0.04)	0.15 (0.06)	0.11 (0.07)	0.13
EI of area 2 (SD)	0.1 (0.07)	0.1 (0.05)	0.22 (0.08)	0.003*
EI of area 3 (SD)	0.05 (0.1)	0.1 (0.13)	0.15 (0.15)	0.23
EI (second stage - discectomy)				
EI of second stage (SD)	0.31 (0.12)	0.58 (0.23)	0.66 (0.19)	0.013*

EI of area 1 (SD)	0.16 (0.06)	0.22 (0.08)	0.21 (0.06)	0.13
EI of area 2 (SD)	0.11 (0.05)	0.21 (0.11)	0.26 (0.26)	0.01*
EI of area 3 (SD)	0.05 (0.05)	0.15 (0.1)	0.20 (0.09)	0.025*
EI (total task - both stages)				
EI of total task (SD)	0.3 (0.09)	0.53 (0.19)	0.62 (0.16)	0.01*
EI of area 1 (SD)	0.14 (0.04)	0.2 (0.07)	0.19 (0.06)	0.15
EI of area 2 (SD)	0.11 (0.04)	0.19 (0.09)	0.24 (0.05)	0.009*
EI of area 3 (SD)	0.05 (0.04)	0.14 (0.08)	0.19 (0.08)	0.017*

Table 5: Summary of the amount and rate of removal of the disc during the simulated discectomy procedure.

	Medical students (n=6)	**Residents (n=12)**	**Post-residents (n=9)**	**P value (Kruskal–Wallis test)**
Volume removed during the first (annulotomy) stage				
ΔV_1 mean in cm^3 [SD] (% of total disc)	0.113 [0.0792] (10.98%)	0.157 [0.0809] (15.25%)	0.229 [0.0846] (22.25%)	0.027*
ΔV_{A1} mean in cm^3 [SD] (% of total annulus)	0.022 [0.0177] (33.53%)	0.0365 [0.0188] (55.64%)	0.039 [0.0189] (59.45%)	0.25
ΔV_{N1} mean in cm^3 [SD] (% of total nucleus)	0.092 [0.0627] (9.50%)	0.120 [0.0671] (12.46%)	0.190 [0.0738] (19.72%)	0.02*
Rate of removal during the first stage				
$Rate_1$ mean (in mm^3/sec) (SD)	1.03 (0.56)	1.71 (0.86)	2.52 (1.15)	0.018*
$Rate_{A1}$ mean (in mm^3/sec) (SD)	0.196 (0.121)	0.402 (0.227)	0.432 (0.256)	0.07
$Rate_{N1}$ mean (in mm^3/sec) (SD)	0.833 (0.453)	1.31 (0.684)	2.09 (0.944)	0.015*
Volume removed during the second stage				
ΔV_2 mean in cm^3 (% of V_1) [SD]	0.77 (84.1%) [0.296]	0.835 (95.8%) [0.109]	0.74 (92.5%) [0.108]	0.42

ΔV_{A2} mean in cm^3 (% of V_{A1}) [SD]	0.0417 (95.8%) [0.019]	0.0267 (91.8%) [0.0198]	0.0245 (92%) [0.018]	0.2
ΔV_{N2} mean in cm^3 (% of V_{N1}) [SD]	0.728 (83.5%) [0.286]	0.809 (95.9%) [0.099]	0.716 (92.5%) [0.098]	0.37
Rate of removal during the second stage				
$Rate_2$ mean (in mm^3/sec) (SD)	1.79 (0.74)	2.42 (0.773)	2.17 (0.601)	0.17
$Rate_{A2}$ mean (in mm^3/sec) (SD)	0.111 (0.065)	0.0697 (0.0511)	0.065 (0.0474)	0.23
$Rate_{N2}$ mean (in mm^3/sec) (SD)	1.68 (0.71)	2.35 (0.59)	2.10 (0.76)	0.12
Volume removed during the total discectomy task				
ΔV mean in cm^3 (% of total disc) [SD]	0.88 (85.52%) [0.280]	0.99 (96.21%) [0.0563]	0.97 (94.27%) [0.0682]	0.78
ΔV_A mean in cm^3 (% of total annulus) [SD]	0.064 (97.25%) [0.0033]	0.0632 (96.34%) [0.0046]	0.0635 (96.8%) [0.0024]	0.51
ΔV_N mean in cm^3 (% of total nucleus) [SD]	0.820 (85.12%) [0.277]	0.929 (96.43%) [0.055]	0.906 (94.04%) [0.067]	0.84
Rate of removal during the whole discectomy task				
$Rate_2$ mean (in mm^3/sec) (SD)	1.66 (0.597)	2.27 (0.670)	2.24 (0.605)	0.15
$Rate_{A2}$ mean (in mm^3/sec) (SD)	0.132 (0.056)	0.145 (0.046)	0.148 (0.043)	0.80

$Rate_{N2}$ mean (in mm^3/sec) (SD)	1.53 (0.575)	2.13 (0.625)	2.09 (0.563)	0.13

Table 6: Summary of the disc residual by area.

Volume removed during the first stage				
	Medical students (n=6)	**Residents (n=12)**	**Post-residents (n=9)**	**P value (Kruskal–Wallis test)**
Area 1 mean removed volume in cm3 [SD] (% of total area)	0.062 [0.038] (21.47%)	0.098 [0.043] (33.94%)	0.115 [0.029] (39.83%)	0.072
Area 2 mean removed volume in cm3 [SD] (% of total area)	0.0395 [0.036] (8.81%)	0.047 [0.039] (10.49%)	0.087 [0.038] (19.4%)	0.035*
Area 3 mean removed volume in cm3 [SD] (% of total area)	0.01 [0.014] (3.46%)	0.012 [0.011] (4.11%)	0.027 [0.036] (9.24%)	0.63
Residual at the end of the task (per area)				
Area 1 mean residual volume in cm3 [SD] (% of total area)	0.021 [0.045] (7.27%)	0.003 [0.004] (1.03%)	0.004 [0.007] (1.39%)	0.37
Area 2 mean residual volume in cm3 [SD] (% of	0.069 [0.0033]	0.014 [0.0046]	0.025 [0.0024]	0.5

total area)	(15.4%)	(3.12%)	(5.58%)	
Area 3 mean residual volume in cm3 [SD] (% of total area)	0.0554 [0.107] (18.96%)	0.0188 [0.033] (6.43%)	0.0303 [0.039] (10.26%)	0.57